University of Stirling
Department of Environmental Science

Wetland Change Assessment on the Kafue Flats, Zambia: A Remote Sensing Approach

Submitted for the degree of
Doctor of Philosophy (Ph.D.)
by
Christopher Munyati

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DECLARATION

I declare that this thesis has been composed by me and that the work which it embodies has been done by me and has not been included in another thesis. Where data from secondary sources have been used, they have all been duly acknowledged.

Signed: C. Munyati
Christopher Munyati

Date: 28th July 1997

DEDICATION

To father, Mwenda Munyati, whose endurance of odds was the inspiration which saw me through some trying moments during the study

ABSTRACT

The Kafue Flats floodplain wetland system in southern Zambia is under increasing climate and human pressures. Firstly, drought episodes appear more prevalent in recent years in the region and secondly, two dams were built on the lower and upper ends of the wetland in 1972 and 1978, respectively, across the Kafue River which flows through the wetland. The study uses multi-temporal remote sensing to assess change in extent and vigour of green vegetation, and extent of water bodies and dry land cover on the Kafue Flats. The change detection's management value is assessed. Four normalised, co-registered digital Landsat images from 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994 were used. The main change detection method used was comparison of classifications, supplemented by Normalised Difference Vegetation Index (NDVI) and Principal Component Analysis (PCA) change detection. Ancillary land use and environmental data were used in interpreting the change in the context of cause and effect.

The results indicate inconsistent trends in the changes of most land cover classes, as a result of manipulation of the wetland by man through annual variations in the timing and magnitude of regulated flows into the wetland, as well as burning. However, the results also show spatial reduction in the wetland's dry season dense green reed-grass vegetation in upstream sections which are not affected by the water backing-up above of the lower dam. Sparse green vegetation is replacing the dense green vegetation in these upstream areas. It is inferred that this dry season degradation of the wetland threatens bird species which may use the reeds for dry season nesting. It is proposed that ground surveying and monitoring work at the micro-habitat level is necessary to ascertain the implications of the losses. It is concluded that, in spite of difficulties, multi-temporal remote sensing has a potential role in wetland change assessment on the Kafue Flats at the community level, but that it needs to be supplemented by targeted, micro-habitat level ground surveys.

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CONTENTS

Page

LIST OF FIGURES

Figure | Page

LIST OF TABLES

Table		Page

Chapter 1

INTRODUCTION

1.1 Statement of the Problem

Concern about change in the size and quality of many of the world's wetland systems has been increasing as more and more wetlands are being converted to agricultural or urban use and by natural factors like and drought (Williams, 1990; Markham *et al*, 1993; Jensen *et al*, 1995; Ringrose *et al*, 1988; Mackey, 1993; Haack, 1996). Wetlands are important natural habitats which must be conserved (Williams, 1990). As a prelude to their conservation it is necessary to map them, determine whether or not they have changed over specified time periods, and quantify the changes, if any (Jensen *et al*, 1993). This task often may require timely and synoptic data collection and analysis. Remote sensing techniques can be helpful in such wetland studies and this study is an investigation into wetland change on a section of the Kafue Flats wetland area in Zambia (Figure 1.1), by remote sensing.

The simplest definition of a wetland is a land with soils that are periodically flooded (Williams, 1990). The Kafue Flats are flooded annually and, therefore, qualify to be placed in the wetland category. A general reduction in the amount and reliability of rainfall received in Zambia during the 1980s and early 1990s has been observed (Daka, 1995; Muchinda, 1988; Kruss, 1992; Sakaida, 1994). The reduction has generally resulted in an increase in the pressure on the ecological stability of river and wetland systems like the Kafue Flats, from enhanced human use of the water resource. Under this increased climatic and human pressure regime the underground and surface water

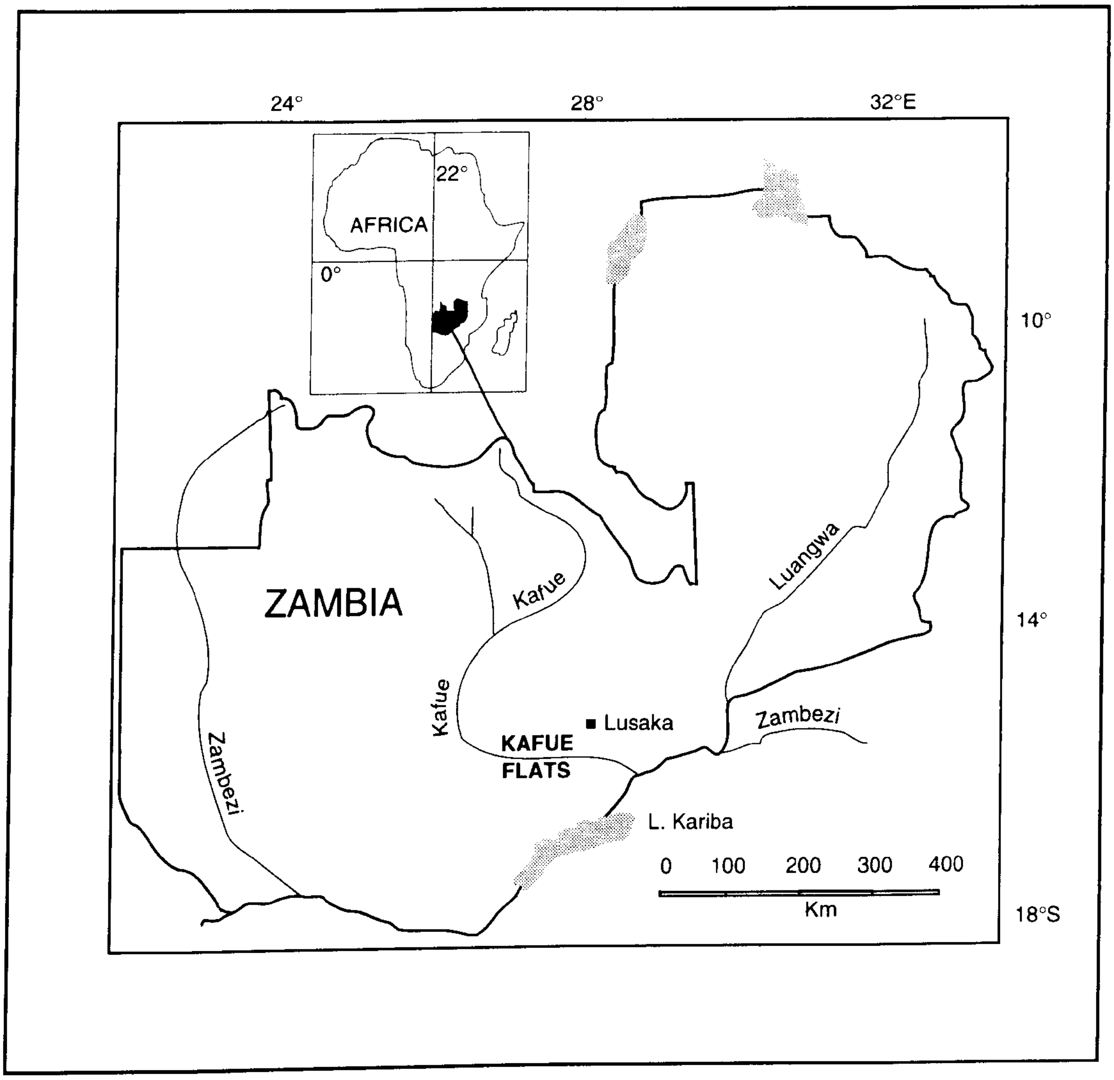


Figure 1.1 Location of the Kafue Flats in Zambia (modified from Rees, 1978).

recharge may not be sufficiently rapid to sustain a dense and vigorous green vegetation cover on the Kafue Flats. Assessing the trends in land cover characteristics of the Kafue Flats during the period 1984 - 1994 was the focus of the investigation that was undertaken. The study was restricted to the period 1984 - 1994 by the high cost and availability of digital images out with this period.

Being a wetland system under the threat of economic exploitation of its water resources, the Kafue Flats area has attracted a lot of research interest in the past. Zambia's largest hydroelectric scheme has been developed by damming the Kafue River which flows through the Flats. The country's largest irrigation scheme is also located on the Kafue Flats. The wetland, therefore, is of vital strategic importance to the Zambian economy in terms of energy and water supply. The wetland's importance as a habitat is underscored by the fact that it is home to a large variety of birds and mammals, including the endemic Kafue lechwe (*Kobus leche kafuensis*), a semi-aquatic antelope. Intercontinental migratory birds use the Kafue Flats on route to and from northern hemisphere areas during their escape from the northern hemisphere winter (rain season and summer on the Kafue Flats) (Douthwaite, 1978). Among the birds which live on the Kafue Flats is the wattled crane (*Grus carunculatus*) which was once said to be endangered (Douthwaite, 1974).

The combination of climatic and anthropogenic pressures by way of droughts, irrigation and dam storage, respectively, have led to speculation about land use change on the Kafue Flats. Investigating whether or not change had occurred in this study is undertaken primarily by multi-temporal remote sensing data analysis in a geographic information system (GIS) framework. Details about the environment and the climatic and anthropogenic pressures on the Kafue Flats are given in Chapter 2.

1.2 Scope of the Study

The study investigated the applicability of remote sensing to wetland change assessment on the Kafue Flats, and had the following hypothesis and objectives:

Research Hypothesis

- As a wetland habitat, the Kafue Flats are undergoing a trend of land cover degradation as a result of reduced amounts of water received. Multi-temporal, multi-spectral remote sensing can help in the identification, characterisation and quantification of the change.

Research Objectives

To test the hypothesis, the research objectives were:-

1. To assess the Kafue Flats vegetation regime for change in terms of vigour and spatial extent of cover, using multi-temporal remote sensing data.

2. To assess the Kafue Flats for other land cover changes, especially areal extent of water bodies and dry land, using multi-temporal remote sensing data.

3. To assess the wildlife habitat implications and usefulness of the changes detected, and methodology developed, for nature conservation and planning future use of the water resources on the Kafue Flats, in conjunction with ancillary land use and environmental data.

A review of the literature (Chapter 3) revealed that no comparable work had been done for the Kafue Flats, although Turner (1982) attempted a flood monitoring study by manually overlaying Landsat Multi-Spectral Scanner (MSS) image transparencies, with limited success. In addition, the World Wide Fund for Nature (WWF) Wetlands Project in Zambia used NOAA AVHRR Channel 2 data to monitor the extent of the annual flood on the Kafue Flats, until about 1994/1995, using IDRISI GIS software (WWF-Zambia, 1995, pers. comm.).

1.3 Rationale of the Study

The study was undertaken against the background of predictions about the ecological and hydrological changes on the Kafue Flats likely to result from dam operations which were made by many researchers (e.g. Chabwela and Ellenbroek, 1990; Douthwaite, 1974; Douthwaite, 1978; Howard and Aspinwall, 1984; Muyanga and Chipundu, 1978; Rees, 1976; Rees, 1978; Sayer and van Lavieren, 1975; Schuster, 1980; Sheppe, 1985; Turner, 1982). In general, verifying whether or not any of the predicted changes have occurred is important.

The methodology used for monitoring any of the predicted changes on the Kafue Flats will depend on factors like period of monitoring, the size of the area to be monitored, accessibility of ground sites to be monitored and the particular environmental aspect being monitored (e.g. wildlife numbers, water quality, vegetation). Changes relating to site specific phenomena in accessible parts of the Kafue Flats can be determined by ground surveys, even when the time scale is as long as ten years. Monitoring spatial phenomena like vegetation cover, extent of water bodies and other land cover phenomena, however, is more problematic. This is especially so, when it is being done over a long period of time, given the inaccessibility of some wetland areas, the large spatial extent of the area to be monitored and the lack of up to date maps. Remote sensing techniques may be more appropriate in this case because:

- Compared to ground surveying, remote sensing has the advantage of a synoptic coverage at any given time.
- Remote sensing techniques give more timely answers.
- The danger posed by wetland hazards like water accidents and encounters with dangerous animals (e.g. snakes and crocodiles) on the ground is reduced when remote sensing techniques are used (Jensen *et al*, 1986).

The main disadvantage of undertaking a study of land cover change on the Kafue Flats by remote sensing, in addition to other technical problems, is that subtle, gradual vegetation and other changes may not be detected at all. This is a general disadvantage of satellite imagery, because gradual deterioration in vegetation cover associated with drought or overgrazing occurs without distinct boundaries. This type of change is characterised by only a slight change in the spectral reflectance of large areas and is usually more difficult to detect on satellite imagery (Milne, 1988).

1.4 An Overview of Digital Image Processing in Remote Sensing and Relationship to Thesis Structure

The process of digital image processing in remote sensing typically involves some or all of the steps shown in Figure 1.2, as outlined by Jensen (1986). First, the nature of the problem is defined and all objectives and methods necessary to accept or reject research hypotheses defined. In this study the problem was wetland change assessment as outlined in Section 1.2, which, it was hypothesized, warranted a remote sensing approach (Section 1.3). Acquisition of alternative forms of remotely sensed digital data

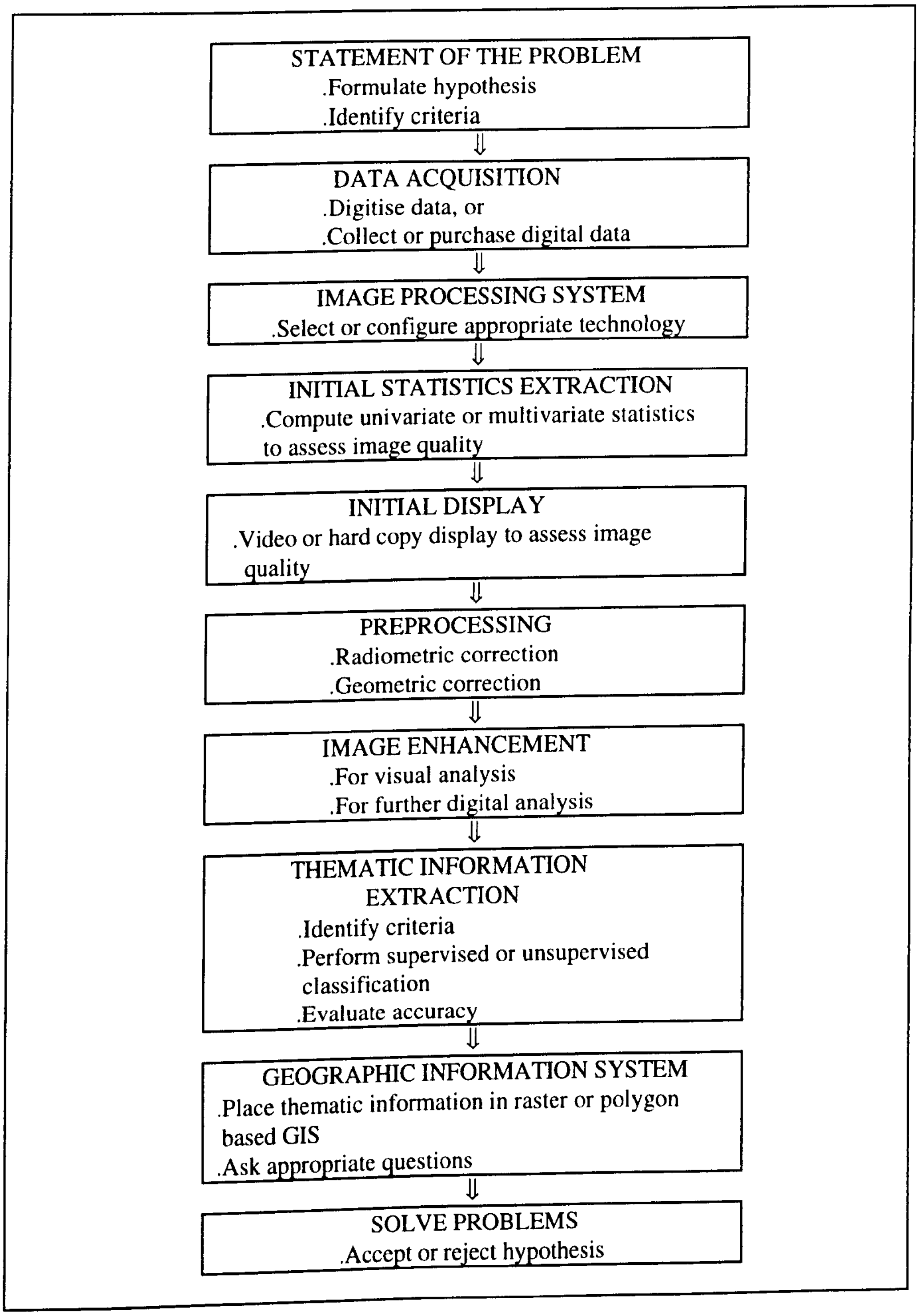


Figure 1.2 Digital image processing considerations in remote sensing (After Jensen, 1986).

must then be evaluated, for example digitising existing aerial photographs or obtaining already digital images. In this study, data already in digital form were purchased. Then, if the analysis is to be performed digitally, an appropriate digital image processing system is obtained. In this case the work was carried out using the Earth Resources Data Analysis System (ERDAS) image processing software.

Fundamental univariate and multivariate statistics used to display the raw digital data (mean, median, mode, minimum, maximum, standard deviation, correlation) are then computed. These and the initial display help assess the image quality. This and the rest of the steps in Figure 1.2 are outlined in Chapters 4 to 8. Based on the initial statistics and display the imagery is then pre-processed to reduce environmental and/or remote sensor system distortions in the data, usually by both radiometric and geometric correction.

Various image enhancements may then be applied to the corrected data for improved visual analysis or as input to further digital image processing. Then important thematic information is extracted from the imagery using either supervised (human assisted) or unsupervised techniques. For some problems, research answers may result from this stage, but for others, as in this study, placing the thematic information in a geographic information system may improve its usefulness. Chapters 7 and 8 consider the usefulness of remote sensing in solving the problem of wetland change assessment on the Kafue Flats.

1.5 Characteristics of Images from Major Imaging Systems

Images (defined as pictorial representations of features under investigation) can be photographic or non - photographic. Photographs are images detected on film and recorded as photographic prints (Lillesand and Kiefer, 1994). Non - photographic images are detected electronically and recorded on magnetic tape. Satellite images are mainly non - photographic. The major satellite imaging systems available for civilian use in earth resource studies are Landsat Multi-Spectral Scanner (MSS), Landsat Thematic Mapper (TM), NOAA AVHRR (National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) and SPOT (Systeme Pour l'Observation de la Terre). Their characteristics will be summarised.

Landsat MSS and TM images have been acquired by the Landsat 1-5 series of satellites. Landsat 1 operated from 23 July 1972 to 6 January 1978 (with MSS), Landsat 2 from 22 January 1975 to 5 November 1979 and again from 6 June 1980 to 27 July 1983 (with MSS), Landsat 3 from 5 March 1978 to 7 September 1983 (with MSS and Return Beam Vidicon (RBV) camera), Landsat 4 from 16 July 1982 onwards (with MSS and TM), and Landsat 5 from 1 March 1984 onwards (with MSS and TM) (Lillesand and Kiefer, 1994; Jensen, 1986). Landsats 1-3 orbited the earth at approximately 919 km in near polar, sun synchronous orbits, crossing the equator at 9:30 to 10:00 a.m. local time at an angle approximately 9^0 from normal, with 14 orbits per day, and returning to a given spot every 18 days. The orbits of Landsats 4 and 5 are also near polar and sun synchronous but the altitude is 705 km. This lower orbit produces an earth coverage cycle of 16 days. The sensors on board the Landsat satellites have included the Multi-Spectral Scanner (MSS), Thematic Mapper (TM), and the Return Beam Vidicon (RBV) camera.

The characteristics of the Landsat MSS and RBV bands are summarised in Table 1.1. MSS bands 4, 5, 6 and 7 were renumbered as bands 1, 2, 3 and 4, respectively, on Landsats 4 and 5 (Jensen, 1986; Lillesand and Kiefer, 1994) and will subsequently be called bands 1, 2, 3 and 4 hence forth in this thesis. Each MSS image covers a scene of 185 x 185 km in size (185 x 178 km on Landsats 1-3; Jensen, 1986) and each picture element (pixel) covered 79 x 79 m on Landsats 1-3, 82 x 82 m on Landsats 4 and 5 (Lillesand and Kiefer, 1994). These are the smallest ground areas that can be distinctly recorded by the MSS sensor, known as the sensor's *spatial resolution.*

Table 1.1 Characteristics of Landsat MSS Bands

Band (sensor)	Wavelength (μm)	Electromagnetic spectrum region
1 (RBV)	0.475 - 0.575	green
2 (RBV)	0.580 - 0.680	red
3 (RBV)	0.690 - 0.830	near infrared
4 (MSS)*	0.5 - 0.6	green
5 (MSS)*	0.6 - 0.7	red
6 (MSS)*	0.7 - 0.8	near infrared
7 (MSS)*	0.8 - 1.1	near infrared

*Numbering of MSS bands 4, 5, 6 and 7 later 1, 2, 3 and 4, respectively; see text. RBV refers to Return Beam Vidicon. (Summarised from Lillesand and Kiefer, 1994; Jensen, 1986).

The characteristics of Landsat TM bands are summarised in Table 1.2. With seven spectral bands compared to 4 bands in MSS, and finer spectral regions in the equivalent bands, TM has a higher *spectral resolution* than MSS. The TM spatial

Table 1.2 Characteristics of Landsat TM Bands

Band	Wavelength (μm)	Electromagnetic Spectrum Region	Major Applications
1	0.45 - 0.52	blue-green	Designed for water body penetration. Uses:- -coastal water mapping -soil/vegetation differentiation -forest type mapping, e.g. deciduous/coniferous differentiation -cultural feature identification
2	0.52 - 0.60	green	Designed to measure visible green reflectance peak of vegetation. Uses:- -healthy growth estimation -cultural feature identification
3	0.63 - 0.69	red	A chlorophyll absorption band. Uses:- -plant species differentiation -cultural feature identification
4	0.76 - 0.90	near infrared	For determining biomass content and delineating water bodies. Uses:- -biomass surveys -water body delineation -soil moisture discrimination
5	1.55 - 1.75	mid infrared	Indicative of vegetation and soil moisture content. Uses:- -vegetation moisture measurement
6	10.4 - 12.5	thermal infrared	For use in vegetation stress (temperature) analysis, soil moisture discrimination. Uses:- -plant heat stress management -other thermal mapping
7	2.08 - 2.35	mid infrared	For discriminating rock types. Uses:- -mineral and petroleum geology -hydrothermal mapping

(Summarised from Lillesand and Kiefer, 1994) resolution is also higher, having a 30 x 30m pixel size compared to 79 x 79m or 82 x 82m in MSS. Each TM scene covers 185 x185 km, the same as an MSS image.

The Advanced Very High Resolution Radiometer (AVHRR) has 5 channels (Table 1.3), some of which overlap with some TM bands but one (Channel 3) covers a region of the electromagnetic spectrum that is not covered by TM bands. Each pixel covers 1.1 x 1.1 km and a scene covers 3000 - 4000 km north-south, and 1000 km east-west. Therefore, AVHRR data are of coarser spatial resolution than either Landsat MSS or TM data. AVHRR images of an area can be obtained every 12 hours (Lillesand and Kiefer, 1994), which is a higher *temporal resolution* than either Landsats 1-3 (18 days) or Landsats 4 and 5 (16 days).

Table 1.3 Characteristics of NOAA AVHRR Channels

NOAA Satellites	Channel	Wavelength (μm)	Electromagnetic Spectrum Region
6, 8, 10, 12	1	0.58 - 0.68	red
	2	0.72 - 1.10	near infrared
	3	3.55 - 3.93	thermal infrared
	4	10.50 - 11.50	thermal infrared
	5	10.50 - 11.50	thermal infrared
7, 9, 11	1	0.58 - 0.68	red
	2	0.72 - 1.10	near infrared
	3	3.55 - 3.93	thermal infrared
	4	10.30 - 11.30	thermal infrared
	5	11.50 - 12.50	thermal infrared

(Summarised from Lillesand and Kiefer, 1994)

NOAA AVHRR images are acquired by a number of satellites in the NOAA programme: NOAA's 6, 7, 8, 9, 10, 11 and 12. Their launch dates were 27 June 1979

(NOAA 6), 23 June 1981 (NOAA 7), 28 March 1983 (NOAA 8), 12 December 1984 (NOAA 9), 17 September 1986 (NOAA 10), 24 September 1988 (NOAA 11) and 14 May 1991 (NOAA 12). Images are acquired in north- or south-bound orbits whose crossing times at the Equator are 7:30 p.m. and 7:30 a.m., respectively. The satellites orbit the earth at an altitude of 833 km (Lillesand and Kiefer, 1994). AVHRR data are suitable for environmental applications such as vegetation monitoring of large areas (Lillesand and Kiefer, 1994).

SPOT images have been acquired by the SPOT -1, 2, and 3 series of satellites with sun-synchronous, near polar-orbits. SPOT -1 was launched on 21 February 1986 and retired from service on 31 December 1990. SPOT -2 was launched on 21 January 1990 and SPOT -3 on 25 September 1993. The sensors on SPOT satellites include High Resolution Visible (HRV) imaging systems designed to operate in either panchromatic (P; black and white) or multi-spectral (XS) mode, as summarised in Table 1.4.

Table 1.4 SPOT Sensor System Characteristics

Characteristics of the HRV sensors	Multi-spectral mode	Panchromatic mode
Spectral bands	XS1:0.50-0.59 μm (green) XS2:0.61-0.68 μm (red) XS3:0.79-0.89 μm (near infrared)	0.51-0.73 μm (green-red)
Spatial resolution	20 m	10 m
Ground swath width at nadir (image size)	60 km	60 km
Satellite orbit repeat cycle	26 days	
Satellite equatorial crossing time	10:30 a.m.	
Satellite orbit altitude	832 km	

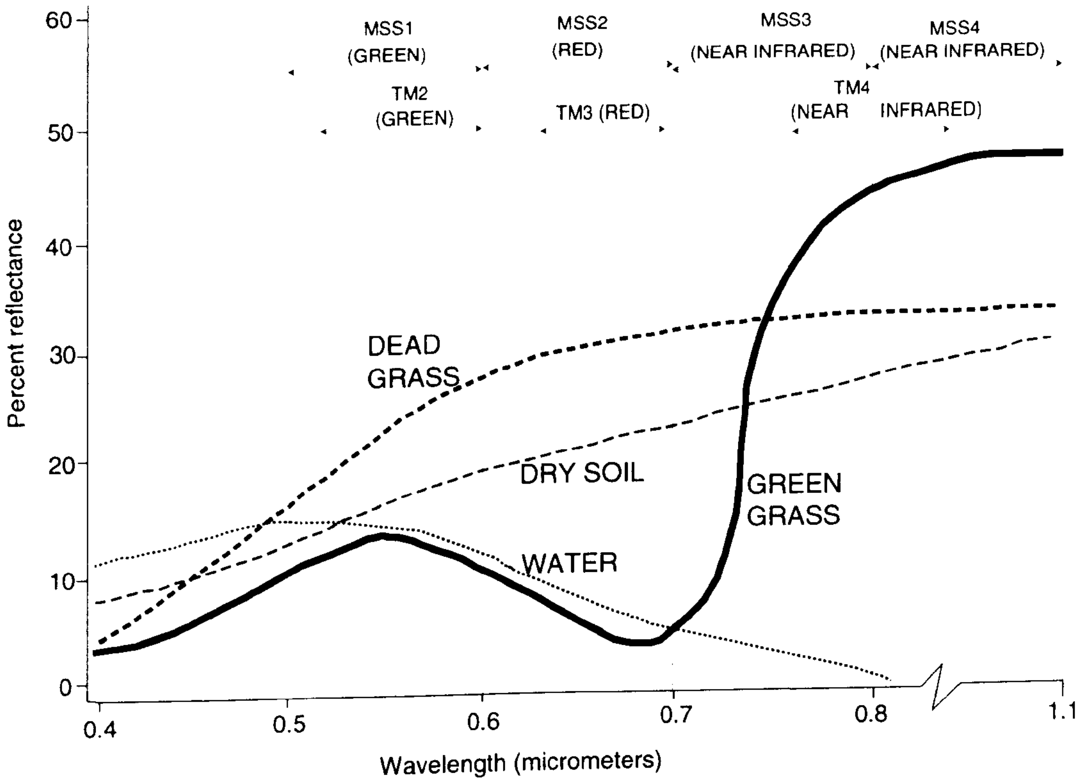
(Summarised from Jensen, 1986; Lillesand and Kiefer, 1994)

With only three channels, SPOT images have lower spectral resolution than either Landsat MSS or TM images but they have higher spatial resolution. The temporal resolution is also less in SPOT (26 days compared to 16 or 18 days in Landsat) but images of off-nadir areas can be acquired by SPOT (Lillesand and Kiefer, 1994; Jensen, 1986).

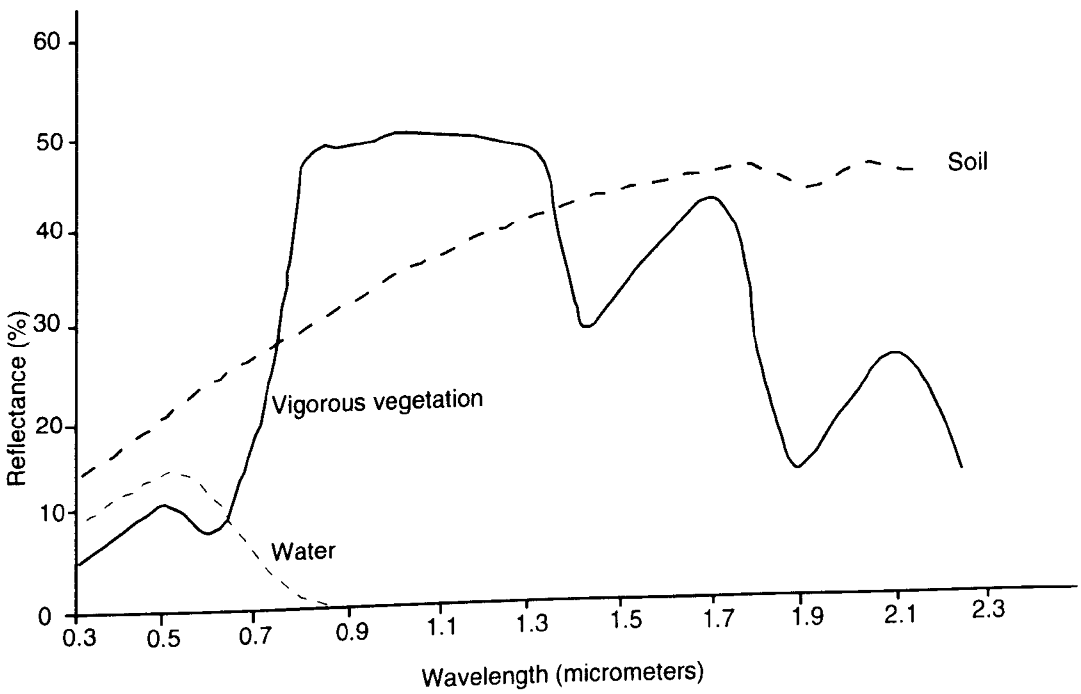
Aerial photographs can be panchromatic black and white, infrared black and white, true colour or infrared false colour. Panchromatic black and white photographs are produced from film recorded in the visible region of the electromagnetic spectrum (ranging from 0.4 - 0.7 μm in wavelength, i.e. blue to red) in shades ranging from black through grey to white. True colour photographs are produced from film depicting the true (visible) colour of objects. Infrared photographs are produced from film recorded in the green, red and the 0.7-0.9 μm near infrared portion of the electromagnetic spectrum. In false colour infrared photographs, features reflecting green energy appear blue, those reflecting red appear green, and those reflecting near infrared energy appear red. Black and white infrared photographs depict these same features in shades ranging from black to grey. The size of the ground covered by each photograph (and hence the scale) varies depending on the flying height above ground and the focal length of the camera lens used.

1.6 General Spectral Reflectance Characteristics of Water, Vegetation and Soil

Typical (average) reflectance characteristics for clear water, healthy green vegetation, dead or senescent vegetation and dry (grey-brown loam) soil are shown in Figure 1.3, together with the spectral ranges of Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) bands. Water which is deep and free of suspended sediments



(a) Typical reflectance characteristics for clear water, healthy green grass, dead or senescing grass and dry bare soil in the 0.4 - 1.1 micrometer region (modified from Jensen, 1986). Arrows indicate the spectral range of coverage of equivalent MSS and TM bands (Tables 1.1 and 1.2).



(b) Spectral reflectance curve for vigorous vegetation, soil and water in the 0.3 - 2.3 micrometer region (after Mather, 1987).

Figure 1.3 Spectral reflectance characteristics of clear water, vegetation and soil.

or plants has very little infrared reflectance. The peak reflectance of clear water is in the blue-green (0.4 - 0.6 μm) region of the electromagnetic spectrum. Healthy green vegetation generally reflects 40 to 50% of the incident near infrared energy (0.7-1.1 μm), with the chlorophyll absorbing approximately 80 to 90% of the incident energy in the visible (0.4 - 0.7 μm) part of the spectrum (Jensen, 1986), especially at about 0.45μm (blue) and 0.67 μm (red) (Lillesand and Kiefer, 1994).

Plant reflectance in the range 0.7 to 1.3 μm results primarily from the internal structure of plant leaves. Because this structure is highly variable between species, reflectance measurements in this range often permit species differentiation. Many plant stresses alter the reflectance in this region, and sensors operating in this range are often used for vegetation stress detection. Beyond 1.3 μm, leaf reflectance is approximately inversely related to the total water present in a leaf, as a function of both the moisture content and the thickness of the leaf (Lillesand and Kiefer, 1994). There are dips in the green vegetation reflectance curve at 1.4, 1.9 and 2.7 μm (Figure 1.3b) due to the fact that water absorbs strongly at these wavelengths.

Dead or senescent vegetation reflects a greater amount of energy than healthy green vegetation throughout the visible spectrum (0.4 - 0.7 μm). Conversely, it reflects less than green vegetation in the near infrared region. Dry soil generally has higher reflectance than green vegetation and lower reflectance than dead vegetation in the visible region, whereas in the near infrared, dry soil generally has lower reflectance than green or senescent vegetation (Jensen, 1986). Beyond the wavelength of 1.3 μm, dry soil has higher reflectance than green vegetation (Figure 1.3b). The factors that influence soil reflectance include moisture content, soil texture, surface roughness, presence of iron oxide, and organic matter content (Lillesand and Kiefer, 1994). These factors are complex, variable and interrelated. Because they act over less specific spectral bands, the dry soil reflectance curve shows considerably less peak-and-valley variation than the green vegetation curve. Soil moisture content is strongly related to the texture of a soil (in the absence of over-riding hydrological controls): coarse, sandy soils are usually well drained, resulting in low moisture content and relatively high reflectance; poorly drained fine textured soils will generally have lower reflectance (Lillesand and Kiefer, 1994).

These generalised spectral reflectance characteristics can help in the interpretation of reflectance remote sensing images. However, an inherent problem in remote sensing is the lack of unique spectral signatures for many features (Lillesand and Kiefer, 1994). Several, different features could have the same spectral signatures, making interpretation of images of the features difficult. For example, different vegetation species could have the same near infrared or visible spectral signatures, depending on their vigour, density, colour and leaf type. In general, though, broad leaved plant species have higher near infrared reflectance than narrow leaved species (Lillesand and Kiefer, 1994), for a given vegetation density and stage of growth. There are frequent departures from the idealised reflectance curves in Figure 1.3. If, for example, water is turbid, very shallow or contains emergent vegetation or is rich in chlorophyll due to eutrophication, it acquires some of the reflectance characteristics of the suspended sediments, the stream/river bed material, or vegetation, respectively. If soil is wet, its reflectance generally decreases, especially in the water absorbing bands at about 1.4, 1.9 and 2.7 μm.

1.7 General Characteristics, Function and Monitoring of Wetland Environments

Wetlands have been defined in various ways, depending upon cumulative experience and personal needs (Williams, 1990; Kent, 1994a). They defy a unifying functional definition, and each wetland is unique with respect to its size, shape, hydrology, soils, vegetation and position in the landscape (Kent, 1994a; Jensen *et al*, 1993). There are, therefore, various types of wetland, as shown in Table 1.5. By consensus, however, there are three characteristics (parameters) that distinguish all wetlands (Tammi, 1994):

1. Presence of (surface) water, typically from a surface or ground water source.
2. Presence of unique (hydric) soils which are diagnostic of wetland conditions. The soils display properties which indicate anaerobic conditions in the root zone resulting from prolonged saturation or inundation.
3. Presence of wetland vegetation which possesses morphological adaptations that enable it to tolerate frequent root zone saturation or inundation, and anaerobic conditions (i.e. hydrophytic vegetation).

These three main parameters of wetlands are interlinked. Permanent or periodic inundation or saturation of the root zone during the growing season results in the development of anaerobic conditions, which is one of the determinants of hydric soil conditions. Root zone saturation is in turn responsible for the occurrence and distribution of hydrophytic vegetation, which can withstand these conditions.

Hydrophytic vegetation is the most visible and easily recognisable diagnostic feature of wetlands (Tammi, 1994). It may, therefore, be the most recognisable diagnostic feature of wetland change, from a remote sensing perspective. However, wetland hydrology is

Table 1.5 Classification of Wetlands by System, Location, Water Properties and Vegetation (after Orme, 1990)

System	Location	Water regime	Water chemistry*	Vegetation type
Coastal wetlands				
Marine	Open coast	Supratidal	Euhaline-mixohaline	Shrub wetland
		Intertidal	Euhaline	Salt marsh, mangrove
		Subtidal	Euhaline	Sea grass, algae
Estuarine	Coastal sabkha	Supratidal	Hyperhaline-mixohaline	Algae, barren sabkha
	Estuaries deltas lagoons	Supratidal	Mixohaline-fresh	Brackish-freshwater marsh, shrub wetland
		Intertidal	Euhaline-mixohaline	Salt marsh, mangrove
		Subtidal	Euhaline	Sea grass, algae
Interior wetlands				
Riverine	River channels	Perennial	Fresh	Aquatics, algae
		Intermittent		Aquatics, emergent wetland
		Ephemeral		Aquatics, emergent wetland
	Flood plains	Ephemeral or stagnant	Fresh	Emergent wetland, shrub and forest wetland
Lacustrine	Lakes lake deltas	Perennial >2 m deep	Fresh limnetic	Aquatics, algae
		Perennial-intermittent <2 m deep	Fresh littoral	Aquatics, emergent wetland, shrub/forest wetland
	Sabkhas	Ephemeral	Hypersaline-mixosaline	Algae, barren sabkha, some phreatophytes
Palustrine	Ponds	Perennial	Fresh littoral	Aquatics, algae
	Turloughs	Intermittent	Fresh	Aquatics, emergent wetland
	Lowland mires	High water tables	Fresh	Aquatics, *Sphagnum* moss, bog plants, emergent wetland
	Upland mires	Perennial to ephemeral surface water		shrub wetland, forest wetland

* Halinity refers to ocean-derived salts and salinity to land-derived salts. The prefixes are defined in terms of parts per thousand salts as follows: hyper, >$40^0/_{00}$, eu, 30 - $40^0/_{00}$, mixo, 0.5 - $30^0/_{00}$ (brackish); fresh, <$0.5^0/_{00}$.

the single greatest impetus driving wetlands because it drives the development and distribution of the other two parameters of wetlands (Tammi, 1994). Wetland hydrology is characterised by permanent, temporary, periodic, seasonal or tidally influenced inundation or soil saturation within the root zone. A wetland's net hydroperiod (duration and depth of surface water cover) can be represented by the following equation (Tammi, 1994):

$$\Delta V = Pn + Si + Gi - Et - So - Go +/- T \quad (1.1)$$

Where:

V	=	Volume of water storage
ΔV	=	Change in volume of water storage
Pn	=	Net precipitation
Si	=	Surface inflow
Gi	=	Ground water inflow
Et	=	Evapotranspiration
So	=	Surface outflow
Go	=	Ground water outflow
T	=	Tidal inflow (+) or outflow (-)

Wetlands have both functions and values. Wetland functions is the collective term for the physical, chemical and biological interactions within wetlands, while characteristics of wetlands that are beneficial to society are considered as wetland values (Reimold, 1994). Examples of wetland biological functions are the provision of habitats for animal reproduction, feeding and resting. Physical functions of wetlands include flood attenuation, ground water recharge and sediment entrapment, and chemical functions include nutrient removal and toxins decontamination (Reimold, 1994; Jensen *et al*, 1993). Examples of wetland values are production of peat, fishing, supply of water, maintenance of species diversity, and aesthetics.

As habitats, however, wetlands are transitional in the sense that they are neither terrestrial nor aquatic, but exhibit characteristics of both. Their boundaries are part of a continuum of physical and functional characters, and may expand or contract over time depending upon factors such as average annual precipitation, evapotranspiration, modifications to the watershed and presence of non-persistent (plant) species (Kent, 1994a; Jensen *et al*, 1993). The transitional nature of wetland characteristics, and the shifting of wetland boundaries, renders precise identification of wetland boundaries difficult, if not impossible (Kent, 1994a). Wetlands, therefore, play a crucial role in the survival of numerous fauna and flora living within, as well as fauna and flora living adjacent to them. Their functions are frequently based on vegetation (species, coverage, survival), fauna (species, density and habitat quality), sanctuary refuge value for fish, wildlife and waterfowl, and food chain production export to adjacent ecosystems (Reimold, 1994).

Changes in wetland functions and values are concepts used in monitoring and managing wetlands (Reimold, 1994). Since hydrology is the main parameter driving wetlands formation (Tammi, 1994), factors that induce changes in a wetland's water content will cause wetland changes (e.g. in plant communities; Wilcox, 1995). From Equation 1.1, net precipitation, surface inflow, ground water inflow and tidal inflow add water to a wetland and, therefore, increases in these factors will increase the wetland's water content, and vice versa. Evapotranspiration, surface outflow, ground water outflow and tidal outflow subtract water from the wetland and increases in these factors will reduce the wetland's water content. The changes in water content result in changes to a number of wetland characteristics which can be monitored (Table 1.6).

Two broad approaches are available for monitoring wetlands: remote (i.e. remote sensing) and contact (i.e. ground surveys) (Kent, 1994b; Wilcox, 1995). All of the

Table 1.6 Measures of wetland structure and function
(After Kent, 1994b)

Properties of Individual Plants		
Basal Area	Growth Rate	
Biomass	Productivity	
Canopy Diameter	Stem Diameter	
Cover	Survival	
Properties of Vegetation Communities		
Basal Cover	Cover Type	Richness
Biomass	Density	Survival
Cover	Evenness	Stratification
Landform Properties		
Accessibility	Heterogeneity	Interaction
Dispersion	Isolation	Shape
		Size
Properties of Soil		
Classification	Organic Content	
Moisture	Texture	
Hydrologic and Hydraulic Properties		
Flood Storage Volume	Surface Water Depth	
Frequency of Flooding	Surface Water Area	
Groundwater Depth	Surface Water Velocity	
Groundwater Recharge	Surface Water Width	
Aquatic Physical/Chemical Properties		
Biological Oxygen Demand	pH	
	Salinity	
Chlorophyll	Temperature	
Turbidity	Toxicants	
Dissolved Salts	Nutrients	
Organismal Properties		
Behaviour	Metabolism	
Bioaccumulation	Reproduction	
Growth and Development	Tissue Health	
Properties of Individual Wildlife and Fish Species		
Abundance	Age Structure	Mortality
Association	Density	Presence/Absence
Properties of Wildlife Communities		
Abundance	Evenness	
Biomass	Niche Overlap	
Density	Richness	

measures in Table 1.6 can be monitored by ground surveys, where practical. For example, field studies of vegetation can provide information on plant community changes by repeated sampling of quadrats over time, gradient analyses, or sampling along topographic or bathymetric contours that reflect significant water level events (Wilcox, 1995). Routine water level measurements over time from staff gauges or shallow, hand driven wells can help indicate hydrologic changes (Wilcox, 1995). When the level of spatial and temporal sampling is impractical with contact techniques, remote sensing can be used. Because remote sensing data are available at large and synoptic scales, large scale wetland patterns can be discerned and large scale processes measured (Kent, 1994b). This study employs this approach in monitoring the Kafue Flats wetland, as justified in Section 1.3. The vegetation cover and density (which fall under the `Properties of vegetation communities' category in Table 1.6) are the main wetland characteristics being monitored. As shown in Table 1.7, the temporal nature of wetland changes that can be monitored depends on the imaging system from which the remote sensing data are obtained. However, spatial resolution, spectral resolution and cost are important considerations. For example, the National Wetlands Inventory (NWI) in the USA periodically (every 10 years) maps wetlands (type and extent) mainly by high altitude colour infrared aerial photographs (Hefner and Storrs, 1994). This is probably because colour infrared aerial photographs have high spatial resolution.

Using the classification system in Table 1.5, the Kafue Flats wetland falls under the Interior Wetlands, Riverine category, with both river channel and floodplain wetland characteristics. The river channel (Kafue River) is perennial, while floodplain wetland locations are both ephemeral and perennial, with stagnant water in some depressions. The wetland's water is fresh, and the vegetation includes aquatic vegetation, algae, emergent vegetation and shrubs. Details of the Kafue Flats wetland environment are given in Chapter 2.

Table 1.7 Comparison of Potential Ability of Imaging Systems to Monitor Wetland Changes, Based on Temporal Resolution

Where: ✓ = sensor able to monitor changes
✗ = sensor unable to monitor changes

Imaging system	Temporal nature of wetland changes				
	< daily	daily	1 - 14 days	14 - 28 days	28 days - annual
Aerial photographs	✓ (probably*)	✓ (probably*)	✓	✓	✓
NOAA AVHRR	✗	✓	✓	✓	✓
Landsat MSS	✗	✗	✗	✓	✓
Landsat TM	✗	✗	✗	✓	✓
SPOT	✗	✗	✓ (probably**)	✓ (probably**)	✓

*Depending on speed of film processing and developing of photographic prints.
**Possible due to off-nadir imaging ability of SPOT sensors.

1.8 Structure of the Thesis

The thesis has eight chapters, as follows:

- Chapter 1 states the nature of the problem investigated, the research hypothesis, aim and objectives. Broad aspects of the remote sensing procedures undertaken, alternative sources of remote sensing data, spectral reflectance of basic land surface materials, and wetland environments are introduced.
- Chapter 2 describes the study area (the Kafue Flats), the natural and human pressures bearing on it (potential causes of wetland change), and outlines the recent trends in hydrological, climatic and wildlife population data, as indicators of the nature of the pressure. Ideal aspects of the Kafue Flats as a habitat for selected (threatened) species are summarised.

- Chapter 3 summarises material from literature concerning methodological aspects of the use of remote sensing in change detection, the error factor involved and how to minimise it, as well as predictions of change that have been made for the Kafue Flats.
- Chapter 4 details the methodology employed in conducting the research.
- Chapter 5 describes the criteria and organisation of the process of extracting thematic information from the multi-temporal remote sensing data, as well as the significance of the procedures.
- Chapter 6 details the change detection results.
- In Chapter 7, the methodological procedures are appraised and the significance of the results in relation to the original objectives is evaluated.
- Chapter 8 outlines the conclusions arising from the study, with recommendations for future work.

Chapter 2

THE STUDY AREA

2.1 Introduction

This chapter summarises the physical environment and land use characteristics of the study area, a section of the Kafue Flats wetland area in southern Zambia (Figures 1.1 and 2.1) between latitudes $15^0 30'$ to $15^0 50'$S and longitudes $27^0 00'$ to $27^0 50'$E (about 90 km x 50 km). The main focus of the chapter is on the aspects of land use and the physical environment which are causing increased pressure on the stability of the wetland in terms of input and output of water, and vegetation cover. It was pointed out in Chapter 1 that a wetland's hydrological regime is the single greatest impetus driving the other wetland attributes like hydric soils and hydrophytic vegetation. Changes in the Kafue Flats' water input and output may, therefore, result in changes in the flora and fauna. Within the constraints of data availability, trends in climate, river discharge and water levels at hydrological stations, populations of animal species and human use of water on the Kafue Flats are outlined in this chapter.

2.2 Climate

According to the Koppen Classification System, Zambia lies almost entirely in the *Cwa-Zone*, "*C* (standing) for warm climate (coldest month 18 to -3^0C) with sufficient heat and precipitation for forest vegetation, *w* for winter dry season and *a* for temperature of the warmest month over 22^0C" (Ellenbroek, 1987, p.10). Rainfall and temperature are more prominent in dictating the rhythm of life on the Kafue Flats as an

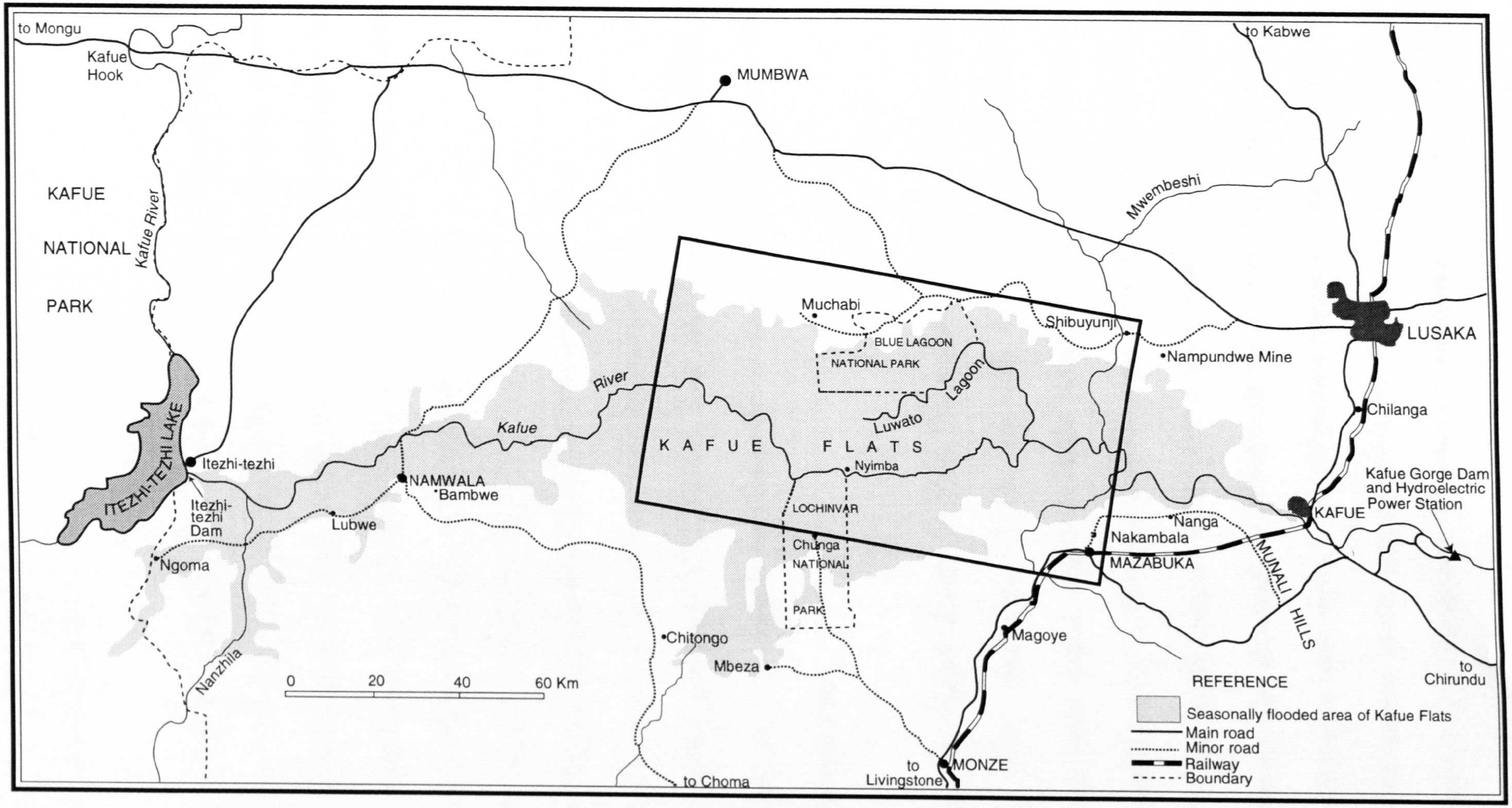


Figure 2.1 Geographical and land use setting of the study area (in rectangle) on the Kafue Flats (modified from Handlos, 1978). See also Figure 4.1

ecosystem compared to the other climatic parameters like wind velocity, sunshine hours and relative humidity.

There is a distinct rainy season in the study area, coinciding with the southward migration of the Inter Tropical Convergence Zone (ITCZ). The rainy season is normally from November to March/April. It is followed by a cool, dry season from May to July/August, and a hot, dry season from August/September to November. Ellenbroek (1987) has divided the seasons as follows:

1. The cool, dry season from April to August
2. The hot, dry season from August to November
3. The warm, wet season from November to April.

Handlos (1978) gives a similar division: cool, dry season from April/May to July/August, hot, dry season from September to October, and wet season from November to March.

In normal years, rainfall averages at about 800 mm per year in the area of the Flats (Handlos, 1978; Douthwaite, 1974). According to the Zambia Meteorology Department, mean annual rainfall at Kafue Polder (Nanga) and Mazabuka (for location, see Figure 2.1) is 771 mm (period of measurement unspecified). Seasons with less than 771 mm could, therefore, be classified as having below normal rainfall. Within a given year the rains are usually distributed as shown in Figure 2.2, although there are considerable year to year variations. The temperature pattern in a year is such that June is usually the coldest month (average 16^0C) and October (average 24 - 27^0C) the hottest (Figure 2.3). Unlike rainfall, mean monthly temperatures do not fluctuate very

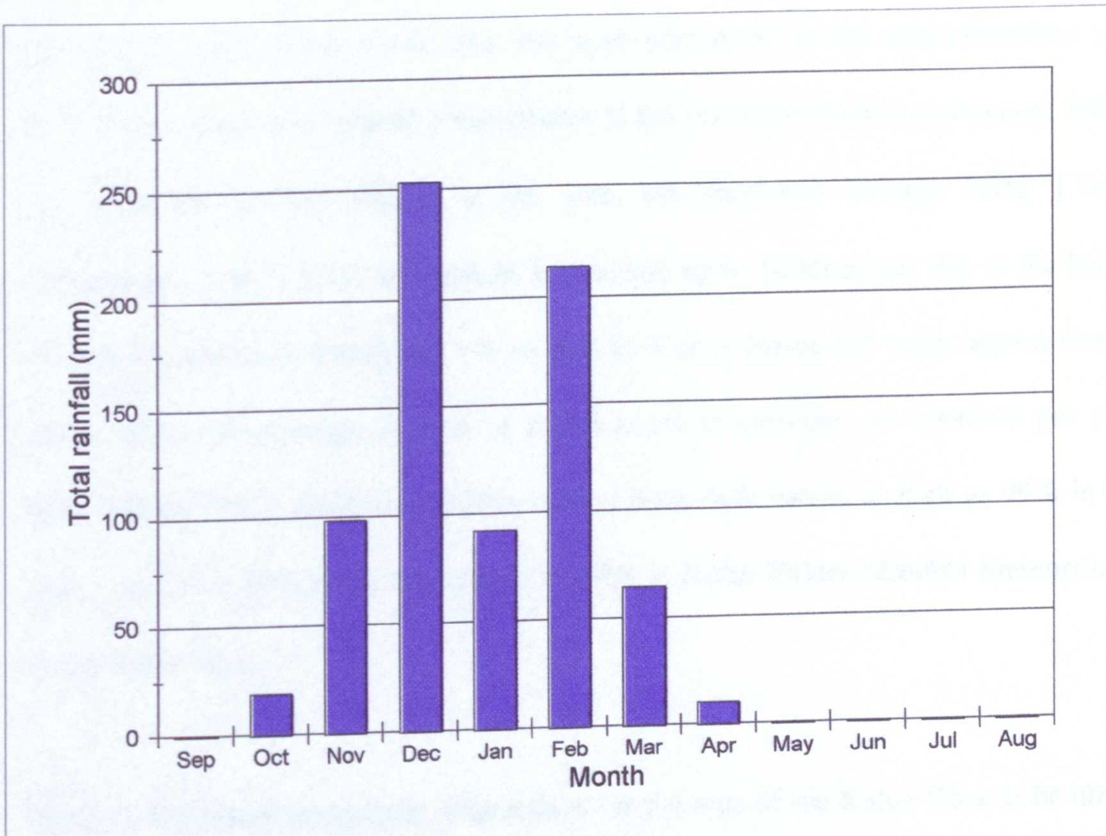


Figure 2.2 Monthly rainfall at Kafue Polder on the Kafue Flats in the 1992/93 season (Sep. 1992 - Aug. 1993). Data: Meteorology Department, Lusaka (See also Figure 2.5).

Figure 2.3 Mean monthly temperature at Kafue Polder in 1993 (see also Figure 2.6a). Data: Meteorology Department, Lusaka.

much from year to year in the area, but years with poor or late rains (therefore with less cloud cover) have highest temperatures in the period November to January. Winds are generally of low velocity in the area, the maximum average being 1.7ms^{-1} (Ellenbroek, 1987). A lot of sunshine is received, up to 10 hours per day at the height of the dry season in September but as few as 4 or 5 during the rainy season due to cloud cover. On average, a total of 2 810 hours of sunshine are received per year (Ellenbroek, 1987). Relative humidity ranged from daily means as high as 99% in the rainy season to 20% in the dry season in 1993 at Kafue Polder (Zambia Meteorology Department data).

Weather data show annual pan evaporation for the area of the Kafue Flats to be about 2 200mm but Penman calculations of potential evapotranspiration show about 1 700 to 1 800mm; both figures being greater than the annual rainfall in the area (Handlos, 1978). The actual evapotranspiration changes from month to month as the height, density, species composition and stomatal activity of the vegetation, winds, light and temperature change from month to month. Using the Penman equation, Ellenbroek (1987) determined average monthly values of the reference crop evapotranspiration (ET_0), defined as `the rate of evapotranspiration from an extended surface of 8 to 15cm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water'. Between September 1978 and May 1981, the values (in mm per day) ranged from 4.1 (lowest, in June) to 7.4 (highest, in October). The form of the Penman equation used in estimating these values was:

$$ET_0 = W.Rn + (1 - W).f(u).(ea - ed) \qquad (2.1)$$

Where:

ET_0 = reference crop evapotranspiration in mm.d^{-1}

W	=	the temperature and altitude related weighting factor
Rn	=	the net radiation in equivalent evaporation in $mm.d^{-1}$
f(u)	=	the wind related function
(ea - ed)	=	the difference between the saturation vapour pressure at mean air temperature and the mean actual pressure of the air in mbar

The factors affecting evapotranspiration are many and may interact with one another in a complex fashion. Although average estimates give some indication, the real situation is beyond our own capabilities to measure accurately (Handlos, 1978).

2.2.1 **Recent Climatological Trends**

Long term daily climate data from the Zambia Meteorology Department were statistically analysed in order to determine trends. The data selected constituted daily temperature and rainfall records for Ndola, Lusaka and Kafue Polder, representing the upper, middle and lower portions of the Kafue River basin respectively (Figure 2.4). The records were from 1950 - 1994 for Ndola and Lusaka, and 1957 - 1994 for Kafue Polder. No records outside these periods were available.

The rainfall fluctuations from year to year at the stations analysed (Figure 2.5a), appear to show wet and dry phases. Examining the graphs in Figure 2.5a reveals these phases, which have been arbitrarily delineated from the trends in the graphs and summarised in Table 2.1. Eight year moving average trend analysis of Kafue Polder rainfall data reveals this cyclic nature of the rainfall (Figure 2.5b). The rainfall in each of the periods is characterised by very high variability (Table 2.1a). Although there have been alternating wet and dry phases in the period analysed, the declining trend in seasonal rainfall from 1978 - 1993 (Period III in Table 2.1a) seems to be longer than any previous dry period. This has led to debates about whether or not the climate is

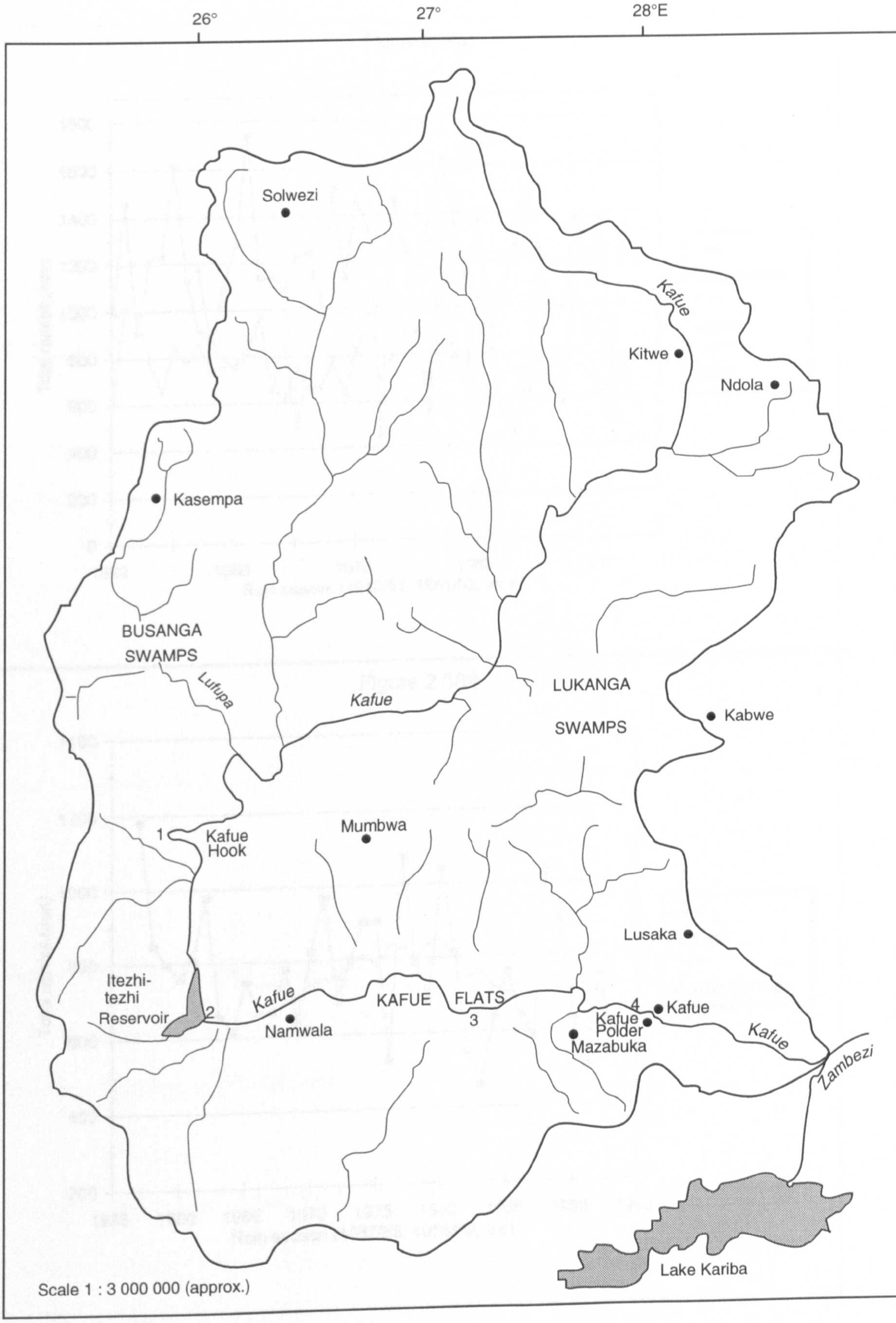


Figure 2.4 The Kafue River catchment area (modified from Burke, 1994). Hydrological stations are numbered as follows: 1. Kafue Hook, 2. Itezhi-tezhi, 3. Nyimba, 4. Kafue Polder

Figure 2.5(a)

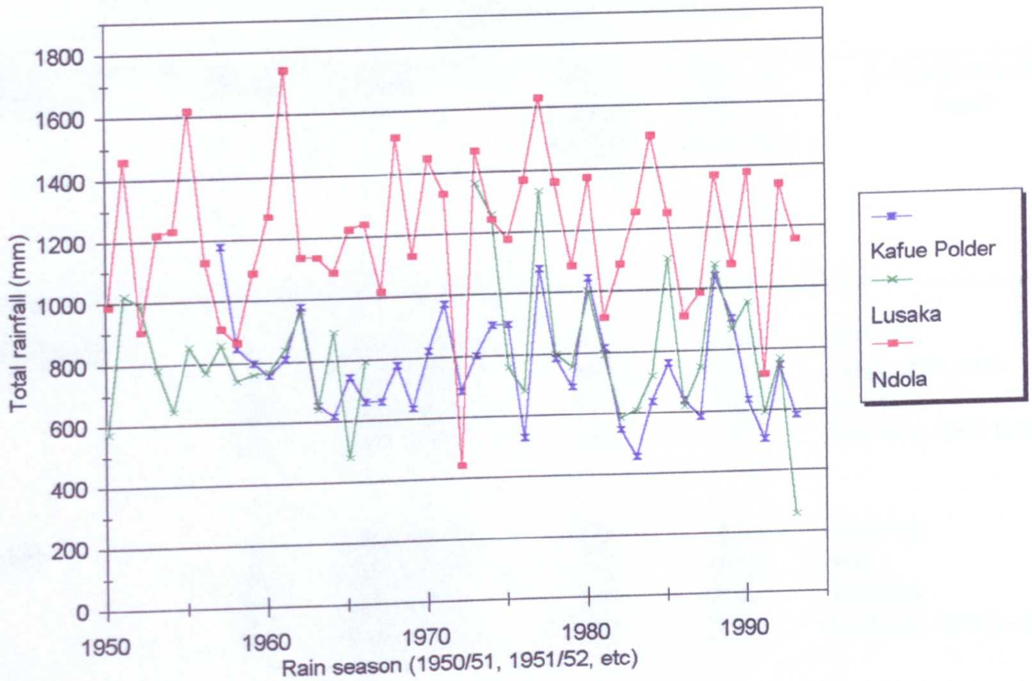


Figure 2.5(b)

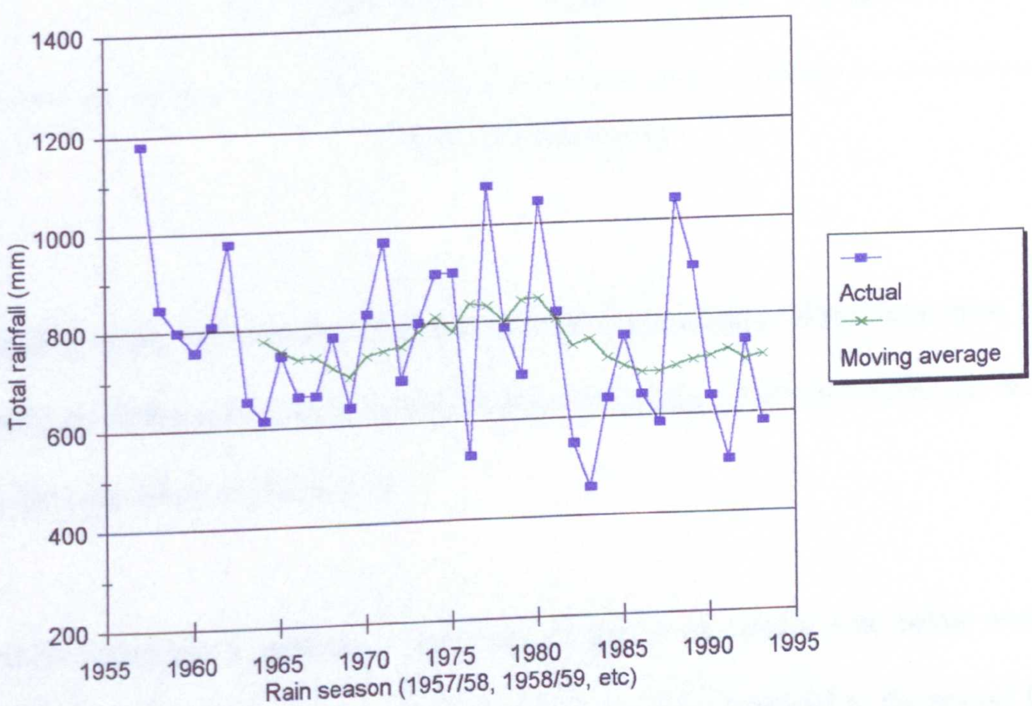


Figure 2.5 Long term seasonal rainfall trends on the Kafue basin
(a) Long term seasonal rainfall fluctuations at Kafue Polder (1957 - 1994), Lusaka (1950-1994) and Ndola (1950-1994). Data: Meteorology Department, Lusaka (1968-1972 Lusaka data missing).
(b) Eight year moving average seasonal rainfall trends at Kafue Polder, 1957 - 1994.

Table 2.1 Rainfall Statistics at Three Stations on the Kafue Basin, 1950 - 1994.
(a) Apparent wet and dry phases

Station	Period	Seasons	Mean Seasonal Rainfall (mm)	Seasonal Rainfall's Coefficient of Variation (%)	Seasonal Rainfall Trend
Kafue Polder	I	1957 - 1969	781	20.10	declining
	II	1970 - 1977	838	20.29	rising, then peak
	III	1978 - 1993	714	24.51	declining
	IV	1957 - 1977	803	19.93	declining, then rising
Lusaka	I	1950 - 1967	788	18.27	declining
	II	1973 - 1977*	1 083	30.56	peak
	III	1978 - 1993	768	27.86	declining
	IV	1950 - 1977	855	26.90	declining, then peak
Ndola	I	1950 - 1961	1 205	23.65	rising
	II	1962 - 1977	1 228	22.07	mixed/rising
	III	1978 - 1993	1 177	18.52	declining
	IV	1950 - 1977	1 218	22.33	rising/mixed

* 1968 - 1972 data missing

changing under the influence of global warming. According to these data there is no significant difference in mean rainfall between this latter period and either the wet or the dry period before (Table 2.1b).

Another trend that is apparent is increasing frequency of seasons with below average total rainfall from 1978 to 1993 (Period III in Table 2.1) compared to the period 1950 - 1977 (Period IV in Table 2.1). For the Kafue Flats area the mean seasonal rainfall is 771 mm at Mazabuka and Kafue Polder, according to the Zambia Meteorology Department. Years with total seasonal rainfall less than 771mm could, therefore, be

Table 2.1 Rainfall Statistics at Three Stations on the Kafue Basin, 1950 - 1994.
(b) Differences between rainfall means of wet and dry phases

Station	periods compared (see part (a) of table above)	rainfall means compared (mm)	s* (mm)	No. of years (n)	t**	Probability (P)	Significance***
Kafue Polder	IV III	803 714	160 175	21 16	1.58	0.12	not significant
	II III	838 714	170 175	8 16	1.67	0.12	not significant
	I III	781 714	157 175	13 16	1.08	0.29	not significant
Lusaka	IV III	855 768	230 214	22 16	1.21	0.24	not significant
	II III	1083 768	331 214	5 16	2.00	0.10	not significant
	I III	788 768	144 214	17 16	0.32	0.75	not significant
Ndola	IV III	1218 1177	272 218	28 16	0.55	0.58	not significant
	II III	1228 1177	271 218	16 16	0.59	0.56	not significant
	I III	1205 1177	285 218	12 16	0.29	0.78	not significant

considered as below average rainfall years. Statistically, there is no significant difference in frequency of below average rain seasons between the period 1978 - 1993

* Standard deviation
** Student's t statistic
*** Using 5% level of probability to determine significance

and the period 1950 - 1977 for Kafue Polder (Table 2.2). The cold season versus dry season temperature difference at the three stations seems to be changing. October is normally the hottest month of the year and June the coldest. From the records available, June has been getting warmer while October has been getting cooler (Figure 2.6). This is likely to have resulted in increased evaporation and evapotranspiration losses in June and possibly reduced losses in October.

It is difficult to make conclusive statements about the latest climate trends in the area, given the short record available (1950 - 1994 only). It remains to be seen how long the latest trend (since 1978) will last. Staff at the Zambia Meteorology Department urge similar caution about the issue, adding that what is certain is that rainfall has become erratic and very unpredictable (in terms of beginning and end of rain season, as well as amount of rain) lately, and that the rains have been consistently poor in the 7 years before 1995 (Daka, 1995 and pers. comm.; Muchinda, 1988 and pers. comm.)[1]. Sakaida (1994) and Kruss (1992)[2] made a similar observation of reduced rainfall in Zambia in the 1980s, with the 1991/92 rain season being the driest on record. A WWF commissioned report on climate change in the southern Africa (Hulme, 1996) states that rainfall in the region is variable from year to year and droughts have occurred from time to time. However, the report states, the last twenty years have seen a trend towards reduced rainfall. The decade 1986-1995, as well as being the warmest this century, has also been the driest, according to the report. The observed rate of warming in southern Africa during the present century - about 0.05^0C per decade - is

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[1] Muchinda was Chief Meteorologist (Agronomy) and Daka was Meteorologist at Zambia Meteorology Department in 1995.

[2] Kruss was working at Zambia Meteorology Department in 1993 and previously at the World Meteorology Organisation, Geneva, Switzerland.

Table 2.2 Differences in frequency of below average rain seasons at Kafue Polder, 1957 -1977 versus 1978 - 1993

Seasonal rainfall class (mm)*	1957 - 1977 (period IV)** frequency	1978 - 1993 (period III)** frequency	Total (No. of years in class)
< 771	9	11	20
≥ 771	12	5	17
Total (No. of years in period)	21	16	37

$\chi^2 = 2.451$, $P = 0.118$ (not significant at 5%)

*Mean rainfall is 771mm (Zambia Meteorology Department)
**See Table 2.1(a)

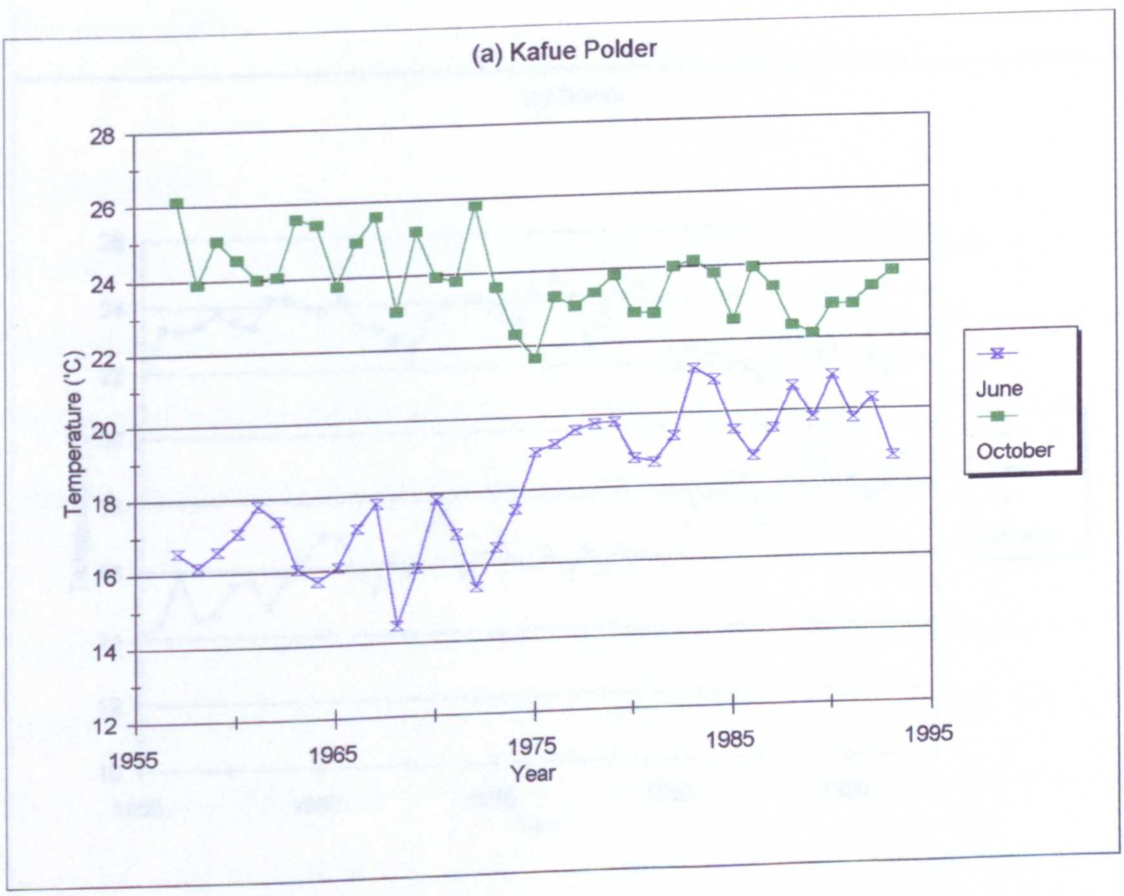
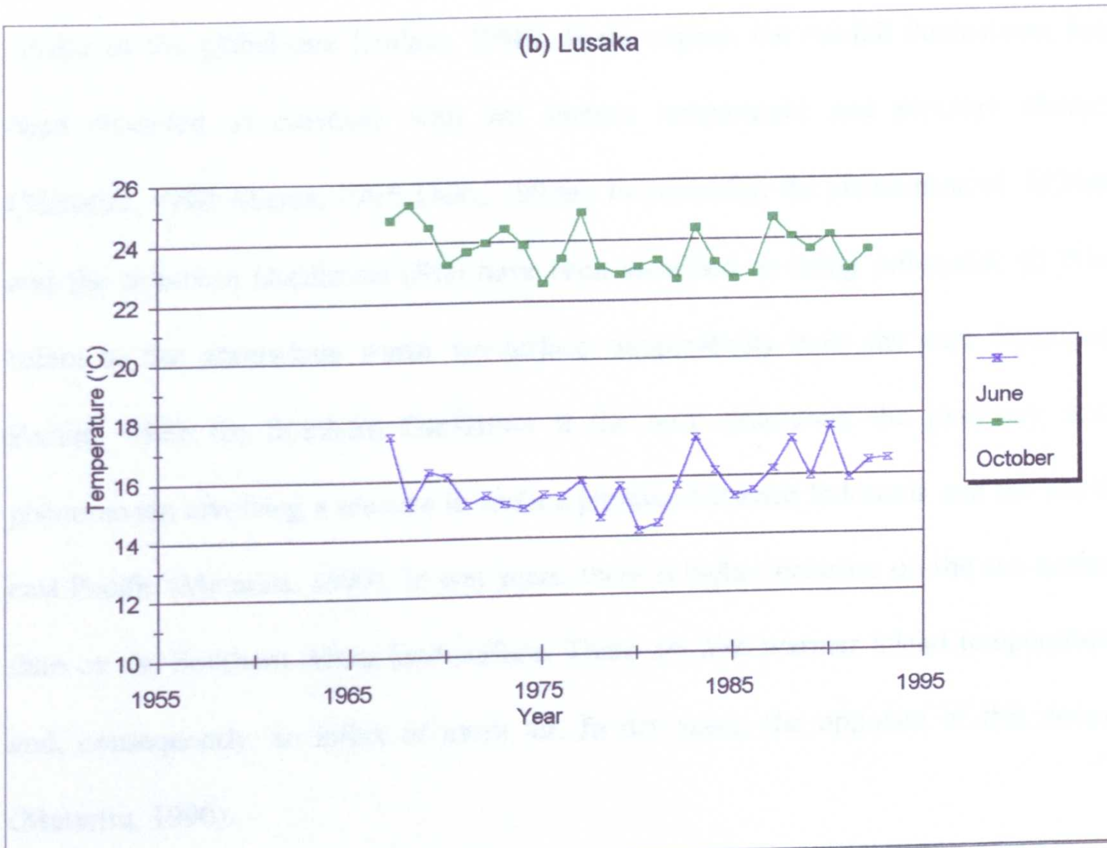


Figure 2.6 June and October temperature trends on the Kafue basin (a) Kafue Polder, 1957-1994.



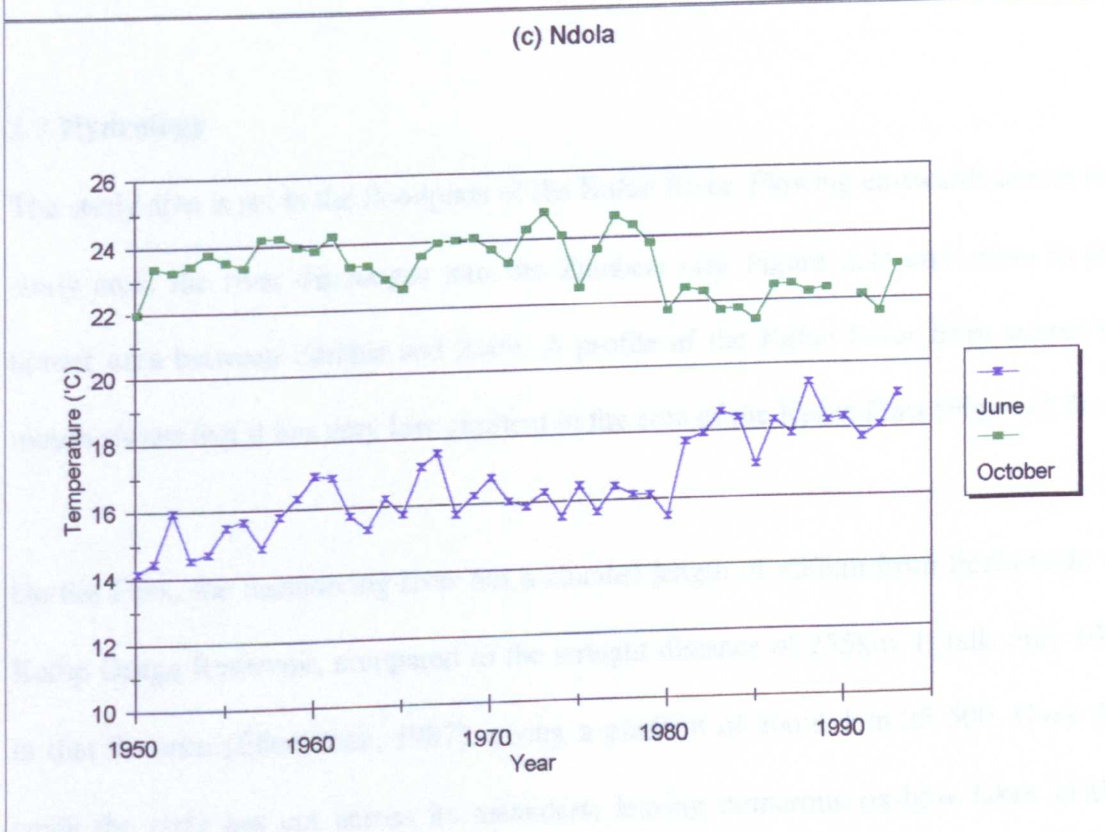


Figure 2.6 *(continued)* June and October temperature trends on the Kafue basin
(b) Lusaka, 1967-1994.
(c) Ndola, 1950- 1994.
(Data: Zambia Meteorology Department, Lusaka).

similar to the global rate (Hulme, 1996). In the region, the rainfall fluctuations have been observed to correlate with sea surface temperature and pressure changes (Matarira, 1990; Mason, 1995; Daka, 1995b). In particular, the phenomena of El Nino and the Southern Oscillation (SO) have been identified as being influential. El Nino refers to the anomalous warm sea-surface temperatures over the east Equatorial Pacific, while the Southern Oscillation is the term describing the planetary scale phenomenon involving a sea-saw in surface pressure between Indonesia and the south-east Pacific (Matarira, 1990). In wet years, there is higher pressure on the sea surface than on the Southern Africa land surface. There are also warmer inland temperatures and, consequently, an influx of moist air. In dry years, the opposite of this occurs (Matarira, 1990).

2.3 **Hydrology**

The study area is set in the floodplain of the Kafue River. Flowing eastwards across the study area, the river discharges into the Zambezi (see Figure 2.4) and starts in the border area between Zambia and Zaire. A profile of the Kafue River from source to mouth shows that it has very low gradient in the area of the Kafue Flats (Figure 2.7).

On the Flats, the meandering river has a channel length of 450km from Itezhi-tezhi to Kafue Gorge Reservoir, compared to the straight distance of 255km. It falls only 10m in that distance (Ellenbroek, 1987), giving a gradient of about 1 in 25 500. Over the years the river has cut across its meanders, leaving numerous ox-bow lakes in the stranded former channels. These former channels form an integral part of the wetland system (Ellenbroek, 1987).

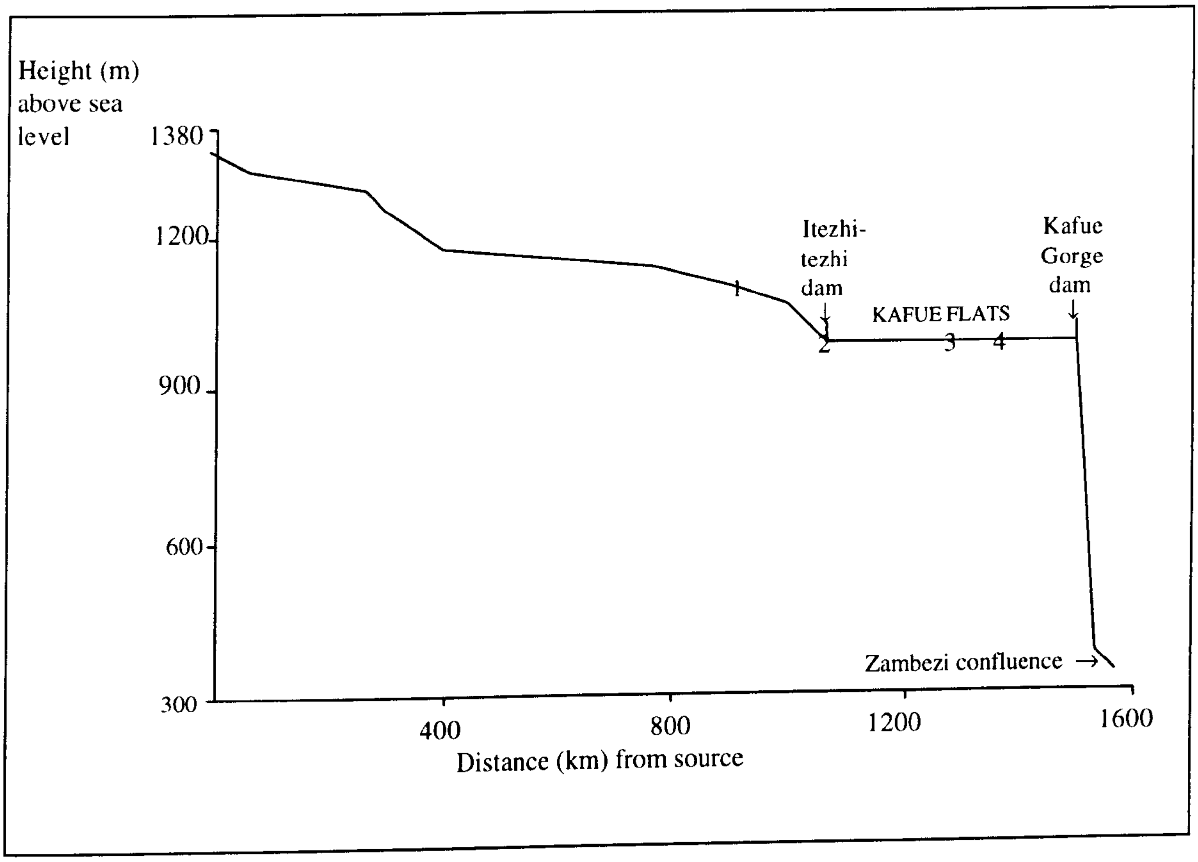


Figure 2.7 Profile of the Kafue River (after Handlos, 1978). Hydrological stations are numbered as follows: 1. Kafue Hook, 2. Itezhi-tezhi, 3. Nyimba, 4. Pumping Station 1 (opposite Nakambala, Figure 2.1).

2.3.1 The Kafue Basin

The Kafue River basin (Figure 2.4) covers an area of 154 000km^2 (Ellenbroek, 1987) and can be divided into two sections: (1) the upper and mid Kafue (2) the lower Kafue and Kafue Flats.

2.3.1.1 The Upper and Mid Kafue

The water level in the upper Kafue starts to rise with the onset of the rains in November in the northern part of the basin, having been at its lowest in October. The level continues to rise as the rainy season progresses until maximum discharges are reached at the height of the rains in January/February (Figure 2.8). The flood proceeds

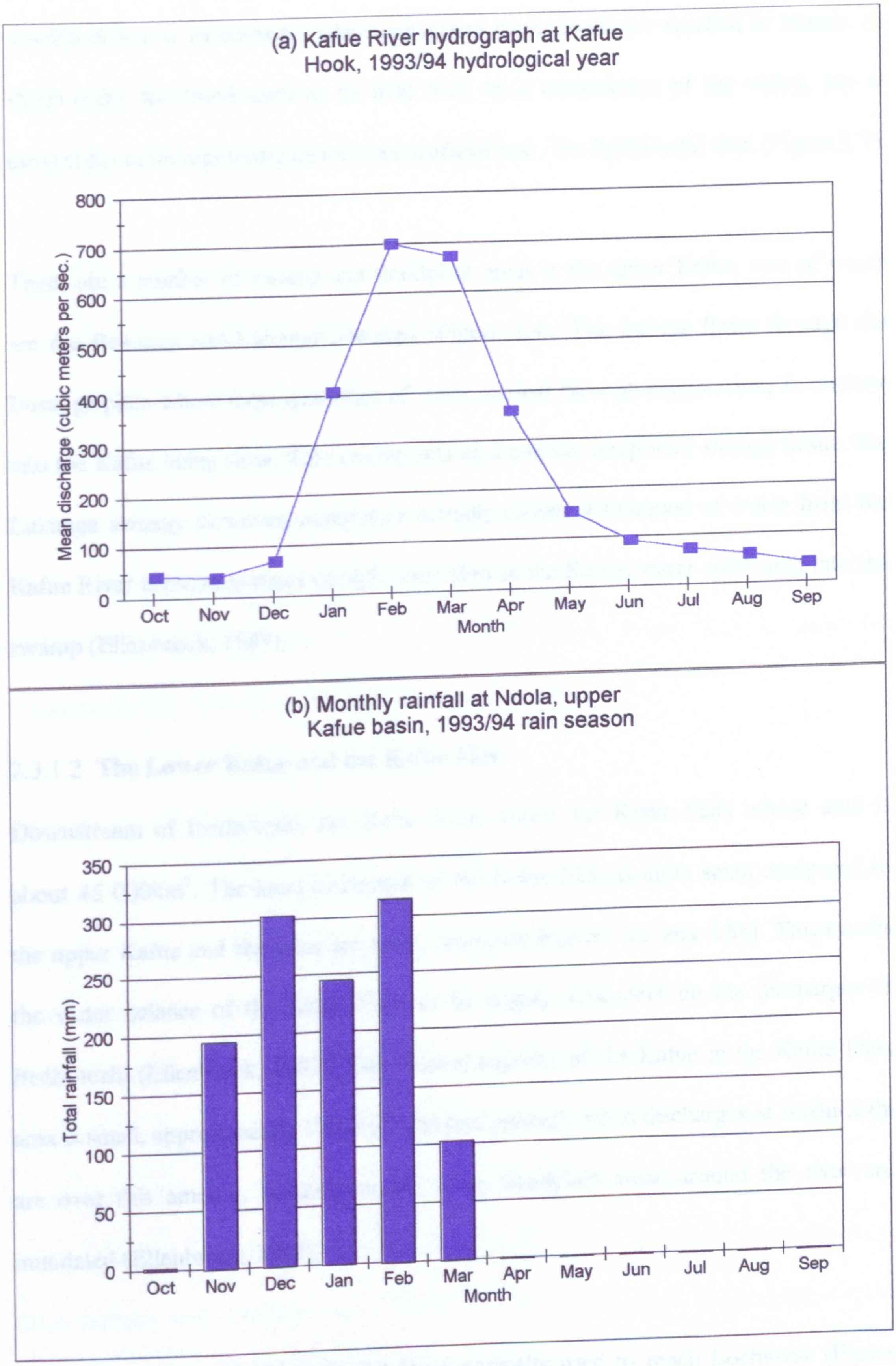


Figure 2.8 Relationship between middle basin river discharge and upper basin rainfall on the Kafue basin. Data: (a) ZESCO, Lusaka (b) Meteorology Department, Lusaka (April data missing).

quickly down to Itezhi-tezhi, where maximum water levels are reached in March. At Itezhi-tezhi, the flood used to be held back by a constriction of the valley, but at present the main regulating factor is an artificial one - the Itezhi-tezhi dam (Figure 2.7).

There are a number of swamp and floodplain areas in the upper Kafue, two of which are the Busanga and Lukanga Swamps (Figure 2.4). The Lufupa flows through the Busanga plain where large quantities of water are lost through evaporation, its outflow into the Kafue being slow. This swamp acts as a natural, temporary storage basin. The Lukanga swamp, however, sometimes actually causes withdrawal of water from the Kafue River because in times of high flood flow in the Kafue, water spills over into the swamp (Ellenbroek, 1987).

2.3.1.2 **The Lower Kafue and the Kafue Flats**

Downstream of Itezhi-tezhi, the Kafue River enters the Kafue Flats whose area is about 45 000km^2. The local catchment of the Kafue Flats is quite small compared to the upper Kafue and the rains are lower (compare Figures 2.2 and 2.8b). This causes the water balance of the Kafue Flats to be largely dependent on the discharges at Itezhi-tezhi (Ellenbroek, 1987). The channel capacity of the Kafue in the Kafue Flats area is small, approximately 170m^{3}s^{-1}, and consequently when discharges at Itezhi-tezhi are over this amount, flooding occurs - i.e. floodplain areas around the river are inundated (Ellenbroek, 1987).

Before damming at Itezhi-tezhi, the flood normally used to reach Lochinvar (Figure 2.1) in April and Kafue Gorge late in May, although there was considerable variation in timing and scale (Douthwaite, 1974). Since damming at Itezhi-tezhi, the regulated flood progresses slowly to the Kafue Gorge Reservoir where it arrives between June and August (Ellenbroek, 1987). There is a lag in the timing of the flood between upper and lower sections of the Kafue Flats in any given year (Figure 2.9; see also Figure 4.1).

As a result of damming at Itezhi-tezhi, the total area flooded, flood level, duration and timing of flooding on the Kafue Flats all depend on the discharge from Itezhi-tezhi dam. The regulation of the discharge at Itezhi-tezhi is targeted primarily at satisfying reservoir level needs for generating electricity at Kafue Gorge (as will be described in Section 2.7.1), which means that there are annual differences in flood pattern and timing depending on the rainfall received (Figure 2.10). When there is high total seasonal rainfall, there is wider flooding on the floodplain.

2.3.2 Recent Hydrological Trends

Long term daily discharge and river level data from four stations in the Kafue basin were obtained from the Zambia Electricity Supply Corporation (ZESCO) and the Zambia Sugar Company (ZSC). The stations were: (1) Kafue Hook, (2) Itezhi-tezhi and (3) Nyimba (ZESCO data), and (4) Pumping Station 1 opposite Nakambala (ZSC data) (Figure 2.4) for the periods 1973-1994, 1976-1994, 1962-1986 and 1983-1994, respectively. The data for Nyimba were incomplete between 1977 and 1986 because the station was in a state of disrepair. No records outside of these periods or from other stations were available from ZESCO or ZSC. Kafue Hook is up stream of the dam at Itezhi-tezhi (Figure 2.7) and, therefore, served as a control.

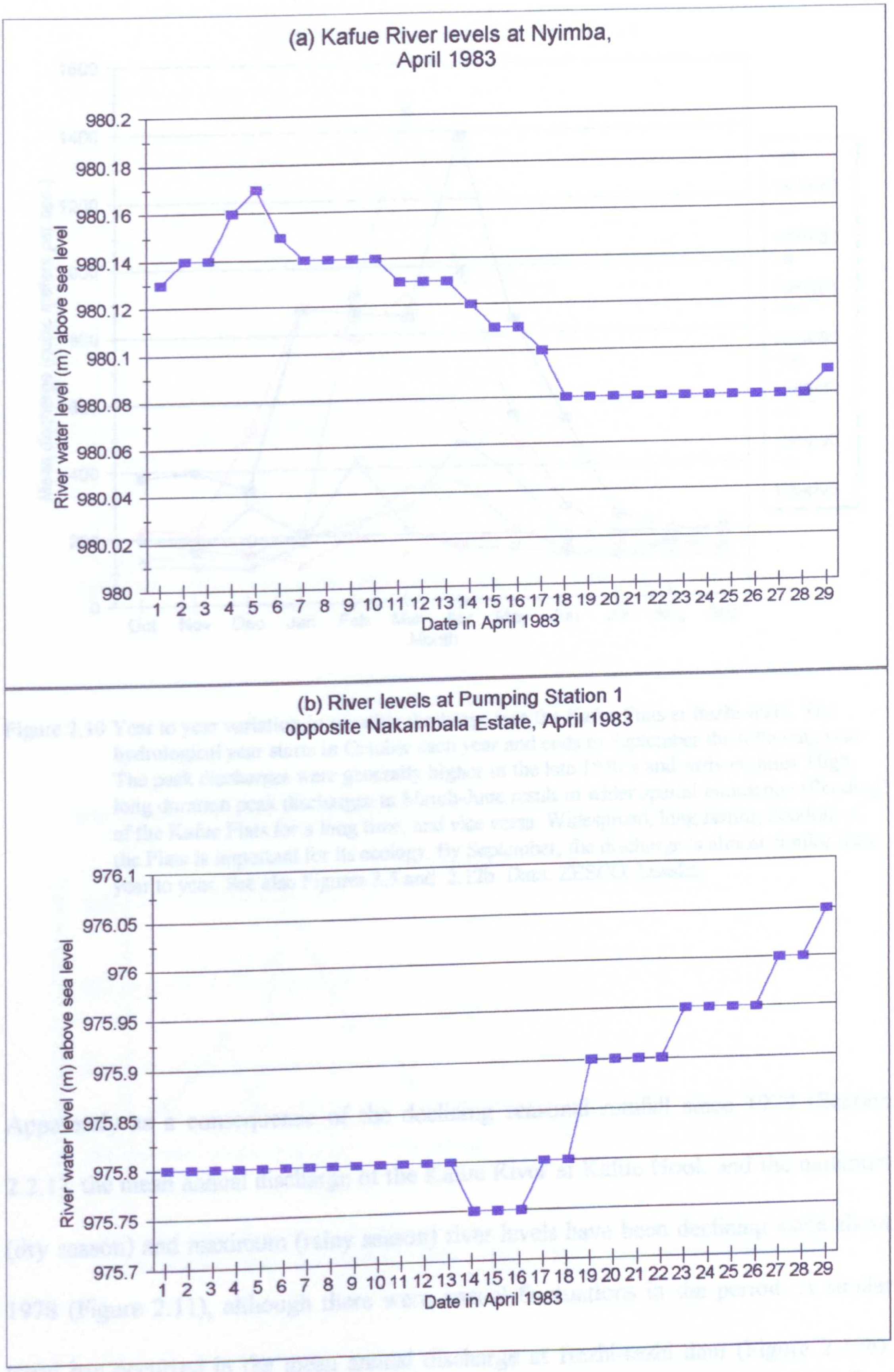


Figure 2.9 Kafue River levels (a) at Nyimba (b) Opposite Pumping Station 1, Nakambala in April 1983. The flood started to raise the river level at Nyimba (upstream) before 1 April, but only arrived opposite Mazabuka at Pumping Station 1 on 16 April. Data (a) ZESCO, Lusaka, (b) Zambia Sugar Company, Mazabuka.

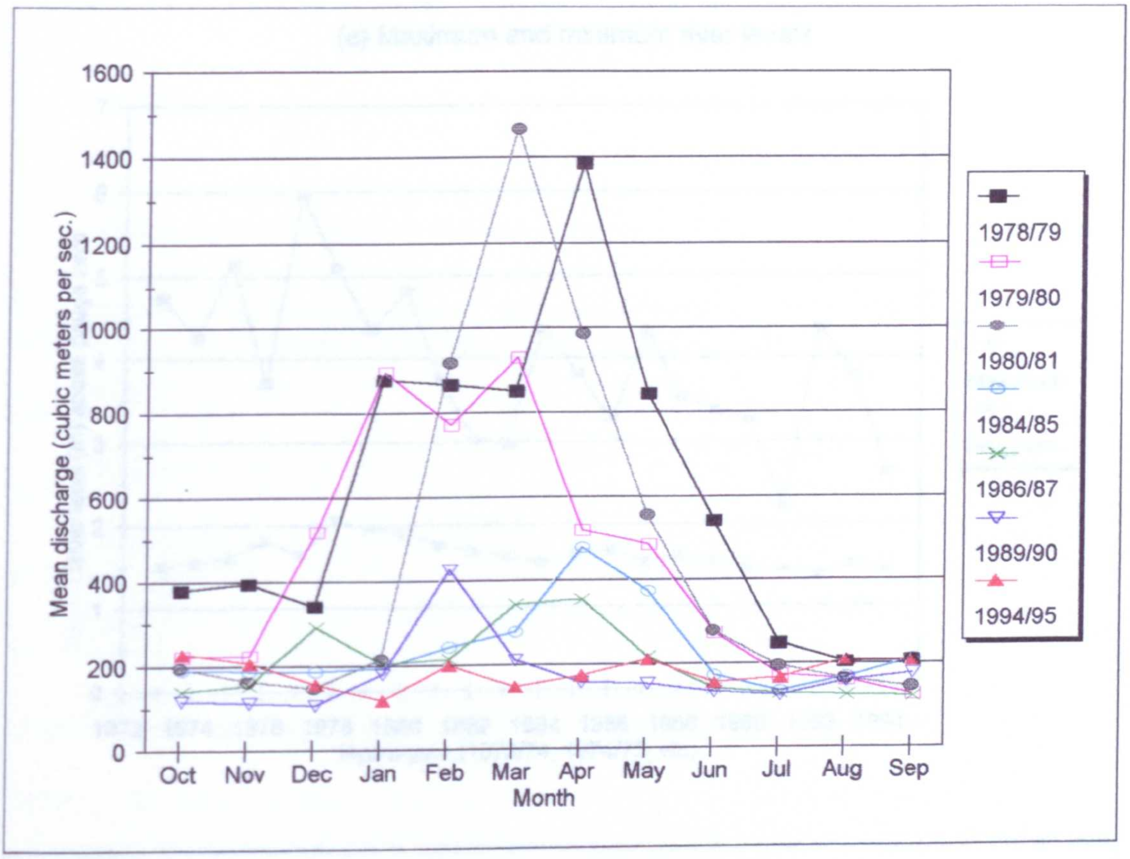
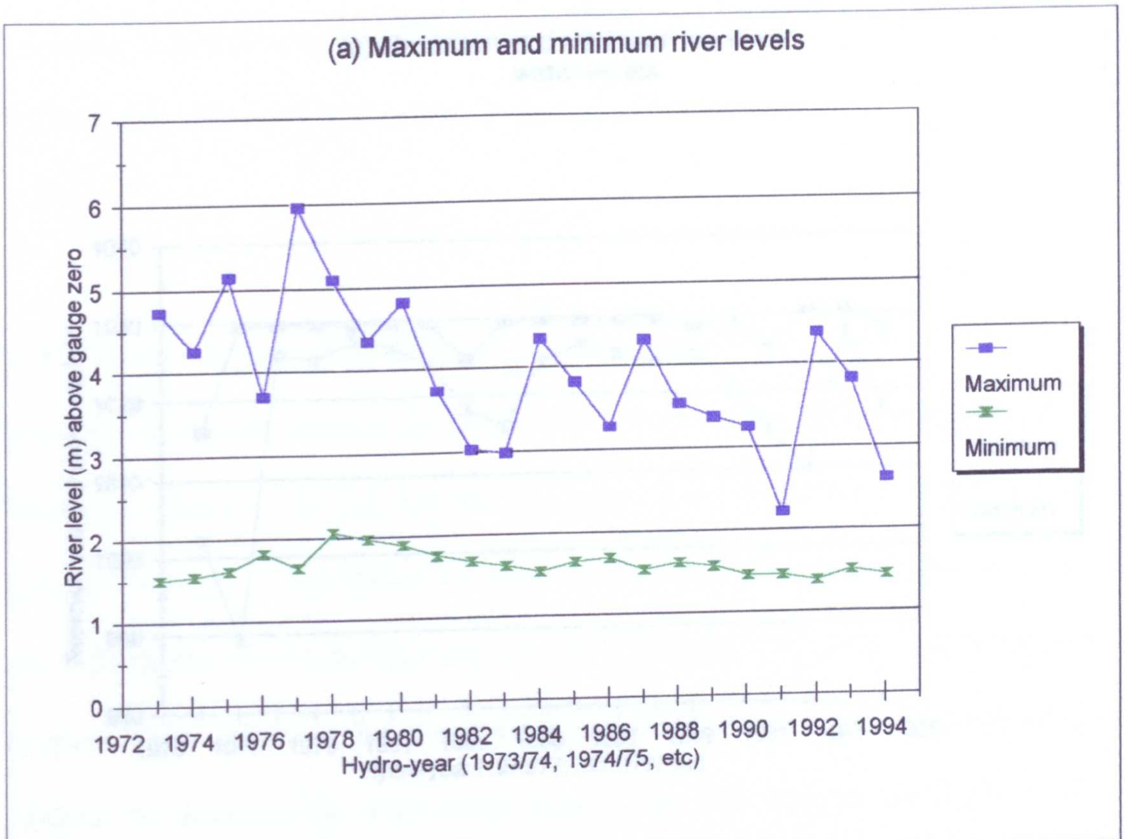


Figure 2.10 Year to year variation in monthly discharge into the Kafue Flats at Itezhi-tezhi. The hydrological year starts in October each year and ends in September the following year. The peak discharges were generally higher in the late 1970's and early eighties. High, long duration peak discharges in March-June result in wider spatial inundation (flooding) of the Kafue Flats for a long time, and vice versa. Widespread, long lasting flooding of the Flats is important for its ecology. By September, the discharge is almost similar from year to year. See also Figures 2.5 and 2.12b. Data: ZESCO, Lusaka.

Apparently as a consequence of the declining seasonal rainfall since 1978 (Section 2.2.1), the mean annual discharge of the Kafue River at Kafue Hook and the minimum (dry season) and maximum (rainy season) river levels have been declining since about 1978 (Figure 2.11), although there were annual fluctuations in the period. A similar trend has occurred in the mean annual discharge at Itezhi-tezhi dam (Figure 2.12b). Since the completion of the dam in 1978, the minimum and maximum water levels in the reservoir have been maintained at fairly constant levels (Figure 2.12a; maximum



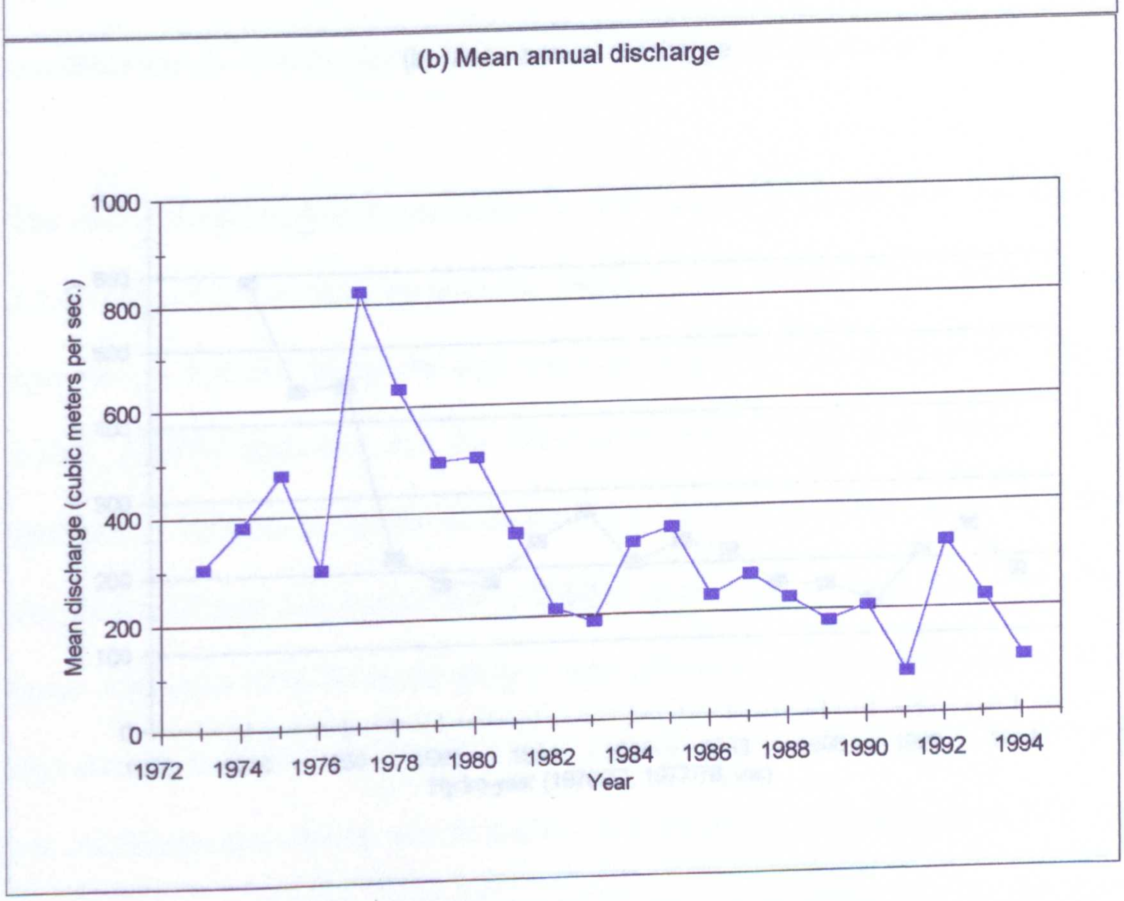


Figure 2.11 Hydrological trends at Kafue Hook, 1973 - 1994.

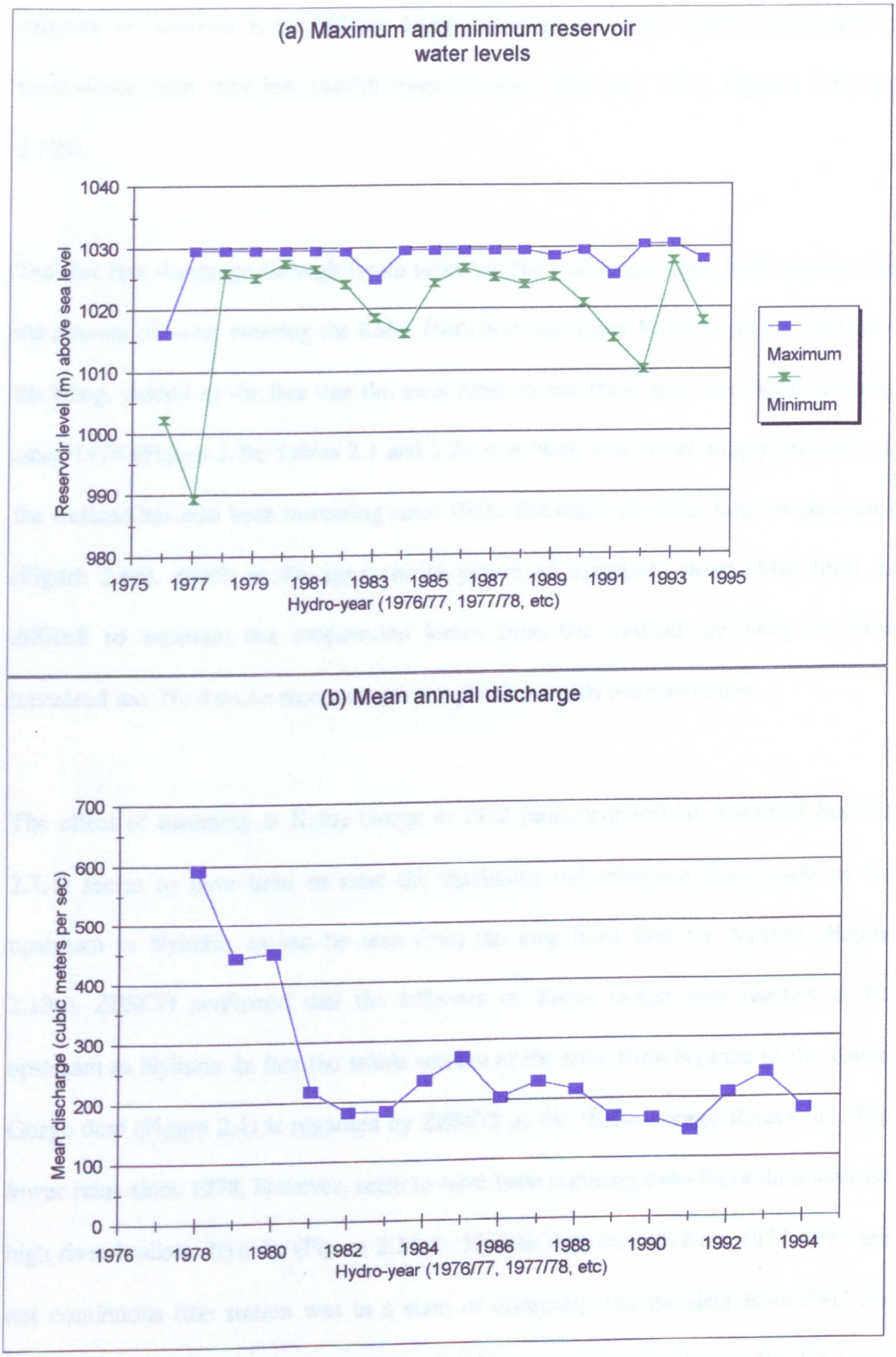


Figure 2.12 Hydrological trends at Itezhi-tezhi, 1976 - 1994.

capacity of reservoir is at 1029.5m level), although they have fallen occasionally in coincidence with very low rainfall years (around 1982 and 1991; Figures 2.5a and 2.12a).

The fact that discharge through Itezhi-tezhi has been declining since 1978 implies that the amount of water entering the Kafue Flats from the upper Kafue basin has also been declining. Added to the fact that the local rains on the Flats have also been declining since 1978 (Figure 2.5b; Tables 2.1 and 2.2), it is likely that water supply pressure on the wetland has also been increasing since 1978. The effect of rising June temperatures (Figure 2.6a), which is the approximate period of maximum flood (May-July), is difficult to ascertain but evaporation losses from the wetland are likely to have increased too. No data on recent evapotranspiration trends were available.

The effect of damming at Kafue Gorge in 1972 (damming will be described Section 2.7.1) seems to have been to raise the maximum and minimum river levels as far upstream as Nyimba, as can be seen from the long term data for Nyimba (Figure 2.13a). ZESCO confirmed that the influence of Kafue Gorge dam reaches as far upstream as Nyimba. In fact the whole section of the river from Nyimba to the Kafue Gorge dam (Figure 2.1) is regarded by ZESCO as the 'Kafue Gorge Reservoir'. The lower rains since 1978, however, seem to have been reducing even these dam induced high river levels at Nyimba (Figure 2.13a). Nyimba data records from 1977-1994 are not continuous (the station was in a state of disrepair), but the data from ZSC for Pumping Station 1 (1983 - 1994; Figure 2.13b) may partly compensate for this since both stations are in the section of the Kafue River between the dams (Figure 2.7).

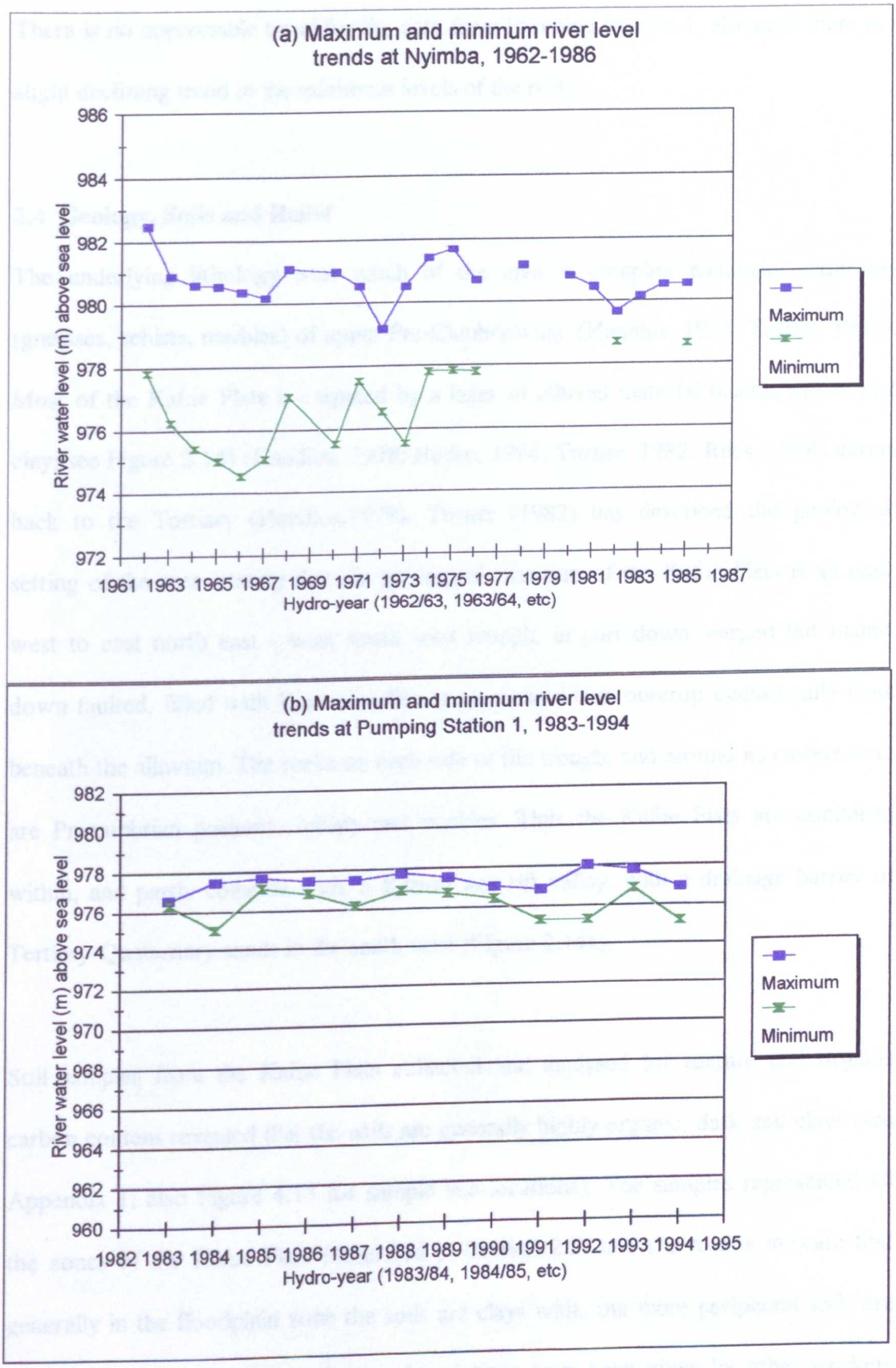


Figure 2.13 Hydrological trends at Nyimba (1962-1986) and Pumping Station 1 opposite Nakambala Sugar Estate (1983-1994).

There is no appreciable trend for the data from Pumping Station 1, although there is a slight declining trend in the minimum levels of the river.

2.4 Geology, Soils and Relief

The underlying lithology over much of the area is complex Katangan sediments (gneisses, schists, marbles) of upper Pre-Cambrian age (Handlos, 1978; Turner, 1982). Most of the Kafue Flats is carpeted by a layer of alluvial material (sands, gravel and clay; see Figure 2.14) (Handlos, 1978; Burke, 1994; Turner, 1982; Rees, 1978) dating back to the Tertiary (Handlos,1978). Turner (1982) has described the geological setting of the area, stating that the geological structure of the Kafue Flats is an east-west to east north east - west south west trough, in part down warped but mainly down faulted, filled with Karroo sedimentary rocks which outcrop occasionally from beneath the alluvium. The rocks on each side of the trough, and around its eastern end, are Precambrian gneisses, schists and marbles. Thus the Kafue Flats are contained within, and partly coincide with, a Karroo age rift valley, with a drainage barrier of Tertiary-Quaternary sands in the south west (Figure 2.14a).

Soil samples from the Kafue Flats collected and analysed for texture and organic carbon content revealed that the soils are generally highly organic, dark and clays (see Appendix 1; also Figure 4.13 for sample site locations). The samples represented all the zones of the Kafue Flats (described in Section 2.5) and the results indicate that generally in the floodplain zone the soils are clays while the more peripheral soils are loams (sand-silt-clay loams). Similar descriptions have been given by other workers (e.g. Handlos, 1978; Turner, 1982; Rees, 1978; Ellenbroek, 1987; FAO, 1968 Vol. II).

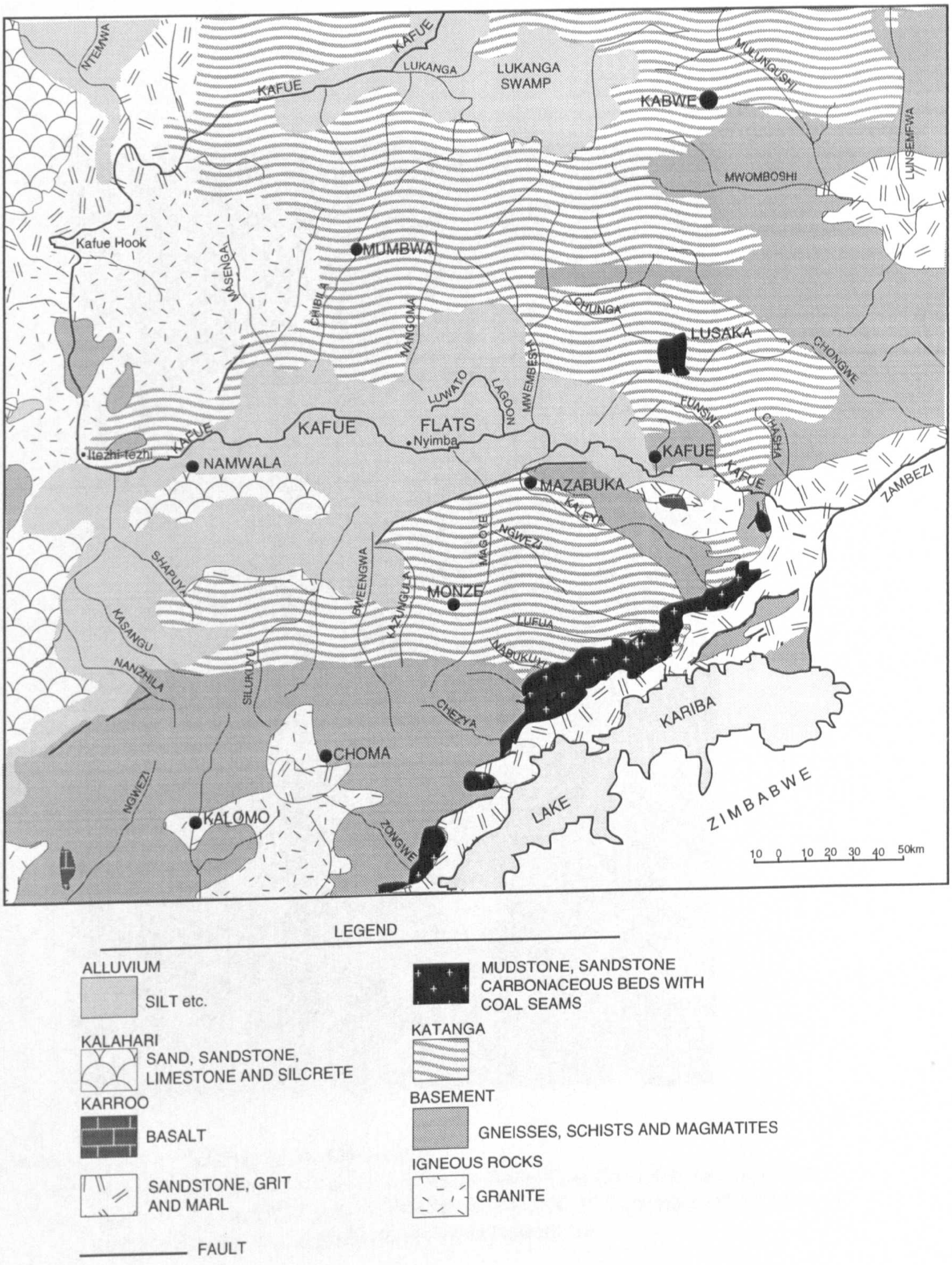


Figure 2.14 Geology of the Kafue Flats
(a) Geology map of the Kafue Flats and surrounding areas (modified from Ellenbroek, 1987). The map shows that the Kafue Flats (centre of map) are underlain mainly by alluvial material.

Figure 2.14 (*continued*) Geology of the Kafue Flats
(b) Alluvial and rock layering in a well on the Kafue Flats floodplain (just north of Luwato Lagoon, UTM grid 35 558829E, 8294452N, 27 September 1995). The soil horizon textures in the profile (from top to bottom) are:

0 - 35cm:	dark clay
35 - 60cm:	clay sand
60cm - 1.15m:	sand
1.15 - 1.56m:	gravel
1.56 - 6.00m:	rock (water table at 6m)

Handlos (1978) has described the trend in soil distribution on the Kafue Flats, stating that a transition of soils occurs depending on the local relief and the parent material. The more peripheral soils are clays and loams, while, on the Flats, those areas that are flooded consist of clay soils rich in carbon, giving a dark black colour. Turner (1982) gives a similar description, stating that the soils of the floodplain are dark margallitic clays, very heavy and sticky when wet, but cracking when dry. At the margins of the floodplain, these may give way abruptly to sandy loam `upland' soils, or there may be a gradual or patchy transition to clay-loam.

Departures from this general trend in the soils analysed (Appendix 1) may be attributed to local site conditions such as presence of old, flattened termite mounds or the action of local plants in trapping wind borne silt particles, or variations in sediment deposition resulting from site flood characteristics.

The area is generally very flat (Figure 2.15), with very little macro-relief variation. It has an average elevation of 900m above sea level (Howard, 1985). Only in the woodland zone (which will be described in Section 2.5) do relief differences in the land begin to be noticeable. There is notable micro-relief on the Kafue Flats which results from the contraction, expansion or drying up of the clay soils. The montmorillonitic (smectite) clays expand when wet and contract when dry. Such expansion and contraction gives rise to what is termed gilgai micro relief (2-6 m wide and up to 50 cm high; Rees, 1978). Deep cracks in the clay result when the clay soils dry up in the dry season and are a prominent feature of the micro relief of the area in the dry season.

Figure 2.15 Floodplain relief on the Kafue Flats (north east of Shalwembe Lagoon, UTM grid 35 521087E, 8280058N, looking south east, 25 September 1995, afternoon). This area is heavily grazed by zebra and lechwe. Green shoots of *Vossia cuspidata* grass can be seen. See also Figure 2.22.

2.5 **Vegetation**

There is distinct zonation in the distribution of vegetation on the Kafue Flats. The major vegetation zones are woodland, termitaria zone and floodplain zone (Table 2.3). In between the zones are sharp or gradual ecotones. From Table 2.3 it can be inferred that the zones are largely controlled by hydrology and soil spatial variations. The woodland zone is on the periphery. The major woodland types are munga woodland (mainly *Acacia* species), miombo woodland (mainly *Brachystegia* species), and mopane woodland (mainly *Colophospermum* species) (Ellenbroek, 1987). Some stretches of woodland consist largely of dense stands of a particular species (e.g. see

Table 2.3. Major Vegetation Zones of the Kafue Flats

Zone	Description	Major vegetation types
Woodland	Located on the fringes, soils mainly clays and loams.	(i) Munga woodland - mainly *Acacia* species (ii) Miombo woodland - mainly *Brachystegia* species (iii)Mopane woodland - mainly *Colophospermum* species
Termitaria zone	Located between woodland and floodplain proper, characterised by termite mounds of different sizes and types, waterlogged in wet season, mainly grey clay soils.	Grasses (e.g. *Acroceros macrum, Panicum* species) and shrubs associated with occasional flooding, occasional trees (*Acacia*) on termite mounds.
Floodplain	Generally impervious soils, subject to seasonal inundation.	Major plant species are water lilies (*Nymphaea*), hippo grass (*Vossia cuspidata*), water grass (*Echinochloa stagnina*), *Phragmites mauritianus* and *Aeschynomene fluitans*; other species are abundant in localised sections of the floodplain; there are up to 28 species of grasses.

(Summarised from Howard, 1985, and Handlos, 1978).

Figure 2.16), but most of the woodland is mixed and open. In the open spaces between the trees grow a variety of grass species, most of which are of the genera *Hyparrhenia, Setaria, Brachiaria, Echinochloa* and *Panicum*. The grasses are mostly perennial, being senescent in the dry season. The woodland species are mostly deciduous, losing their leaves in June/July and re-growing them in September/October (southern hemisphere spring time). Where substantial cutting of trees by man has been sustained,

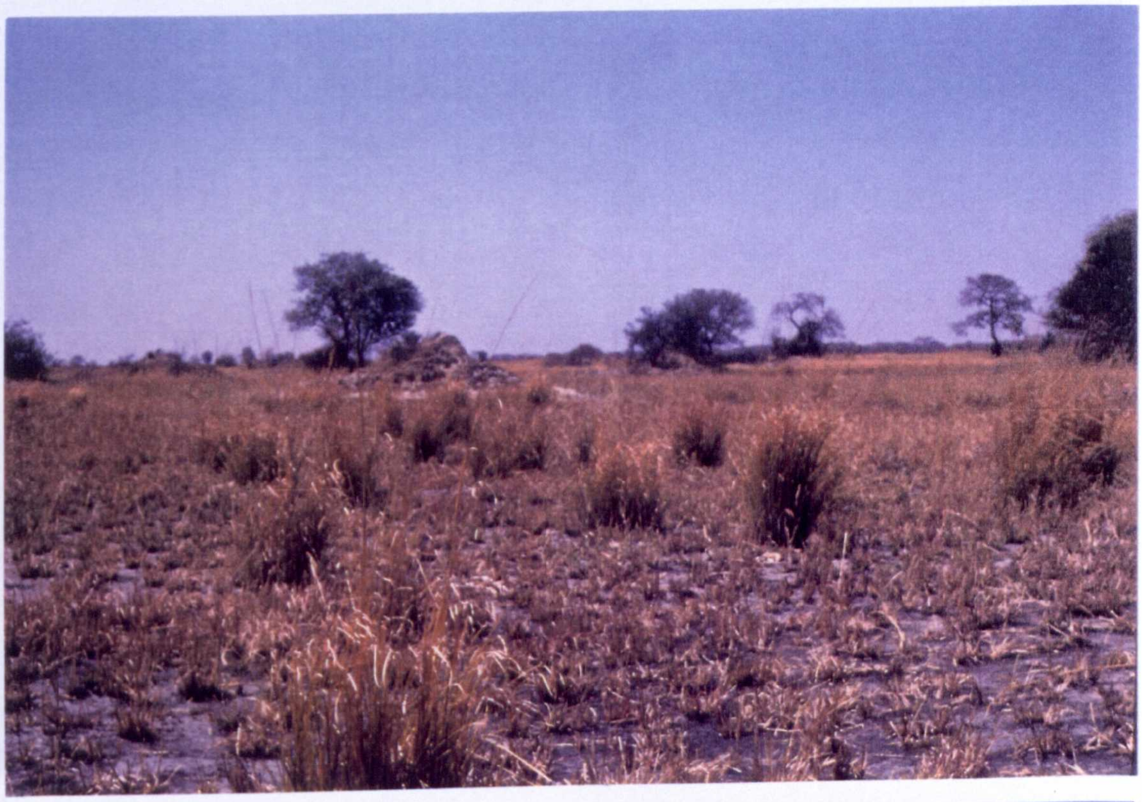
Figure 2.16 Dense *Acacia polyacantha* woodland on the northern fringes of the Kafue Flats (near Nangoma River, just west of Muchabi School, UTM grid 35 5**29**706E, 82**92**732N, looking west, 25 September 1995, morning).

Figure 2.17 A sparse stand of woodland (*Albizia harveyi* in the center) on the northern Kafue Flats (in the former village areas south of Muchabi, UTM grid 35 5**27**592E, 82**89**917N, looking east, 25 September 1995, morning). The trees are in spring.

the woodland will degenerate into shrubs, and regenerating woodland areas appear as coppiced areas. *Albizia harveyi* (in munga woodland; Figure 2.17) is favoured for wood and *Colophospermum mopane* (in mopane woodland) is favoured for house building by the local people. Close to human settlement areas, these trees are coppiced (Figure 2.17).

Woodland gradually gives way to the termitaria zone (e.g. Figure 2.18) which has termite mounds of different sizes, built by different termite species. *Macrotermis* species build large mounds (about 1.5 - 2m tall), *Odontotermis* species build rounded, medium sized mounds (about 80cm - 1m tall) and *Cubitermis* species build very small mounds (about 30cm tall) (FAO, 1968, Vol. IV). Grasses grow between the termite mounds, and in some areas isolated shrubs of woodland tree species can be found (see Figure 2.18b). The grasses include *Setaria sphacelata, Vitiveria nigritana* and *Setaria eylesii.*

The lower limit of the termitaria zone roughly marks the edge of the upper limit of flooding (Ellenbroek, 1987; Turner, 1982). On the floodplain are vast areas of grassland, either largely with stands of a particular dominant species or with mixtures of grass species (e.g. Figure 2.19). In areas with wildlife or cattle, the floodplain grasses are grazed (see Figures 2.15 and 2.22). The timing and duration of the flood (see Section 2.3.1.2) determines the nature of floodplain vegetation, and as a result (of annual flood variations) annual changes in the species composition of the floodplain grassland community are common (Ellenbroek, 1987).



(a)

(b)

Figure 2.18 The Termitaria zone on the Kafue Flats.
(a) woodland-termitaria (*macrotermis*) mixture, with *Vitiveria nigritana* grass in the foreground (south of Nachaba, UTM grid 35 5**63**446E, 82**56**978N, looking south east, 21 September 1995, noon).
(b) termitaria (*odontotermis*)-grassland mixture, with isolated *Acacia* shrubs (south of Nachaba, UTM grid 35 5**64**184E, 82**50**996N, looking east, 8 September 1995, afternoon). The grass still has faint greenness in lower portions.

(a)

(b)

Figure 2.19 Ungrazed floodplain grassland on the Kafue Flats
(a) Just south of Namatusi village, south bank (UTM grid 35 5**36**530E, 82**56**867N, looking east, 19 September 1995, noon).
(b) *Hyparrhenia rufa* (right and background) grassland, north bank and south of Muchabi (UTM grid 35 5**23**802E, 82**82**487N, looking southeast, 25 September 1995, afternoon). In the central fore-ground is a mixture of *Eragrotis lappula* and *Setaria sphacelata*.

Along the Kafue River and around lagoons, ox-bow lakes, pans and on swamps are water reeds and other water fringe vegetation. There are many species in this zone. Swamp and marsh areas which are permanently wet have dense stands of *Cyperus papyrus* and *Typha domingensis*[1]. Other species on the fringe of wet areas include *Phragmites mauritianus, Polygonum senegalense,* sedges, *Vossia cuspidata* and *Sesbania sesban* (see Figures 2.20 and 2.21). On the surface of calm waters are floating plant species like water lilies (*Nymphaea* sp.) and *Salvinia molesta* (see Figure 2.21c).

In all the vegetation zones, human induced fires are a significant ecological factor every year. The fires are started as soon as the grass is dry enough to burn at the end of the dry season, usually in June-July and throughout the dry season (Ellenbroek, 1987). The main reason for the burning is to stimulate the growth of fresh grazing grass for livestock, although fires are started by accident or simply to clear the land.

2.6 **Wildlife**

As a wetland habitat, the Kafue Flats support a variety of fauna, whose population sizes would be affected by habitat change. In addition, grazing and browsing animals could cause vegetation change. The endemic lechwe (*Kobus leche kafuensis*), a grazer, is one of the many species living on the Kafue Flats, mainly in the national parks and adjacent areas (see Figure 2.21e). The lechwe is numerically superior over the other large wild animal species found in the area. The other animals include zebra (*Equus*

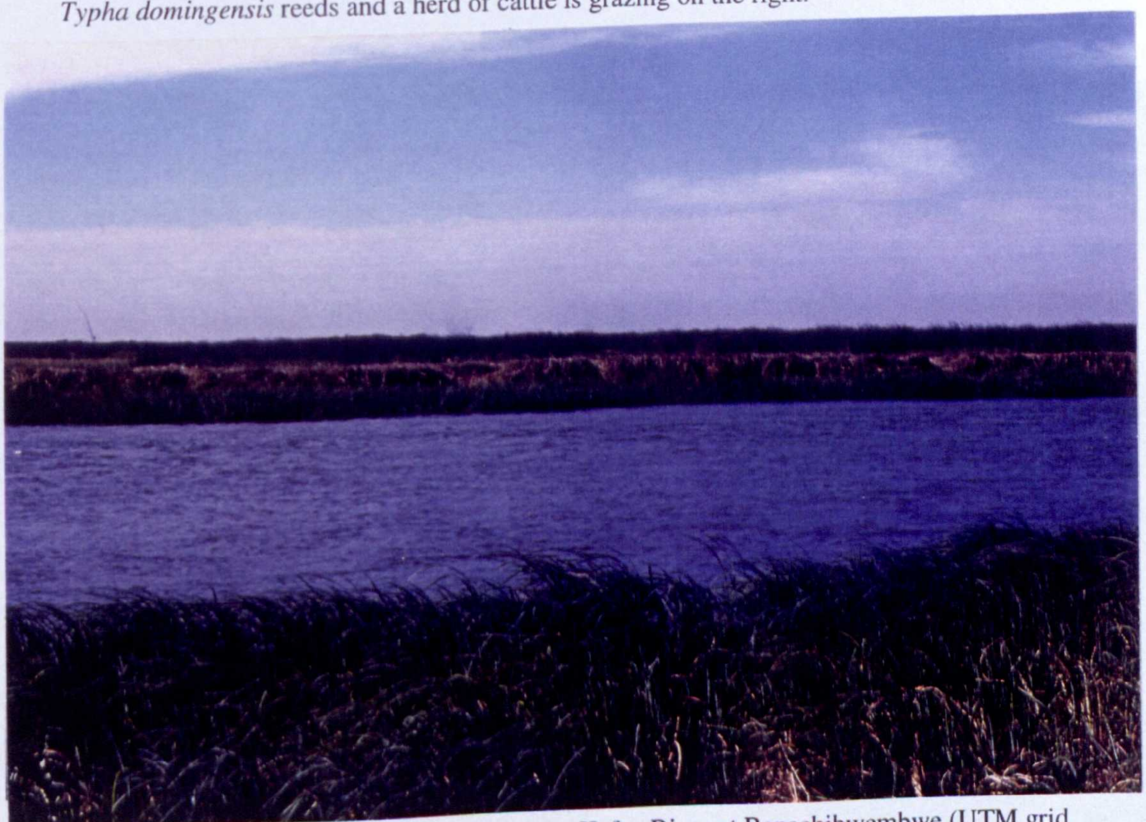
[1] Phiri (Department of Biology, University of Zambia) identified this as *T. australis* while Ellenbroek (1987) apparently calls it *T. domingensis*. Phiri (pers. comm.) points out that in *C. papyrus*/ *T. australis* communities, *C. papyrus* tends to be dominant.

burchelli)(Figure 2.22) - second most abundant after lechwe (Ellenbroek, 1987), wildebeest (*Connochaetus taurinus*) - the next most numerous although much fewer, buffalo (*Syncerus caffer*), oribi (*Ourebi ourebi*), reedbuck (*Redunca arundinum*) and kudu (*Tragelaphus strepsiceros*). Most of these animals are found in Lochinvar National Park (Figure 2.1) on the Flats and adjacent wooded areas. Buffaloes are rare in Blue Lagoon National Park, although the other herbivores listed above (excluding buffalo) were seen there also in 1995.

Figure 2.20 A dense stand of water reeds and water fringe vegetation on the Kafue Flats (bordering the eastern edge of Shalwembe Lagoon, UTM grid 35 517618E, 8279633N, looking north, 25 September 1995, mid afternoon). In the foreground is *Polygonum senegalense*. *Cyperus papyrus* is in the top right and top left corners, and *Phragmites mauritianus* is in the middle of the background.

Figure 2.21 Hydrophytic vegetation on the Kafue Flats

(a) *Polygonum senegalense* and water grass mixture (foreground, right bank), with *Vossia cuspidata* on the banks of the Kafue River at Banachibwembwe (UTM grid 35 533451E, 8260878N, looking east, 7 September 1995, afternoon). Across the river (background) are dense *Cyperus papyrus* and *Typha domingensis* reeds and a herd of cattle is grazing on the right.



(b) Dense *Vossia cuspidata* along the banks of the Kafue River at Banachibwembwe (UTM grid 35 533451E, 8260878N, looking north, 7 September 1995, afternoon). Across the river (background) is a dense, vigorous stand of *Typha domingensis.*

Figure 2.21 (continued) Hydrophytic vegetation on the Kafue Flats

(c) A dense stand of *Vossia cuspidata* on the south bank of the Kafue River at Kabwe village just north of Lochinvar (UTM grid 35 5**32**500E, 82**59**412N, looking west, 7 September 1995, mid afternoon). In the lower portion of the picture, behind the grass, is floating *Salvinia molesta*.

(d) A dense stand of *Cyperus papyrus* and water grass on the banks of the Kafue at Shakapinka (UTM grid 35 5**67**256E, 82**64**201N, looking west from south bank, 8 September 1995, noon).

Figure 2.21 (continued) Hydrophytic vegetation on the Kafue Flats

(e) *Sesbania sesban* shrubs stranded by the retreating water line in a depression north east of Chunga Lagoon, just outside Lochinvar National Park (UTM grid 35 532717E, 8255682N, looking east, 7 September 1995, morning). Notice the lechwe (in middle) and zebra (background).

Figure 2.22 Zebra in the heavily grazed floodplain grassland of the Kafue Flats (north east of Shalwembe Lagoon, just outside Blue Lagoon National Park, UTM grid 35 518150E, 8279705N, looking northeast, 25 September 1995, mid afternoon).

Large carnivores such as lions (*Pantheras leo*), leopards (*Pantheras pardus*), wild dogs (*Lycon pictus*) and cheetah (*Acynonix jubatus*) are absent because they were systematically exterminated when the parks were cattle ranches, but, according to Ellenbroek (1987), the spotted hyena (*Cracuta crocuta*), serval (*Felis serval*) and side striped jackal (*Canis adustis*) are still permanent residents. Primates such as vervet monkeys and baboons (*Papio ursinus*) are also present in the woodland zone. The hippopotamus (*Hippopotamus amphibius*) occurs in small herds in most parts of the Kafue Flats (river and other deep water areas) while sitatunga (*Tragelaphus spekei*), a true aquatic ungulate confined to *Papyrus* and reed marshes, has also been observed locally (Ellenbroek, 1987).

Over 400 species of birds are listed for the Kafue Flats (Handlos, 1978; Douthwaite, 1974), about 125 of which are water birds (Sheppe, 1985). Some of the birds are migrants and come to the Flats to breed in the wet season (northern hemisphere winter). The birds found on the Flats include ducks, cormorants, darters, pelicans, herons, king fishers, fish eagles, storks, geese, spoon bills, red billed teal, ibises and wattled cranes. Most of the birds live on or around water bodies (e.g. see Figure 2.23).

Concern about the plight of some of these birds prompted ornithologists, including the International Waterfowl and Wetlands Research Bureau (IWRB), to conduct bird counts (especially of wattled cranes) on the Kafue Flats. The figures (e.g. as in Table 2.4), however, are incomplete and unreliable (Dodman[1], 1995, pers. comm., confirmed this with respect to the wattled crane). Studies of birds on the Kafue Flats were started

[1] Tim Dodman was Technical Advisor, Africa Programme at IWRB in 1995.

Figure 2.23 A Flock of egrets (center of picture on water fringe) on the fringe of Luwato Lagoon (UTM grid 35 560401E, 8290070N, looking south from north bank, 27 September 1995).

Table 2.4 Bird Populations on the Kafue Flats

Date	Bird	Population	Source
June 1972	wattled crane	1 601	Douthwaite, 1974
November 1972	wattled crane	2 932	Douthwaite, 1974
May 1973	wattled crane	3 085	Douthwaite, 1974
August 1973	wattled crane	2 336	Douthwaite, 1974
21 - 24 May 1982	wattled crane	3 282	Howard and Aspinwall, 1984

as early as 1970 (Douthwaite, 1974). There have not been many (published) recent quantitative studies of bird populations but numbers seem to be on a declining trend as a result the regulation of flooding due to dam operations (Sheppe, 1985).

The habitat requirements of most wildlife species on the Kafue Flats all center around the availability of water and green or other fresh vegetation. The wattled crane (*Grus carunculatus*) breeds in the grass left by the retreating flood and even in shallow flood water areas. More wattled cranes breed when there is extensive flooding. Its diet consists of grass seeds and insects sometimes, but mainly rhizomes which it digs out of soft clay soils (Douthwaite, 1974). The availability of an extensive, shallow flood is, therefore, very important to the wattled crane, whose distribution around the year follows the flood water line. Wattled cranes occur elsewhere in Africa but as far as is known, the largest concentration of these birds in Africa occurs on the Kafue Flats in the latter half of the dry season (Douthwaite, 1974). For fish eating birds, whatever affects fish numbers affects their populations in the long term. Low dry season water levels increase both natural and fishing (by birds and man) induced mortality of fish (Dudley and Scully, 1980).

The habitat requirements of the semi aquatic lechwe are also related to water (i.e. hydrological availability). Handlos (1978), Rees (1978) and Sayer and van Lavieren (1975) have described the habitat requirements and distribution around the year of the Kafue lechwe. During the early dry season (April-June) the grasses of the termitaria zone (especially *Oryza longistaminata, Sporobolus festivus, Brachiaria rugulosa, Vossia cuspidata, Vitiveria nigritana* (see Figure 2.18a), *Cynodon dactylon*) form the largest part of the diet. In all up to 30 species of grass and two dicotyledons have been identified as lechwe food, from lechwe lumen studies (Handlos, 1978; Rees, 1978; Sayer and van Lavieren, 1975). In general, vegetation species of the woodland are not utilized by lechwe because the lechwe normally do not spend much of their time there, although on occasion some animals may graze in the area. Like that of the wattled crane, the distribution of lechwe follows the flood (see Figure 2.24).

Currently lechwe are confined to the vicinity of Lochinvar and Blue Lagoon national parks and the area between (Sheppe, 1985). Interest in animal counting on the Kafue Flats has mainly focused on the lechwe which was said to be endangered. Recent recovery in lechwe numbers (Table 2.5) has been attributed to a number of factors, including the involvement of the local people in wetland management (Jeffrey and Chooye, 1991), which has reduced poaching. Poaching is the lechwe's key mortality factor, although over population induced stresses and diseases also cause lechwe mortality (Schuster, 1980).

2.7 Land Use and Commercial Pressures on Wetland Stability on the Kafue Flats

Being an important source of water in the semi-arid environment, the Kafue River which flows through the Kafue Flats has attracted conflicting demands for the utilisation of the water. The main demands for the use of the area and its water are:

1. hydroelectricity power generation,
2. sugar cane irrigation,
3. nature conservation,
4. fishing,
5. cattle grazing,
6. municipal water supply.

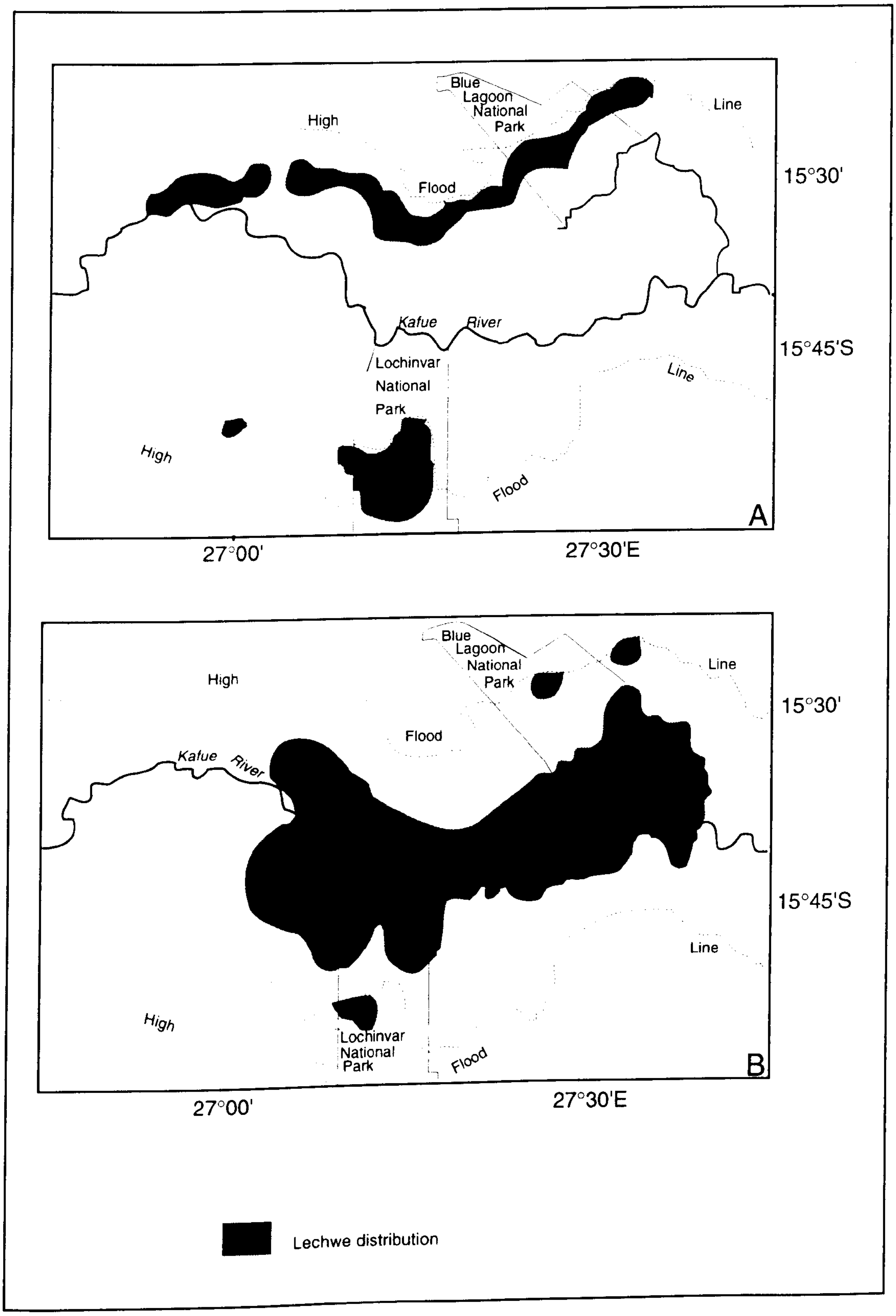


Figure 2.24 Distribution of Kafue Lechwe: A. 17-22 June, 1971 (during peak flood period).
B. 2-14 September, 1971 (during low flood period).
(After Sayer and van Lavieren, 1975)

Table 2.5 Kafue Lechwe Population Trends

Year	Lechwe Population	Source
before 1971	94 000 (stable)	Sayer and van Lavieren, 1975
1972	-	-
1973	-	-
1974	-	-
1975	80 000	Sheppe, 1985; Schuster, 1980
1976	-	-
1977	70 000	Schuster, 1980
1978	-	-
1979	50 000	Schuster, 1980
1980	-	-
1981	45 000 45 867	Sheppe, 1985 Chooye, 1996, pers. comm.[1]
1982	41 000 41 345	Sheppe, 1985 Chooye, 1996, pers. comm.
1983	41 000 41 155	Sheppe, 1985 Chooye, 1996, pers. comm.
1984	-	-
1985	-	-
1986	-	-
1987	50 715	Chooye, 1996, pers. comm.
1988	65 000	Jeffrey and Chooye, 1991
1989	47 145	Chooye, 1996, pers. comm.
1990	44 538	Chooye, 1996, pers. comm.
1991	68 872	Chooye, 1996, pers. comm.
1992	-	-
1993	64 940	Chooye, 1996, pers. comm.

(Where - = no data available)

[1] Chooye was working at the WWF-Zambian Government administered Wetlands Project and had records of aerial censuses of Kafue lechwe.

These will be addressed in turn. Very little arable farming is done as a result of soil and flooding constraints.

2.7.1 **Hydroelectric Power Generation**

The Zambia Electricity Supply Corporation (ZESCO) has implemented a three stage scheme for hydroelectric power generation on the Kafue Flats (Balasubrahmanyam and Abou-Zeid, 1978b). In Stage I, completed in 1972, a 45m dam was built across the Kafue River at Kafue Gorge (Figure 2.1) to utilize a 400m drop of the river in a 14km reach. This resulted in the 800 million m^3 capacity Kafue Gorge Reservoir whose influence in river water levels reaches as far upstream as Nyimba (Figure 2.1) opposite Lochinvar National Park. ZESCO considers the whole section of the Kafue River between Nyimba and Kafue Gorge dam as the Kafue Gorge Reservoir and has water rights for it (Mwasile, 1995, pers. comm.)[1]. A 10km head race tunnel was built to transport water to the underground power station with four units of 150MW each (with provision for two more similar machines in stage II), with a 4km tail race tunnel and vertical penstocks, one for each machine. The Kafue Gorge Reservoir makes available a firm regulated release of $62m^3s^{-1}$. With the four machines from Stage I, the firm output from the Kafue Gorge Power Station was about 1 800GWh (Balasubrahmanyam and Abou-Zeid, 1978b).

Stage II of the scheme aimed at the creation of back up water storage (upstream) at Itezhi-tezhi (Figure 2.1) and the installation of two more 150MW units in the Kafue Gorge Power Station. Backing storage was essential to ensure a constant steady

[1]Mwasile was ZESCO's Chief Engineer, Hydrology, in 1995.

supply of water to the power station. The stage, completed in 1978, involved construction of a 65m dam across the river at Itezhi-tezhi, resulting in a reservoir with a gross capacity of 5 700 million m^3. This capacity, together with that at Kafue Gorge Reservoir, was sufficient to ensure a firm output of just over 5 000 GWh annually from the six machines installed (Balasubrahmanyam and Abou-Zeid, 1978b). In addition, the Itezhi-tezhi reservoir capacity included in it a capacity for the assured flooding of the Kafue Flats (a previous natural annual event; see Section 2.3.1.2) for four weeks, even in the driest years (Balasubrahmanyam and Abou-Zeid, 1978b).

In Stage III of the scheme, a dam site power station is due to be constructed at Itezhi-tezhi to utilize the head created by the dam and the regulation resulting from the operation of the Itezhi-tezhi and Kafue Gorge reservoirs (Balasubrahmanyam and Abou-zeid, 1978b). A component of Stage III which was envisaged was to exploit the 200m drop between the tail race of the Kafue Gorge Power Station and the confluence of the Kafue with the Zambezi (see Figure 2.7). The Kafue Gorge Lower Development Corporation, a private company, has sought investors in a plan to build a $450 million, 600MW power station on the Kafue River to earn $220 million a year exporting power to South Africa (*News From Zambia*, No. 667, 1996). In January 1996, ZESCO signed agreements with the US government and its aid agencies to build a power station at Itezhi-tezhi (*News From Zambia*, No. 667, 1996).

The electricity generated from the scheme accounts for most of Zambia's industrial energy requirements, especially the mining industry on the Zambian Copperbelt which has for a long time been the back bone of the Zambian economy (providing over 90% of Zambia's foreign exchange earnings; *News From Zambia*, No. 667, 1996). The only other large hydroelectric power plant which Zambia has is the Kariba North Bank on the Zambia-Zimbabwe border, which is not solely owned by Zambia because Zimbabwe owns the south bank facility on the same dam and reservoir at Lake Kariba (Figure 2.14a) (Mwasile, 1995, pers. comm.)[1]. The Kafue Flats are, therefore, a vital, strategically important energy source for Zambia.

The recent climate pressure (Section 2.2.1) is inevitably influencing the discharge of water (timing, duration) through Itezhi-tezhi by the Zambia Electricity Supply Corporation. The company's priority is to use the water available to generate electricity, the ecology of the area being only a secondary consideration (Mwasile, pers. comm.).

2.7.2 **Sugar Cane Irrigation**

On the southern edge of the Kafue Flats at Mazabuka (Figure 2.1) is Zambia's largest irrigation scheme (Nang'omba, 1995, pers. comm.)[2], growing sugar cane on the 15 000ha Nakambala Sugar Estate (see Figure 2.25). The estate is owned by the Zambia Sugar Company (ZSC) and managed by Tate and Lyle, a British sugar company (Njobvu, 1990). Sugar cane is grown all year round; in the dry season (defined in Section 2.2) this is accomplished solely by the use of irrigation, while in the rainy season irrigation is used as a supplement to the rainfall (Nang'omba, 1995, pers. comm.). From planting to harvesting the cane requires approximately 2000mm of water, 750mm of which may come from rain and 1250mm from irrigation (Pike, 1978).

[1] Mwasile was ZESCO's Chief Engineer, Hydrology, in 1995.
[2] Nang'omba was Irrigation Manager at Nakambala Sugar Estate in 1995.

The sugar estate draws its water from the Kafue River. A diversion channel was built from the river, through which the water flows by gravity for about 200m to a pumping station (see Figures 2.26 and 2.27) from which it is pumped to a series of storage dams around the estate. The sugar company has water rights for use of the Kafue River's water (Nang'omba, 1995, pers. comm.). The estate has been growing in size since its inception in 1964, from about 2 849ha to over 10 000ha in 1978 (Pike, 1978).

Figure 2.25 Part of the Nakambala Sugar Estate on the edge of the Kafue Flats (UTM grid 35 573891E, 8245457N, looking west from behind Kaleya, 21 September 1995, morning).

Figure 2.26 The water abstraction point at the end of the gravity canal diverting water from the Kafue River to Pumping Station 1, Nakambala Sugar Estate, Mazabuka.

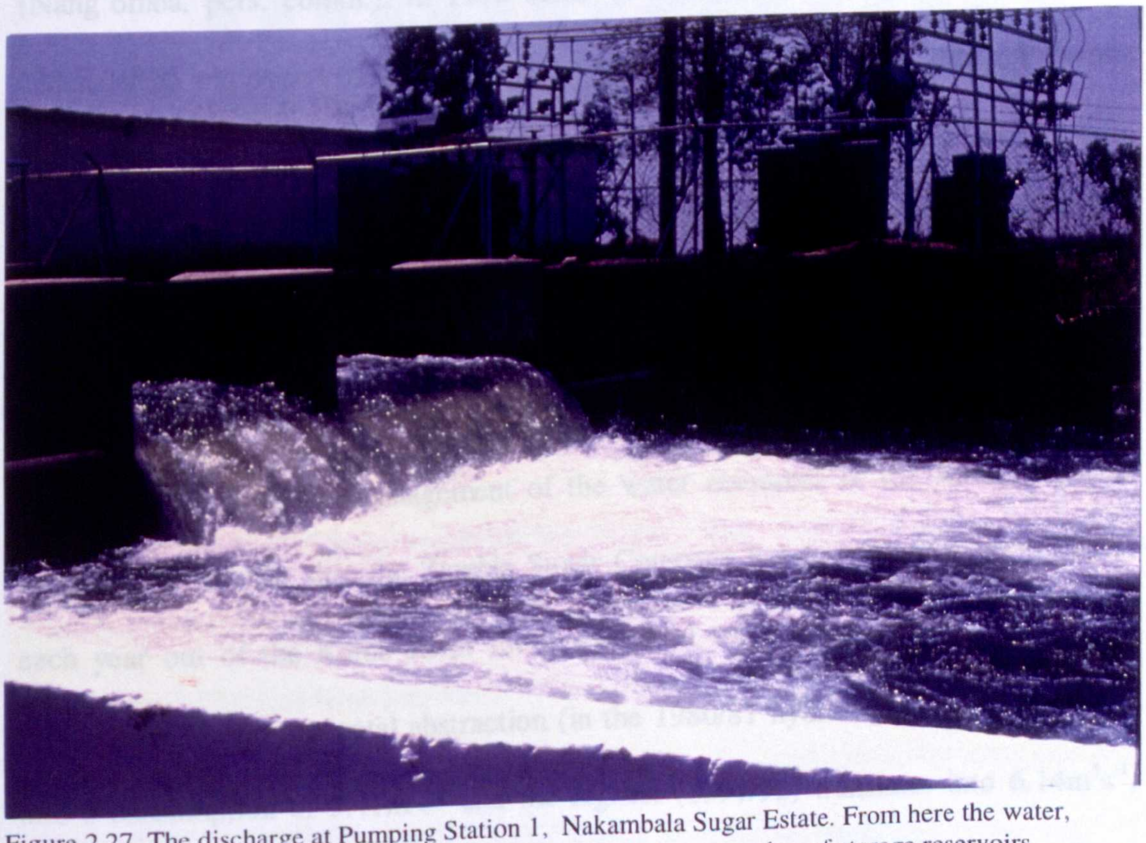


Figure 2.27 The discharge at Pumping Station 1, Nakambala Sugar Estate. From here the water, almost amounting to a river branch, is pumped to a number of storage reservoirs.

A cane factory was commissioned on the estate in 1968. In addition to cane grown by the sugar company, a number of commercial farmers and "small holders" grow cane and sell it to the sugar company, which, by agreement, supplies them with irrigation water (Nang'omba, 1995, pers. comm.). The small holder land size was about 1885ha in 1989/1990 (Njobvu, 1990). Projections were that the estate would grow to 17 000ha, including cane farmers and small holders (Pike, 1978). In 1995 it was about 15 000ha including cane farmers and small holders (Nang'omba, 1995, pers. comm.). Expansion to 17 000ha would, among other things, depend on the availability of the extra water required (Pike, 1978). The 1978 water rights allowed the estate 12 262ha (including farmers), after which further water rights would be required.

Virtually all of Zambia's sugar is produced from cane grown on the Nakambala estate (Nang'omba, pers. comm.). In 1978 some 40 000 tonnes of sugar were produced (Pike, 1978) and over 116 000 tonnes were grown in 1982 (Howard, 1985). Presently about 164 000 tonnes per year are produced (*News From Zambia*, No. 665, 1996). Production of sugar cane is another strategically important use of part of the Kafue Flats to the Zambian economy.

The recent trends in rainfall (and to an extent temperature; Section 2.2.1) seem to have exerted pressure on the management of the water resources of the Kafue Flats, as indicated by the fact that the Zambia Sugar Company has had to pump more water each year out of the Kafue River for irrigation of sugar cane (Figure 2.28). From Figure 2.28, the lowest total abstraction (in the 1980/81 hydrological year) translates into a consumption of $3.41m^3s^{-1}$ and the highest (1991/92) translates into $6.14m^3s^{-1}$, representing 2.0% and 3.1%, respectively, of the channel capacity of the Kafue River on the Kafue Flats, which is $170m^3s^{-1}$ (Ellenbroek, 1987). Increased abstraction of water for irrigation is one indication of rainfall stress, but it could be due to a combination of the climate pressure and the expansion of the sugar estate.

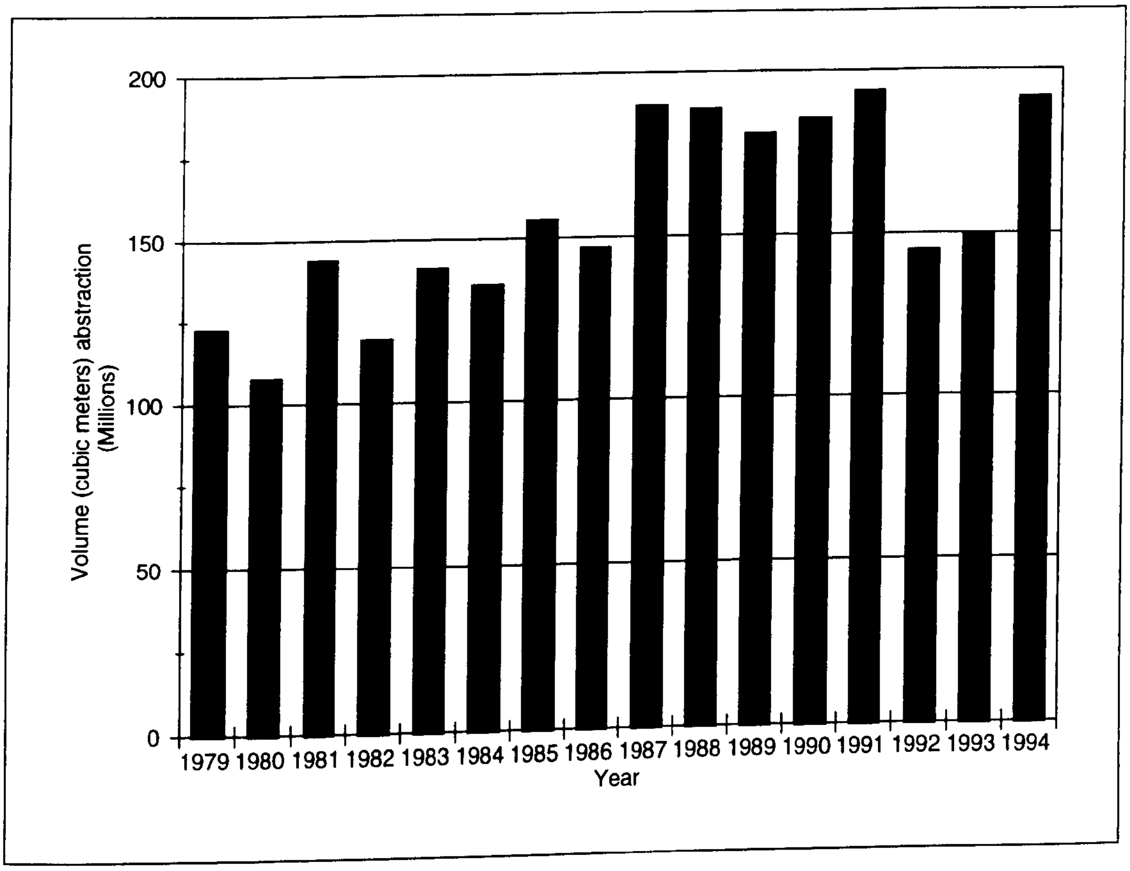


Figure 2.28 Trends in water abstraction from the Kafue River for irrigation at Nakambala Sugar Estate. Data: Zambia Sugar Company, Mazabuka.

2.7.3 Nature Conservation

A variety of birds and large mammals live on the Kafue Flats (as outlined in Section 2.6). In an attempt to conserve them, two small national parks have been established: Lochinvar (1972) and Blue Lagoon (1973) National Parks (see Figure 2.1). Both were cattle ranches previously, from which carnivores were systematically exterminated. Conservation of the biodiversity on the Kafue Flats is an important component of biodiversity conservation in Zambia.

Tourism is a small industry in the national parks and a few wild animals are taken by safari hunters. Poaching is a persistent problem. The World Wide Fund for Nature (WWF) included the Kafue Flats in its Wetlands Project, which was handed over to the Zambian government's Department of National Parks and Wildlife Services in 1995 (WWF-Zambia, 1995, pers. comm.). The project encourages the involvement of the local people in conservation and wetland management, and has largely been successful in doing so (Jeffrey and Chooye, 1991).

The endangered status assigned to the Kafue lechwe (*Kobus leche kafuensis*) (Ellenbroek, 1987; Sayer and van Lavieren, 1975; Schuster, 1980; Chabwela and Ellenbroek, 1990) has meant that most conservation concerns on the Kafue Flats have been about this species. The animal, which is an antelope, is endemic to the Kafue Flats. It lives a semi aquatic way of life and can graze the emergent vegetation in shallow water up to 50cm deep (see Figure 2.29) (Ellenbroek,1987; Rees, 1978; Sayer and van Lavieren, 1975). It is, therefore, highly influenced by the nature (extent and duration) of flooding on the Kafue Flats (described in Section 2.3.1.2).

2.7.4 **Other Uses**

The Kafue River on the Kafue Flats is one of Zambia's commercial fisheries. About 67 species of fish have been listed for the Kafue River system (Handlos, 1978). The fishery is one of the most productive in Zambia, its catches providing about 18% of the national total in 1976 (Muyanga and Chipundu, 1978). Traditional inhabitants (the Twa people) and migrant fishermen sell their fish to middle men who transport the fish (mainly *Tilapia*) to urban markets. In 1982 at least 7 400 tonnes of fish were caught in

Figure 2.29 Lechwe grazing on the edge of Chunga Lagoon, Lochinvar National Park (UTM grid 35 524850E, 8248281N, looking west, 7 September 1995, morning). The animal is semi aquatic, sometimes taking to the water when frightened.

the Kafue Flats fishery (Howard, 1985). Current estimates are 2 500 - 10 200 tonnes of fish per year (Williams, 1990).

During the dry season when the surrounding high ground is dry, herdsmen of the Ila and Tonga tribes bring their cattle down to the wetland to graze (see Figure 2.30). The animals (about 200 000 - 300 000; Williams, 1990) are taken back to the higher ground during the rain season.

Supplying municipalities is one of the uses the water of the Kafue River is put to. The towns of Mazabuka and Kafue, and the city of Lusaka (Figure 2.1), with a population about 1 000 000, draw their water from the river.

Figure 2.30 Cattle grazing (back ground, right) in the wetland areas surrounded by dry grassland on the Kafue Flats (behind Banachibwembwe , UTM grid 35 533201E, 8260455N, looking east, 7 September 1995, afternoon). See also Figures 2.21a and 5.3b).

2.8 Summary

The natural flooding cycle of the Kafue Flats is as follows (Ellenbroek, 1987):

1. *November to January*

A build up of local waters deposited in the catchment below Itezhi-tezhi partly fills the low lying areas with some drainage into the Kafue River, whilst the river level remains low at the beginning of the (rain) season.

2. *January to May*

As the flood level rises in the main river it exploits a limited number of low sections along its banks so that the reversal of flow takes place by water spreading from the main river. Additional inundation occurs from direct rainfall to the flooded area and from local tributaries which are in spate between January and March.

3. *May to October*

As the river level falls again, drainage from the inundated areas will resume but not all the available free water finds its way back to the main river. Large volumes are retained in depressions and are lost by evaporation during the dry season.

Since about 1978, the area has been receiving more unpredictable, erratic and frequently below average seasonal rainfall compared to the period before. Statistically, however, these rains do not significantly differ from those before 1978 in terms of either seasonal totals or frequency of below average rainfall. As a consequence of the reducing seasonal rainfall and the operation of dams, river discharges have been declining. This, in turn, is likely to have resulted in change in wetland attributes.

The potential causes of wetland change on the Kafue Flats (in order of potential magnitude of impact) are fluctuations in:

1. Discharges at Itezhi-tezhi dam (magnitude, duration, timing).
2. Local rainfall (magnitude, duration, timing).
3. Abstraction of water for irrigation of sugar cane on the Nakambala Sugar Estate.
4. Burning (human induced).
5. Grazing pressure (from wildlife and cattle).

The factors influencing the Kafue River's discharge and water levels on the Kafue Flats are:

1. Discharges through Itezhi-tezhi dam (timing, magnitude, duration).
2. Rainfall (timing, magnitude, length of season).
3. Abstractions for irrigation at Nakambala Sugar Estate.
4. Evapotranspiration.
5. Ground water outflow.

Whereas data exist for the first three factors, factors (4) and (5) have scarcely been quantified. There is also a lack of data on the potential indicators (measures) of wetland change listed in Table 1.6. These measures range from properties of plants, vegetation communities, landform, soil, hydrologic and hydraulic properties, aquatic physical and chemical properties, organismal properties, properties of individual wildlife and fish species, to properties of wildlife communities. For wetland change assessment purposes, these attributes would have had to be monitored over time, a very time consuming process. The paucity of data indicates the difficulty of using ground monitoring as a method of assessing long term wetland change. In the case of spatial wetland properties, remote sensing would be a more appropriate approach if historical images are available, because of synoptic coverage of large areas.

The human uses of the Kafue Flats wetland's water are often in conflict with its role as a wetland habitat for many animals and birds. The human use of the area has resulted in increased pressure on the stability of the wetland, in conjunction with climatic pressures. However, because of the economic importance of these human uses, their impact on the wetland is likely to increase, rather than reduce, in the foreseeable future. Striking a balance between resource use and conservation is difficult since the country is under-developed but vitally important, particularly given the role of wildlife in promoting the tourism industry.

Chapter 3

LITERATURE REVIEW

3.1 Introduction

It was shown in Chapter 2 that there have been environmental stresses on the Kafue Flats, in terms of inflow and outflow of water and land use, which could have resulted in wetland changes. The precise nature of these changes can be determined by ground monitoring, remote sensing, or by both approaches. This chapter outlines and summarises material from literature concerning the methodological aspects of change detection by remote sensing, and field-based studies about change on the Kafue Flats. The first part of the chapter reviews the change detection procedures, methods and factors that must be addressed prior to change detection by remote sensing in order to make it more accurate. The strengths and weaknesses of the change detection methods are outlined and examples of wetland studies and land cover change detection studies in southern Africa by remote sensing are pointed out.

The second part of the chapter outlines the results and predictions of change studies of the Kafue Flats. Many studies anticipated and predicted adverse hydrological, vegetation, wildlife and fishery output changes on the Kafue Flats, primarily to result from damming and regulation of discharges into and from the Flats for hydroelectric power generation as outlined in Sections 2.3.1.2 and 2.7.1. These studies and those concerning remote sensing of the Kafue Flats are reviewed.

3.2 Change Detection in Remote Sensing

Change detection involves the selection of a minimum of two images of an area. Prior to change detection analysis of the images, it is important to ensure that any changes detected are the result of change in the land surface target under investigation and not due to any other factors. The other factors that may result in apparent inter image change have been explored by Milne (1988), Jensen (1986) and Mouat *et al* (1993). They are addressed below.

3.2.1 Potential Sources of Change Detection Inaccuracy and Their Prior Elimination

The potential sources of change detection inaccuracy in remote sensing can be grouped into four categories (Milne, 1988):

1. Radiometric factors
2. Temporal factors
3. Spatial aspects
4. Spatial registration aspects

These will be addressed in turn, together with methods of eliminating them or minimising their magnitude.

3.2.1.1 Radiometric Factors and Atmospheric Correction Methods

Differences in the composition of the atmosphere at the time of image acquisition, such as water vapour, aerosols, dust and cloud cover differences, can add to or reduce the apparent reflectance from unchanged ground targets as a result of differences in atmospheric scattering, absorption and reflection of the electromagnetic energy. These factors necessitate radiometric and atmospheric correction before images are used in change detection analysis.

There are four main techniques that can be used to correct images for atmospheric effects (Jensen, 1986; ERDAS Inc., 1994):

1. Dark object subtraction (or zero minimum/histogram adjustment method)
2. Regression adjustment
3. Radiance to reflectance conversion
4. Atmospheric modeling

The methods are reviewed below.

3.2.1.1.1 **Dark Object Subtraction Method**

In the dark object subtraction method, it is assumed that the pixel of lowest digital number in each band should really be zero and hence its radiometric value is the result of atmospheric induced additive factors. Potential targets that can have zero readings are cloud or mountain shadows, dark rocks or volcanic soils in the visible; cloud or mountain shadows, clear and deep water surfaces or burnt areas in the near infrared (Gonima, 1993). The bands are adjusted to have zero as the minimum value, and all the other pixel values are reduced by the same respective amounts as were used to reduce each minimum to zero. The problem with this method is that there may not really be a pixel with zero readings on the image (Crippen, 1987). Work has shown that instead of improving image quality, this method may actually degrade images (ERDAS Inc., 1994). Subtracting a constant value from the entire digital image assumes a constant atmospheric additive effect throughout the entire image, which is often not the case (Chavez, 1988). The method, however, does accomplish first order correction, which is usually better than no correction at all (Chavez, 1988).

3.2.1.1.2 **Regression Adjustment Method**

In the regression adjustment method, an area either in shadow or in homogenous deep, non-turbid water is chosen and then for each pixel in the area, the brightness values of a visible band are plotted against the corresponding values in an infrared band at the same location (Jensen, 1986). If there are no atmospheric effects this plot should pass through the origin. Any shift away from the origin (the x - intercept, called bias) represents atmospheric effects and should be subtracted from all the original data in the visible band concerned. This technique requires many more passes through the digital data than when using the zero minimum method (in the latter method only the band minima are determined). There is no guarantee, however, that it will provide superior results (Jensen, 1986; Crippen, 1987). Although it has a strong statistical footing in that it uses several pixels of various illumination intensities, it provides only relative (not absolute) results (Crippen, 1987).

3.2.1.1.3 **Radiance to Reflectance Conversion Method**

In the radiance to reflectance conversion method, on-site reflectance measurements or standard tables that list the standard reflectance of known targets such as particular soil types, road surfaces or rock types, are used to obtain the true ground reflectance values. The image digital numbers over these known targets are then adjusted to conform to these values, thereby eliminating the atmospheric effects. Use of reflectance tables for standard materials involves assumptions about the targets in the image (ERDAS Inc., 1994) which may not always hold. There is also the disadvantage of the logistical impracticality of ground measurements (Crippen, 1987) because the measurements may have to be made simultaneously at the time of image acquisition.

3.2.1.1.4 **Atmospheric Modeling Methods**

In atmospheric modeling methods (e.g. LOWTRAN or MODTRAN - Kneizys *et al*, 1988), knowledge of the meteorological conditions at the time of satellite overpass, such as aerosol composition, water vapour content, temperature, ozone and pressure, are used to model the path radiance and atmospheric transmission. Though accurate results may result if this information is available, these methods are very complex (ERDAS Inc., 1994). However, the required meteorological information is not always available for a given area, is very expensive to acquire, and is point data and therefore site specific and not necessarily representative of the atmospheric conditions over the entire image (Milne, 1988). Assumptions are often involved which may not always hold.

Work has been done to improve the atmospheric correction methods (e.g. Switzer *et al*, 1981; Chavez, 1988; Crippen, 1987; Kaufmann and Sendra, 1988; Richter, 1990; Gonima, 1993). These improvements may still need further testing and research. The best atmospheric correction method is that which uses *in situ* data from the field at the time of satellite overpass (Chavez, 1988). According to Kaufmann and Sendra (1988), lack of such information means that the only operational use of atmospheric corrections today is that for the ocean colour where the very low reflectance of the water in the red allows a relatively easier correction. Cracknell and Hayes (1991) summarise atmospheric correction by stating that there are several approaches that one can take to the question of applying atmospheric correction to satellite remote sensing data for the extraction of geophysical parameters:

1. Ignore the atmospheric effects completely. There are some applications for which this is often a perfectly acceptable approach, according to Cracknell and Hayes (1991). Ignoring atmospheric effects would probably be acceptable when mapping a phenomenon at a single time, but for change detection purposes, atmospheric effects have to be addressed in order to minimise change detection errors.
2. Calibration with *in situ* measurements of geophysical parameters (the Radiance to Reflectance Conversion Method in Section 3.2.1.1.3).
3. The use of a model atmosphere with parameters determined from historic data.
4. The use of a model atmosphere with parameters determined from simultaneous meteorological data (called Atmospheric Modeling Methods in this section).
5. The elimination of, or compensation for, atmospheric effects on a pixel-by-pixel basis (e.g. the Dark Object Subtraction and Regression Adjustment Methods in Sections 3.2.1.1.1 and 3.2.1.1.2).

The selection of the appropriate option will be governed by considerations both of the sensor that is used to gather the data and the problem to which the data are being applied (Cracknell and Hayes, 1991). Due to problems with these methods, it has been more common in the past to attempt to standardise one data set to another rather than to try and apply the complex modeling that is required to correct for variations in atmospheric transmission and path radiance (Milne, 1988). One technique for standardising image data sets is normalisation (described in Section 3.2.1.2) (Schott *et al*, 1988; Eckhardt *et al*, 1990; Hall *et al*, 1991; Jensen *et al*, 1995; Lee and Marsh, 1995).

3.2.1.1.5 **Sensor Aberrations and Sensor System Factors**

Differences in sensors and sensor systems used to capture the images can also cause apparent changes in the appearance of unchanged ground targets. The sensor and sensor system factors that can cause radiometric differences are principally due to fluctuations in the orbital parameters of the satellite platform and variations in the sensitivity of the sensors to the detection and recording of incoming energy levels (radiometric resolution). One way of dealing with the problem of differences in radiometric resolution is to convert the digital numbers in the data sets to actual reflectance values using standard tables or formulae (Milne, 1988; Lee and Marsh, 1995; Robinove, 1982). Fluctuations in the orbital and platform attitudes of the spacecraft are known and the necessary geometric corrections can be applied in the early stages of the pre-processing of the data, usually by the ground station receiving the raw data from the satellite (Milne, 1988).

Detector response errors (aberrations) also cause change detection inaccuracy and must be corrected. They can be either due to line dropout, striping (banding) or line start problems (Jensen, 1986). Line dropout results if one of the detectors on a sensor fails to function during a scan, resulting in zero values for every pixel in the particular line, or if it is temporarily saturated along a scan, resulting in very high or maximum values in the scan. To correct the data, estimated values can be used in each bad line by averaging the values of the pixels above or below the bad scan line. If a detector goes out of adjustment, for example if it provides readings twice as great as the other detectors for the same band, the problem is referred to as *n*-line striping or banding (Jensen, 1986). One way to identify the bad scan lines is to compute a histogram of the values for each of the detectors over a homogenous area such as a water body. If one detector's mean or median is significantly different from the others, it is possible that this detector is out of adjustment and may require a bias (additive or subtractive) correction or a more severe gain (multiplicative) correction (Jensen, 1986). If a scanning system fails to collect data at the beginning of a scan line, this is called a line start problem. A detector may abruptly stop collecting data somewhere along a scan line and produce results similar to line dropout. Data not recorded by the detector in this way can never be restored (Jensen, 1986).

3.2.1.2 **Temporal Factors**

Diurnal and seasonal differences can cause the appearance of change in unchanged surface conditions between two image dates. These differences result in change in the sun angle and the vegetation (phenological changes) which in turn will result in apparent change on the images. If phenological change is not the subject of the change analysis, selecting data collected on anniversary or near anniversary dates will help eliminate its effects (Milne, 1988; Jensen, 1986; Jensen *et al*, 1995; Eckhardt *et al*, 1990).

Differences in sun angle result in differences in the intensity of radiation received and hence reflected to a sensor by a ground target. These differences, as well as those resulting from differences in atmospheric composition, can be minimised by standardising the data sets using the technique of normalisation (Schott *et al*, 1988; Eckhardt *et al*, 1990; Hall *et al*, 1991; Jensen *et al*, 1995; Lee and Marsh, 1995). The technique attempts to make each spectral band (from the different dates) appear as though imaged through the same sensor, under similar illumination conditions and the same atmosphere for each image. Targets that are common to the images in the image set and are considered to be constant reflectors over time (i.e. their reflectance remains unchanged over time) are selected. For these normalisation targets any changes in their digital numbers between dates will be attributed to detector calibration, atmospheric, astronomic and phase angle (sun-target-sensor geometry) differences. After the removal of these variations, changes in digital numbers may be related to changes in surface conditions. Potential normalisation targets should have the characteristics in Box 3.1.

Potential normalisation targets should have the following characteristics:

1. The target should be at approximately the same elevation as the other land within the scene. Selecting a mountain top normalisation target would be of little use in estimating atmospheric conditions near sea level because most aerosols in the atmosphere occur within the lowest 1000m.

2. The target should contain only minimal amounts of vegetation. Vegetation spectral reflectance can change over time due to environmental stresses and plant phenology.

3. The target must be in a relatively flat area so that incremental changes in sun angle from date to date will have the same proportional increase or decrease in direct beam sunlight for all normalisation targets.

4. When viewed on the image display screen, the patterns seen on the normalisation targets should not change over time. Changing patterns indicate variability within the targets which could mean that the reflectance of the target as a whole may not be constant over time. For example, a mottled pattern on what had previously been a continuous tone dry lake bed may indicate changing surface moisture conditions, which might eliminate the dry lake bed from consideration as a normalisation target.

Box 3.1 Ideal Characteristics of Potential Normalisation Targets (after Eckhardt *et al*, 1990).

Targets that qualify to be potential normalisation targets are wet (water) and dry (e.g. unvegetated bare soil) sites. Where these natural targets are lacking artificial features like car parks, roads and buildings may be used (Schott *et al*, 1988; Hall *et al*, 1991).

The targets used need not be the same throughout the multitemporal data set (Schott *et al*, 1988; Hall *et al*, 1991).

Once the targets have been chosen, their brightness values in the respective image bands (e.g. green, red, infrared) on one image are regressed against their corresponding values in the corresponding bands on the other image. A reference image is chosen, whose brightness values in a given band are placed on the y-axis while those for the image to be normalised are placed on the x-axis. The regression model developed is then used to transform the band brightness values of the image to be normalised into values that they would have been had the image been acquired under scene conditions like those when the reference image was acquired. This technique may be helpful in vegetation change detection in semi-arid areas (Mouat *et al*, 1993). It can, however, be criticised for adding an additional, unstandardised `treatment' and therefore further uncertainty into a study (Stow *et al*, 1990).

3.2.1.3 **Spatial Aspects**

The spatial resolution of the sensors used will determine the nature and scale of the changes that can be identified between images dates (Jensen, 1986; Milne, 1988). For example, if Landsat MSS with a spatial resolution of 80m is used, land surface changes at a (spatially small) rate of (for example) 1.5m per year may not be detected (Milne, 1988).

3.2.1.4 **Spatial Registration Aspects**

Accurate spatial registration of at least two images is essential for digital change detection (Jensen, 1986). In order to accurately measure the difference in brightness values between images of different dates, the images need to be registered together to within an accuracy (root mean square error - RMSE) of 0.25 to 0.5 of a pixel (Jensen, 1986) or one pixel at the most (Milne, 1988). The task necessitates the use of geometric rectification algorithms that register the images to each other or to a standard map projection, by using common ground control points in the image set. The algorithm performs a rotational adjustment and resampling of one image to another so that ground features appear in the same place on each of the images (Milne, 1988). Without accurate co-registration, registration errors could potentially be interpreted as land cover change (Mouat *et al*, 1993).

3.2.2 **Change Detection Techniques**

A number of change detection techniques in remote sensing are described in the literature. They can be grouped as:

1. Transparency Compositing
2. Image Differencing
3. Image Ratioing
4. Classification Comparisons
5. Image Enhancement techniques to facilitate change detection

Within these broad groups are sub categories of change detection techniques and each of the techniques has its own merits and demerits, as outlined below.

3.2.2.1 **Transparency Compositing**

This method involves assigning a different colour to the same band for images from different dates such that when the bands are overlaid, a colour composite transparency is produced. If positive film transparencies of one infrared band are used for two image dates for example, and red is used for the first date and blue for the second, unchanged areas will appear purple and areas of positive or negative change will appear red or blue, respectively (Turner, 1982). MSS Band 5 (renamed band 2, see Table 1.1) images have been used in this manner for change detection, for example using red for one date and blue for another (Jensen, 1986). An alternative approach is to use a negative transparency for the first date and a positive one for the second (Crapper and Hynson, 1983). When the two are overlaid, areas that have not changed between the dates will appear neutral to grey and those that have changed will appear either light or dark depending on the type of change that occurred between the two dates. The method relies on visual interpretation of the imagery and may not be sensitive enough to pick up general environmental degradation (Milne, 1988), especially if the change is very subtle.

3.2.2.2 **Image Differencing**

With this technique (also called Delta Change Detection), changes in radiance between two co-registered image data sets are determined by pixel-by-pixel subtraction of the digital values of one image from those of another (Muchoney and Haack, 1994; Price *et al*, 1992; Jensen, 1986; Dale *et al*, 1996). The subtraction (differencing) produces an image data set where positive and negative values represent areas of change and values equal or close to zero indicate areas that remain relatively unchanged. The potential range of values that can result from the differencing is -255 to 255 if an 8 - bit analysis with pixel values ranging from 0 to 255 is used (Jensen, 1986). The results are often transformed into positive values by adding a constant (e.g. 255) and a threshold boundary is established to define change and no change. After differencing, change maps can be created.

In their studies using image differencing for change detection, Price *et al* (1992) and Muchoney and Haack (1994) recoded the output difference values to numbers ranging from 0 to 255. A value of 127 was assigned to areas where there was no change in reflectance (127 is the median between 0 and 255). A value greater than 127 indicated higher reflectance in the later image and a value less than 127 indicated higher reflectance in the earlier image.

Similar to Image Differencing is the technique called Albedo Differencing (Mouat *et al*, 1993) in which digital image data from two dates are converted to reflectance or radiance values which are then compared to detect changes.

3.2.2.3 **Image Ratioing**

Ratio images result from the division of digital number values in one spectral band by the corresponding values in another and have the major advantage that they convey the spectral or colour characteristics of image features regardless of variations in scene illumination conditions like shadow or sun angle differences (Lillesand and Kiefer, 1994; Jensen, 1986). They are especially useful for change detection when several dates of imagery are used in an analysis because they can reduce the effect of environmental and system multiplicative factors present (Jensen, 1986) and are often useful for discriminating subtle spectral variations in images from individual spectral bands or in standard colour composites (Lillesand and Kiefer, 1994).

If, for example, near infrared band data for the dates under comparison are divided (date 1 divided by date 2), unchanged areas will have a ratio of 1 while changed areas will have values greater than 1 if near infrared reflectance was higher at date 1 than at date 2, or less than 1 if it was higher at date 2.

3.2.2.4 **Classification Comparisons**

Change detection can also be undertaken by evaluating land cover classifications produced either from each separate date of imagery or from the two dates of imagery as a set, by post classification comparison or spectral/temporal change classification, respectively (Jensen, 1986; Lillesand and Kiefer, 1994). Provided good ground information or some baseline classification is available against which the final information classes can be compared and interpreted, multidate classifications can be used to show changed areas. Otherwise unsatisfactory classification may compound classification and registration errors present in individual classes (Milne, 1988).

In post classification comparison (or post classification change detection differencing - Muchoney and Haack, 1994), change is identified by comparing two independently produced classifications on a pixel-by-pixel or polygon-by-polygon basis (Jensen, 1986; Muchoney and Haack, 1994). An algorithm compares class pairs specified by the analyst in the comparison and, by properly coding the classification results for date 1 and date 2, the analyst can produce maps that show a complete matrix of changes. This enables not only the identification of pixels that have changed but also the nature of that change (Howarth and Wickware, 1981).

Where classifications are being compared from an image (or images) with a higher spatial resolution than the other(s), Jakubauskas *et al* (1990) advise that `common ground' be reached between the data sets of differing spatial resolution. They advise that the comparison will be valid provided that it is made after classification, that it is made at a land cover classification level no finer than could be accurately determined by the lowest resolution sensor, and that appropriate generalisation of the finer resolution data is carried out (i.e. the higher resolution sensor classes are made more general).

Spectral/temporal classification detects change by performing a single classification on a multidate data set. Change classes should have significantly different statistics from non-change classes. Though appealing because it requires only a single classification, the method uses a very complex classification. If, for example, the 4 bands of Landsat MSS are used from each image from two dates, 8 bands will have to be used in the classification, some of which will be redundant in information content (because of similarity of spectral range of coverage as is the case with the near infrared bands). Also, if clustering is performed during the classification, the cluster labeling (assigning class names) is usually difficult (Jensen, 1986) because of the large volume of spectral information from which the resulting clusters are derived.

3.2.2.5 **Image Enhancement Techniques for Change Detection**

Before using the techniques described in Sections 3.2.2.1 - 3.2.2.4, pre-processing the remote sensing data by low frequency filtering, high frequency filtering, texture transformations or principal component analysis may be done (Jensen, 1986).

In low frequency filtering the image is smoothed using a spatial moving average filter of a given size (e.g. 3x3 pixels) which enhances areas of homogeneity at the expense of high frequency detail. High frequency filtering enhances high frequency detail, producing a sharp visual image which, however, contains more noise than the original (Jensen, 1986).

With texture transformations, the images to be compared are pre-processed to yield multiple date texture images which can then be analysed using any of the change detection procedures in Sections 3.2.2.1 - 3.2.2.4 (Jensen, 1986).

Muchoney and Haack (1994) describe principal component analysis (PCA) in the context of change detection. The technique is a multivariate statistical one in which the data sets are rotated into principal axes, or components, that maximise the data variance. The original data are then transformed to the new principal axes (components or eigen images). In this manner correlated data sets can be represented by a smaller number of axes, while maintaining most of the variation of the original data. For change detection purposes the authors divide PCA into two categories:

(a) independent data transformation analysis,

(b) merged data transformation analysis.

Independent transformations, they point out, are subsets of post classification change detection that employ PCA independently on co-registered multitemporal data pairs as a prelude to post classification comparisons, while merged data transformations are those that rely upon PCA of combined multitemporal data sets to isolate inter image change (prelude to spectral/temporal change detection). They point out that the premise for this analysis is that multitemporal data sets are highly correlated and that PCA can be used to highlight differences attributable to change. Changes are enhanced in medium to higher order eigen images, whereas unchanged areas dominate the redundant temporal information in the lower order eigen image(s) (Stow *et al*, 1990).

3.2.2.6 **Other Methods**

Some studies have used change in vegetation indices (like the Normalised Difference Vegetation Index (NDVI), near infrared to red ratio (NIR/R), and Tasseled Cap (greenness, brightness, wetness) transformation as indicators of change (Mouat *et al*, 1993). For example, Mikkola (1996) compared NDVI values from different years to analyse vegetation damage around smelters in Russia, in addition to change detection by comparing classifications.

Jensen (1986) describes a detection method called Change Vector Analysis. In this method, if two spectral variables are measured for an area both before and after change occurs and then are plotted on the same graph, the vector describing the direction and magnitude of the change from the first to the second date indicates the type and magnitude of spectral change.

Milne (1988) lists spectral change pattern analysis, logical pattern change detection (`classification routine techniques') and regression analysis as methods for detecting land cover change, in addition to other techniques which seem to be just other names for the same techniques described in Sections 3.2.2.1 - 3.2.2.5.

3.2.2.7 **Comparison of Use and Evaluation of the Change Detection Techniques**

Regardless of the technique used, the success of change detection will depend on the nature of the change involved - whether it is abrupt or gradual. Milne (1988) stresses that provided the areas involved in the change are large enough, changes are relatively easy to detect and measure on imagery, but that more subtle changes like gradual deterioration in vegetation cover associated with drought or overgrazing are more difficult to detect.

Muchoney and Haack (1994) compared principal component analysis (PCA), image differencing, spectral-temporal change classification and post classification comparison change detection techniques in their study of gypsy moth induced forest defoliation, using multitemporal SPOT data. They found that the defoliation was best determined by image differencing and PCA. The four techniques resulted in significantly different accuracies at 95% level of probability. The authors pointed out that PCA and image differencing are generally more complex than post classification change detection because the data no longer represent actual sensor data values, and classification involves identifying change, rather than cover, classes. They concluded that PCA and image differencing are simpler than post classification approaches, which require independent classification prior to change detection. No corrections for atmospheric effects were done because, according to the authors, the imprecision of a scattering model might influence change detection results. Geocoding and rectification (RMSE approximately 1 pixel) were done.

Price *et al* (1992) found the image differencing technique useful for detecting areas of shrub die back between 1975 and 1988 in a semi arid environment. Significant reduction in reflectance was, however, observed both in die back and non die back areas, and the authors suggest that the reduction could be related to calibration differences between the sensors used (Landsat MSS images from Landsats 1, 3, 5), or to large scale environmental differences such as surface soil moisture or vegetation composition. No atmospheric correction or scene normalisation was done. Therefore these authors ignored the pre-change detection considerations outlined in Section 3.2.1.

From a study of vegetation change resulting from fire, Jakubauskas *et al* (1990) report successful use of post classification comparison for vegetation change detection, advising that the technique can be used for vegetation change detection within the context of GIS analysis. The images used were from Landsat 1 (1973 MSS), Landsat 2 (1980 MSS) and Landsat 4 (1982 TM). A 3x3 majority class filter was applied to the classified TM data set to generalise the data to the level of the MSS. No normalisation of the images or atmospheric correction was done.

Stow *et al* (1990) compared image ratioing with principal component analysis in a change detection study involving multitemporal, multispectral imagery of varying spatial resolution (October 1976 MSS, October 1986 TM, November 1986 SPOT HRV XS) which were co-registered. Following change detection mapping with the two techniques, a 5x5 pixel majority filter was passed across each image in an attempt to minimise extraneous errors. No atmospheric correction or image normalisation was done and the authors argue that normalising the multisensor data would have meant an additional, unstandardised treatment that would have added further uncertainty into the study. They found that ratioing produced higher change detection accuracies than did PCA. Applying a majority moving window filter whose size approximated a minimum mapping unit of 1 hectare increased change detection accuracies by 1-3% and reduced commission errors by 10-25%, according to the authors.

Baumgartner and Price (1993) argue that although a non-enhancement technique such as classification comparison can provide information on all changes occurring in a study area (while enhancement techniques only distinguish change from no change), the accuracy of a change map produced with this technique may be poor. The authors point out that the accuracy of a change map produced from two classifications is similar to the product of the two classification accuracies, such that two classifications with 80% accuracy may produce a map that is 64% accurate. The integration of enhancement and non enhancement techniques using Landsat TM data was employed in the authors' study which aimed at accurate detection and measurement of the spatial extent of non urban land cover change, as well as deriving categorical change information between 1982 and 1990. The techniques used were vegetation index differencing with the near infrared/red ratio (TM4/TM3 (date 1) - TM4/TM3 (date 2) plus a constant), image differencing (TM4 (date 1) - TM4 (date 2) + a constant (255)), principal component analysis (combining 6 TM bands from 1982 with 6 TM bands from 1990) and post classification comparison. Image registration (RMSE +/- 10m), atmospheric correction with an improved dark object subtraction technique, and image normalisation were undertaken.

Tao *et al* (1993) introduce a change detection technique employing what they term `three dimensional temporal feature space' which they used to analyse wetland change in coastal Louisiana using single band (Band 4) Landsat TM data (2 December 1984, 28 January 1988, 1 November 1990). The technique is, in effect, a kind of transparency compositing because a different primary colour was assigned to the band 4 images from the three respective dates, which were then overlaid to create a colour composite. The colour composite was then analysed for indications of change using the resulting colours (white or black indicating no change; red, green, blue, yellow, magenta and cyan indicating a specific type of change between the dates). The authors outline the advantages of using the technique: first, that there is data efficiency and saving on data processing time since only one band of data for each of three dates is used (thereby avoiding the complex and intensive labour/computer process of classifying large data sets); and second, that it is possible to perform change detection analysis for three periods simultaneously. However they pay little attention to the effect that temporal differences between the two imaging dates might have on the change results.

From the literature, therefore, there is no consensus on which change detection technique(s) is (are) best or worst. The decision of which technique to use seems to depend on the judgement of the researcher. The enhancement techniques and vegetation indices seem to be widely used, and image differencing and classification comparisons are common. Image ratioing seems to be rarely used solely, and there are very few recent studies using transparency compositing. However, methods which involve a direct comparison of digital (reflectance) values, such as image differencing, image ratioing and vegetation indices, are highly susceptible to radiometric errors (see Section 3.2.1.1) in the original digital image data. Because classification uses a range of values in arriving at classes, it avoids this reliance on comparing the values directly and may, therefore, be a more useful change detection technique if the classification is accurate. Image ratioing and differencing techniques compare only two equivalent bands at a time and may, therefore, not be useful if change detection is required on more than two images simultaneously. Classification can use one or more bands per date, and the resulting classified images (more than two at a time) can be manipulated in a GIS framework to enable a range of change detection queries. Enhancement techniques will be accurate if they adequately enhance the feature(s) under study but have the disadvantage that they modify the original image data, which may complicate further processing of the image.

3.3 Recent Wetland Change Studies by Remote Sensing

No recent work on tropical, Southern African wetland change assessment by remote sensing was found in the literature. However, monitoring and change detection work has been done for the arid lands of Botswana using Landsat images (Ringrose *et al*, 1990), for a forest area in Zaire using Landsat images (Massart *et al*, 1995), for woodland areas around Lusaka in Zambia (Cheattle, 1994) and for the Central and Southern region of Zambia using AVHRR images (Azzali, 1991).

In East Africa, Haack (1996) used a GIS overlay of Landsat MSS near infrared (band 4) black and white film positives at a scale of 1:1 000 000 to monitor changes in the Omo Delta wetland (Kenya). The image dates were 1 February 1973, 1 January 1979 and 1 March 1989. The delta appeared to have grown in the time period, with much of the new delta growth being green vegetation. The data used could not differentiate categories within the green vegetation. Haack (1996) attributes the growth of the delta to a decrease in levels of the lake (Lake Turkana) into which the Omo discharges, which in turn may be a result of increased aridity and/or a decreased flow into the lake. Both a decrease in precipitation within the catchment basin and an increase in temperature could have been contributing factors (Haack, 1996). Upstream diversion of water for small scale irrigation are also likely to have caused the decline in lake level (Haack, 1996).

Three wetland studies in the USA, by Jensen *et al* (1995), Mackey (1993) and Williams and Lyon (1991), give comparative procedural frameworks for wetland change detection work. Jensen *et al* (1995) used a combination of Landsat MSS, TM and SPOT images from the period 1973 - 1991 (6 in total), which were resampled to the 20 x 20 m resolution of SPOT, normalised and co-registered to a common map projection (UTM), to produce a wetland change map following post classification comparison in a GIS framework. No atmospheric correction was undertaken. Mackey (1993) used fifteen dates of spring time SPOT HRV data along with near-concurrent vertical aerial photographic and phenological data from Spring 1987 through Spring 1992 to monitor trends in wetland community changes. No atmospheric correction or scene normalisation was undertaken. Post-classification comparison was used for change detection. Williams and Lyon (1991) used a digital data base constructed by photo interpretation, mapping and digitising seven dates of aerial photography on the St. Mary's River, USA, to examine historical changes in wetland area in a GIS framework. The photos were from 1939, 1953, 1964, 1978, 1984 and 1985. The results indicated that there was greatest variation in areas of emergent wetland and shrub wetland, which appeared to be responding primarily to changes in water level.

In Australia, Dale *et al* (1996) used digitised colour infrared photographs from May 1982, May 1987 and June 1991 to evaluate change in the Moretan Bay inter-tidal wetland, which was modified in 1985 for purposes of managing a mosquito breeding programme. Green, red and near infrared bands were used. Change detection was undertaken by image subtraction and classification comparison techniques. The results indicated that the wetland had become wetter as a result of increased tidal flushing, indicated by reduced spectral values. Mangroves had increased in size and spatial extent, and generally had increased spectral values.

3.4 Studies of the Kafue Flats

Studies involving surveying and describing specific aspects of the Kafue Flats environment prior to the establishment of hydroelectric and irrigation schemes (see Sections 2.7.1 and 2.7.2) are many and have been listed by Turner (1983). These studies were mainly undertaken in order to understand better the area and to assess its potential for economic development. In spite of these studies, understanding of the Kafue basin is still inadequate for satisfactory protection and management of its resources; and the little that is known has had little effect on policy decisions (Sheppe, 1985; Burke, 1994).

After the implementation of the hydroelectric scheme in 1972 considerable research attention focused on predicting and monitoring the impacts of the scheme on the Kafue Flats environment. Interest in studying change in the area has, therefore, been strong. The University of Zambia had, until the late eighties, the Kafue Basin Research Project (KBRP) which coordinated the various research interests on the Kafue Flats and basin (KBRP publications include Howard and Williams, 1977; Turner, 1983).

3.4.1 Change Prediction and Verification Studies

Predictions have been made about the likely hydrological, vegetation, fishery output and wildlife populations changes to result from the hydroelectric scheme. Climate pressure was largely ignored as a cause of change in some of these studies, perhaps because the recent low rainfall trend (see Section 2.2.1) had just began.

3.4.1.1 **Hydrological Changes**

It was widely predicted that the effect of the Kafue Gorge dam (hydroelectric scheme Phase 1; see Section 2.7.1) would result in the maintenance of higher than normal minimum river levels in the dry season, with the result that the area under permanent water would increase. Several studies have emphasized this (e.g. Schuster, 1980; Howard, 1985; Sheppe, 1985; Rees, 1978; Turner, 1982; Douthwaite, 1974; Douthwaite, 1978) and pointed out that Chunga Lagoon at Lochinvar (Figure 4.14) is a direct consequence of this because it did not exist before 1972.

As pointed out in Section 2.5, the timing and duration of the flood on the Kafue Flats determines the nature of floodplain vegetation in terms of vigour and density. Widespread, long lasting flooding is ecologically more beneficial to the wetland in this respect. Therefore, any alteration of the flooding pattern in such a way that flooding starts late, is spatially less widespread and lasts only a short time, is detrimental. The predicted impact of damming at Itezhi-tezhi in 1978 (hydroelectric scheme Phase II) and the consequent regulation of discharges for generation of electricity would be to decrease the size of the area flooded, as well as the duration of the flood, a situation which would be worse in dry years (Balasubrahmanyam and Abou-Zeid, 1978a; Sheppe, 1985; Douthwaite, 1974; Schuster, 1980) when the peak flood in March would be lower than it was under natural conditions. With regulated flow, river levels would be higher than normal in the dry season and the flood would start later than normal and fall more slowly (Douthwaite, 1974).

Balasubrahmanyam and Abou-Zeid (1978a) state that measures were incorporated in the design of Phase II of the hydroelectric scheme to ensure flooding of the Flats even in dry years, by way of releasing at least 300m^3s^{-1} in March of every year. The Itezhi-tezhi Reservoir's capacity was designed to ensure that this happened so that ecological requirements would not be overridden by those of power generation. Only aerated water would be discharged from the reservoir. Compared to natural conditions, the authors point out, this controlled flooding would ensure higher river levels than would otherwise be the case in dry years and in the dry season, which would be beneficial. In wet or normal years the dam would have no adverse effect on the Flats. Sheppe (1985) argues that the 300m^3s^{-1} discharge would be small compared to the former March discharge of 1400m^3s^{-1}. Douthwaite (1978) predicted that even with the 300m^3s^{-1} in March in dry years, there was unlikely to be any extensive flooding.

3.4.1.2 **Vegetation Changes**

As a result of reduced flood extent, disrupted flood timing, and the maintenance of permanent water in seasonally inundated areas (see Section 3.4.1.1) vegetation changes were foreseen. Plants that thrive in wet areas, such as *Cyperus papyrus* and *Typha domingensis* (see Figures 2.20, 2.21a, 2.21b, 2.21d), would occupy permanently flooded areas that previously had floodplain grassland species, and those sections of the floodplain that were no longer flooded would be invaded by woody plant species.

Sheppe (1985) compared a portion of the floodplain at Lochinvar in 1983 with what it was in 1967. Whereas in May 1967 the portion was covered by a dense growth of emergent grasses reaching the horizon and hiding the flood water, in May 1983 there was permanent open water (Chunga Lagoon). The very productive vegetation that had depended on annual flooding had largely been replaced by aquatic plants in the open water, while the former floodplain had a sparse cover of low grasses and was being invaded by woody plants. He further observed that where permanent water had been established on the former floodplain, floodplain grassland had died out and thickets of *Cyperus papyrus*, *Typha domingensis* and other water loving plants were becoming established along the shore of the new water bodies. The reduction in flooding had reduced the productivity of the remaining floodplain grasses and permitted the invasion of the floodplain by woody plants (mainly *Mimosa pigra* and to a lesser extent *Hibiscus diversifolius*) that formerly were suppressed by the floods. Although only a small portion of the floodplain was as yet occupied by such plants, Sheppe (1985) states, they were spreading.

Prior to dam buildings, there existed natural (rainfall and flooding induced) variability in the distribution of vegetation on the Kafue Flats from month to month and year to year (Turner, 1994, pers. comm.; Sheppe, 1985; Howard, 1985; Ellenbroek, 1987), which makes it difficult to draw precise conclusions about the effects of human interference (Sheppe, 1985), but some of the recent changes in floodplain vegetation distribution have been caused by the altered flooding regime (Howard, 1985). Howard (1985) made observations about vegetation change at Lochinvar similar to those by Sheppe (1985). He observed that high water levels at Chunga Lagoon from 1976-1981 resulted in the appearance of *Cyperus papyrus, Typha domingensis* and *Hibiscus diversifolius vivularis* (in contrast to Sheppe, 1985, who attributed the presence of *H. d. vivularis* to reduced flooding), and that in the same period, floating and emergent grasses and water lilies disappeared from the lagoon. The 1981/82 and 1982/83 droughts, Howard (1985) states, resulted in partial drying of the lagoon and in April 1983 the lilies and emergent grasses reappeared; *C. papyrus*, *T. domingensis* and

H. d. vivularis had almost completely disappeared from the part of Chunga Lagoon that dried out. The emergence of *C. papyrus* in former floodplain grassland areas was also observed by Schuster (1980).

3.4.1.3 Fishery Output Changes

It was predicted that after river impoundment, the resulting higher than normal dry season minimum river levels (Section 3.4.1.1) would reduce fish mortality from fishing by man and birds and, therefore, increase fish abundance. Post and pre-impoundment comparison studies have yielded no real evidence of increased fish abundance after impoundment.

Dudley and Scully (1980), from experimental catches at Chunga (lagoon site), Nyimba (flowing river sites) and in a lagoon north of Nyimba (Figure 4.14) found that in the raised water level regime, there was no increased fish abundance; the proportion of *Sarotherodon*, a commercially important fish genus, may have actually decreased after impoundment in 1972.

Muyanga and Chipundu (1978), in a study of 19 commercially important fish species, observed a decline in catches of *Sarotherodon machrochir*, *Tilapia rendalli* and *Tilapia sparrmanii* after damming in 1972 compared to the period before. They attribute the decline to the increase in the area of open water which may have forced the fish to marginal habitats, thus exposing them to predators. There was a significant increase in the abundance of four predatory fish species and little change in twelve others.

Sheppe (1985) predicted unspecified effects on the fish populations, stating that "the dams altered the flooding schedule and the vegetation - undoubtedly with effects on the fish population".

3.4.1.4 **Wildlife Changes**

Wildlife populations, especially those of water birds and lechwe, were generally predicted to reduce as a result of damming and alteration of the flooding pattern. Douthwaite (1978) predicted threats to regional and intercontinental migratory birds which visit the wetland. He stated that birds from the Kafue Flats, like red-billed teal, fulvous whistling ducks, open billed storks, grey herons and little stints, visit other regional wetlands (in Namibia, Botswana, South Africa, Kenya and Sudan) while palaearctic waders from Arctic Russia and Northern Europe visit the area at the end of the dry season on their way south and at the end of the rains as they return north.

The altered flooding regime was seen by Douthwaite (1974 & 1978) and Howard and Aspinwall (1984) as being disruptive to the wattled crane's ecology. With reduced flooding as predicted (see Section 3.4.1.1), suitable breeding and feeding grounds of the crane would become more restricted and in this situation it was likely that the wattled crane population would diminish unless flood levels at Nyimba regularly exceed 5 meters' depth (Douthwaite, 1974 & 1978). Referring to their wattled crane population estimate of 3 282 in May 1982 compared to Douthwaite's (1974) estimate of 3 085 in May 1973 (see Table 2.4), Howard and Aspinwall (1984) suggest that numbers may have increased since 1973 because their study did not include areas to the west which Douthwaite's did. However, they suggest that it is also possible that seasonal flocking areas had moved in response to changes in the flooding patterns.

Also many other external factors which affect bird population numbers could have been responsible.

Water birds in general were identified to be threatened by the flooding alterations. Douthwaite (1978) predicted that they would disappear. Howard and Aspinwall (1984) state that the extent of the effects of changed flooding patterns were still unknown and may prove deleterious to floodplain birds. According to observations by Sheppe (1985), the populations of both fish and fish eating birds had been reduced after the implementation of the hydroelectric scheme, there were fewer populations of herbivorous snails and of open billed storks that fed on them, and a reduction in herbivorous insects had also led to there being smaller numbers of Jacanas and other insect eating birds. Successful nesting of water birds like yellow billed storks and others could be eliminated, largely via interfering with their food supply.

Relatively more attention has been paid to the likely consequences of flood alteration on the lechwe. Many studies predicted a bleak future for the lechwe (e.g. Chabwela and Ellenbroek, 1990; Rees, 1978; Schuster, 1980; Sheppe, 1985; Douthwaite, 1978; Sayer and van Lavieren, 1975; Rees, 1976), stating that the lechwe's ecology is highly influenced by the flood. Douthwaite (1978) points out that persistently high minimum water levels (see Section 3.4.1.1) since 1974 due to retention of water by the Kafue Gorge dam had, in 1978, probably led to decline in *Vossia* grassland in the Chunga Lagoon area (*Vossia* was formerly the most important fodder grass for lechwe in the dry season) (see Figures 2.15, 2.22 and 2.29).

Schuster (1980) suggests that changes in the flooding cycle threatened to disrupt the lechwe's breeding behaviour and social organisation. The lechwe rut was mainly in the dry season when leks (mating grounds) were established. Males were in peak condition then (highest body weight). In the new flooding regime, coarser tussock grasses were expected to replace lechwe's favoured and more nutritious floodplain species in areas that receive less flooding. The resultant scarcity of good grazing in the late dry season where formerly great quantities were exposed by the falling flood waters might mean few males reach prime condition for the rut, resulting in disrupted lekking behaviour. Schuster (1980) points out that the lechwe can also mate, though less successfully, by way of solitary males defending larger territories than those in the crowded leks. Contrary to this prediction of disappearing lekking behaviour, the lek system still existed in 1990 and was studied by Nedft (1992).

Sheppe (1985) sums up the expected changes in wildlife populations in predicting general decline in lechwe and other wildlife populations, with the result that the rich variety of communities that once occurred would be destroyed. One reason for this would be because flow regulation would reduce year to year variability, which is important for species abundance in any ecosystem, according to Sheppe (1985).

3.4.2 **Remote Sensing Studies**

The World Wide Fund for Nature (WWF) has recently (about 1993-1994) used NOAA AVHRR Channel 2 data to monitor the extent of the flooding on the Kafue Flats (WWF-Zambia, 1995, pers. comm.). Map updating and reservoir mapping have been done by the Zambian government's Survey Department and by ZESCO, respectively, using aerial photographs (Turner, 1982).

Work was underway (in the early 1980s) to monitor and quantify the observed and predicted land cover changes (see Sections 3.4.1.1 - 3.4.1.4) by the University of

Zambia's Kafue Basin Research Project using maps, aerial photographs and records, with plans to use Landsat (paper print) imagery for the same purpose (Howard, 1985). In this regard, Turner (1982) undertook a flood extent monitoring study of the Kafue Flats using positive Landsat image transparencies from 1972, 1980 and 1981, which were overlaid manually. Turner concludes that MSS Band 7 (renamed Band 4, see Table 1.1) is useful for mapping open water because it appears black. There is no simple relationship between measured river levels and the area of flooding, Turner (1982) states, and further monitoring by Landsat was needed before the extent of flooding could be accurately predicted. The reason for the lack of a simple relationship between measured river levels and area of flooding is the fact that the spreading of flood water on the plain is influenced by the filling up of old river channels, ox-bow lakes and lagoons, as well as being slowed down by mats of dense aquatic vegetation, all of which are complex and unquantified, according to Turner's observations. A further conclusion was that for mapping seasonal changes, Landsat has great advantages over conventional aerial photography (Turner, 1982).

3.4.3 The Current Study in Relation to Previous Studies of the Kafue Flats

Most of the previous studies predicting changes to the wetland were done mainly in the context of human interference through flood regulation. This study adds climate pressure to human interference as the context of wetland change assessment. The previous studies were mainly speculative about future change. This study came about 10 years after these predictions were made, which was an opportunity to see if some of the predicted changes had occurred, especially spatial and vegetation changes detectable by remote sensing. In addition, most field observations of change were localised at Lochinvar.

This chapter has shown that there have been field observations of some of the effects of the environmental stresses outlined in Chapter 2. The changes on the Kafue Flats range from inherent seasonal and year to year variations to long-term trends which are not inherent and may be a result of long-term environmental stresses. However, there is very little work on quantification of the changes, especially in terms of their spatial extents. Long-term trends in vegetation changes, in terms of vigour, density and spatial extent of cover, could be identified, quantified and mapped using some of the remote sensing change detection methods outlined in this chapter. This would enable an assessment of the effects of the long-term environmental stresses. Chapter 4 gives details of how this approach was employed in conducting this study.

Chapter 4

METHODOLOGY

4.1 Introduction

This chapter details the methodology employed in conducting the study using the remote sensing approach. The first part of the chapter outlines the digital image pre-processing that was done prior to change detection on the images. Pre-processing was necessary in order to make the change detection more accurate (see Section 3.2.1). Then the field work undertaken is described. The final part of the chapter describes the remote sensing change detection technique used.

4.2 Image Data Selection

The criteria used when selecting the image data to be used (within the constraints of affordability) were:

1. Coverage dating back as far as possible
2. High spatial resolution
3. Appropriateness of season of coverage (in relation to cloud interference, plant phenology differences and presence or absence of flooding on the Kafue Flats).

The original, ideal plan was to obtain as many historical images of the Kafue Flats as possible, going back to the period just before the implementation of Phase I of the hydroelectric scheme in 1972 (see Section 2.7.1). This was not possible both because of lack of coverage of the area by the major satellite sensor systems and because of the expenses involved. The Landsat satellite programme started operating in 1972 (see Section 1.5) but there are no images of the Kafue Flats before 1980 except one or two scenes from 1972 and 1973 due to lack of demand and also due to technical problems (Turner, 1982), as is common for many places. The 1972 and 1973 Landsat images, however, have line striping problems and considerable cloud cover. Because of their poor quality, they were of little use. The other imaging systems like NOAA AVHRR and SPOT started operating in 1979 and 1986, respectively.

Landsat images seemed to be more appropriate than AVHRR images because of higher spatial resolution (80m and 30m for MSS and TM, respectively) and coverage dating back to 1972, although TM images are only available for the period after 16 July 1982 and their cost was relatively high. Four Landsat images were selected. The images were from September 1984, 1988, 1991 and 1994 (Table 4.1). An attempt was made to spread the dates of images used evenly over the period after 1980 when Landsat images of the area are available. The latest trend of reducing annual rainfall started around 1978 (see Figures 2.5a and 2.5b, also Tables 2.1 and 2.2), almost coincidentally with the completion of the dam at Itezhi-tezhi (see Section 2.7.1). There was, however, no cloud free September image before 1981 available from the earth receiving station in South Africa and in some years after 1981, no cloud free images were acquired in September by the Landsat imaging system.

For a number of reasons, dry season (September) images were chosen. The wetland system stands out from the surrounding dry land then, which permits differentiation of a larger number of land cover classes than on wet season images. In the wet season

Table 4.1 Digital Image Data Used

Image Date	Landsat Sensor	Pre-processing Level	Other
24 September 1984	MSS	5 - with radiometric correction. Geometric correction both in the across and along scan directions. Corrected to a map projection but orientation not changed.	Acquired by Landsat: 5 World Reference System: 172/71 Acquisition time at centre: --- Sun elevation at centre: --- Sun azimuth at centre: --- (where --- = information not available)
3 September 1988	MSS	5 - with radiometric correction. Geometric correction both in the across and along scan directions. Corrected to a map projection but orientation not changed.	Acquired by Landsat: 5 World Reference System: 172/71 Acquisition time at centre: 7:43 am Sun elevation at centre: 47.27^0 Sun azimuth at centre: 60.16^0
12 September 1991	TM	4 - with radiometric correction. Geometric correction in the along scan direction only. Not corrected to a map projection.	Acquired by Landsat: 5 World Reference System: 172/71 Acquisition time at centre: 7:35 am Sun elevation at centre: 48.29^0 Sun azimuth at centre: 64.12^0
20 September 1994	TM	4 - with radiometric correction. Geometric correction in the along scan direction only. Not corrected to a map projection.	Acquired by Landsat: 5 World Reference System: 172/71 Acquisition time at centre: 7:28 am Sun elevation at centre: 48.81^0 Sun azimuth at centre: 69.13^0

the surrounding land also has green vegetation and is moist, while in the cold season there is usually a rising or receding flood on the floodplain (Figure 4.1; see also Section 2.3.1.2). The wetland system is at its weakest in the dry season and it was

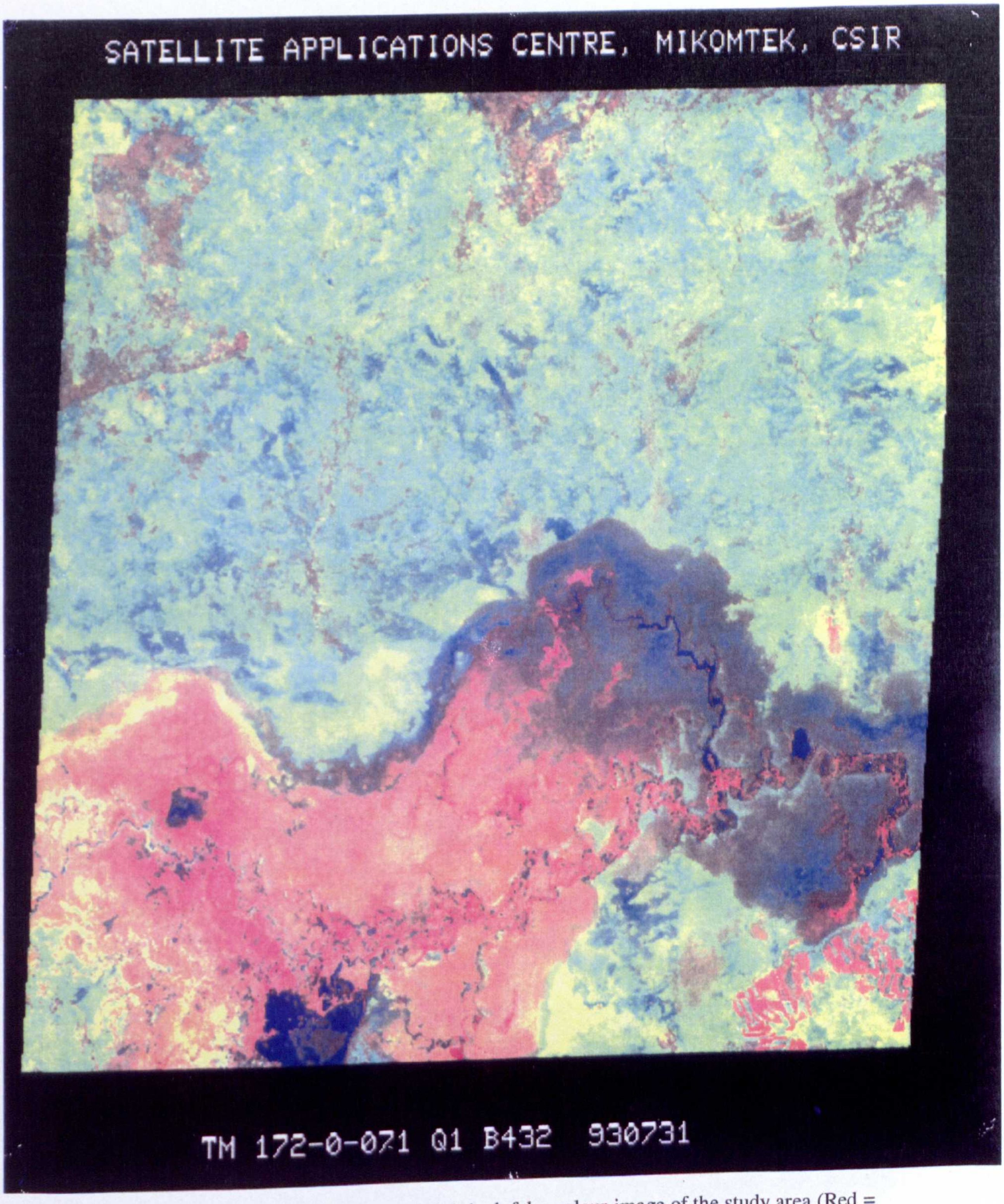


Figure 4.1. A Landsat Thematic Mapper (TM) quick-look false colour image of the study area (Red = Band 4 (Near Infrared), Green = Band 3 (visible Red), Blue = Band 2 (Green)). The scene, 90 x 90 km in size, is the northwestern quadrant (Q1) of Landsat 5 Path 172, Row 071, on 31 July 1993. The green grass and reed vegetation on the Kafue Flats floodplain in the lower (southern) half is highly reflective in the Near Infrared because of chlorophyll content and, therefore, appears red, clearly standing out from the dry, wooded upland in the north whose reddish/brown dry soil and grass appear green in the false colour image. The sugar cane on the Nakambala Sugar Estate at Mazabuka, also rich in chlorophyll, is in the lower right corner. Downstream parts of the floodplain, immediately north and northwest of Mazabuka, are still flooded (appearing dark/black because of low visible and near infrared reflectance from the water). [Image supplied by Satellite Applications Centre, South Africa].

anticipated that any trends in wetland size and quality could best be detected then. In addition, dry season images are largely cloud free (Cheattle, 1994). Starting from October when early rains commence, (Figure 2.2), rain clouds increase the problem of cloud interference. To minimise change detection errors arising from temporal differences (vegetation phenology cycle), images from September of the years under consideration (near anniversary dates; see Section 3.2.1.2) were used (Table 4.1). Change detection errors arising from sensor differences (see Section 3.2.1.1.5) were partly minimised by sticking to one satellite system (Landsat) and partly by image normalisation (see Section 3.2.1.2).

The cost of digital image data was generally very high and imposed limits on the number of images that could be used[1]. The need for a lot of spatial detail made it necessary to purchase at least one Landsat TM image (with high spatial resolution), although Landsat MSS images were cheaper. SPOT images, although they have a high spatial resolution of 20m x 20m (in multispectral mode), were not used because the area under study (about 90km x 50km in size) would have required the use of more than one scene from different, adjacent orbital tracks per date (each SPOT image covers 60km x 60km - see Table 1.4). This would have introduced further costs. In addition, archive lists of SPOT images of the area revealed that there were no same date multispectral images of the area from adjacent orbital tracks to enable change analysis between 1986 (the SPOT launch year) and 1994 when the study was started. AVHRR images were considered but no long term archive was available. Only an archive dating back to 1991 was found at Frascati in Italy. Their coarse spatial

[1] A Landsat TM quarter scene digital image (all bands) cost US$2 600, a full scene MSS digital image cost US$200, a NOAA AVHRR image cost 100 ECU (about £118), and multispectral SPOT images cost FFr12 300 (about US$2 724) for 1990s data, FFr7 000 (about US$1 500) for 1980s data.

resolution (1.1km x 1.1km) and large size of scene coverage made them largely unsuitable for this relatively small area (size 90km x 50km compared to the 3000-4000km x 1000km of one AVHRR scene). AVHRR images have been (more) extensively used for vegetation monitoring of large areas (Lillesand and Kiefer, 1994).

4.3 Image Data Acquisition

Based on the considerations in Section 4.2, the four digital images (Figures 4.2, 4.3, 4.4 and 4.5) were obtained, three directly from the earth receiving station in South Africa, one (the 1984 image) via an individual source. All images were on computer compatible tape, except the 1991 image which was on compact disk read only memory (CDROM). All were already radiometrically corrected and cloud free. The MSS images were geometrically corrected both in the along and across scan directions and corrected to a map projection (unspecified by the earth receiving station). The TM images were geometrically corrected in the along scan direction only. This level of pre-processing was cheaper for the TM images than level 5 with both along and across scan geometric corrections. MSS images were only available at level 5.

With prior radiometric and geometric corrections, therefore, the images did not have errors arising from fluctuations in orbital and platform attitudes of the satellites (see Section 3.2.1.1.5) but could have had non land surface change differences arising from differing atmospheric compositions, detector response errors, spectral and spatial resolutions (see Section 1.5) and sensor calibration (Landsat 5 MSS and TM captured the images, see Table 4.1). For the TM images, quarter scenes (northwestern quadrants) covering the area under study (see Figures 2.1 and 4.1) were obtained from

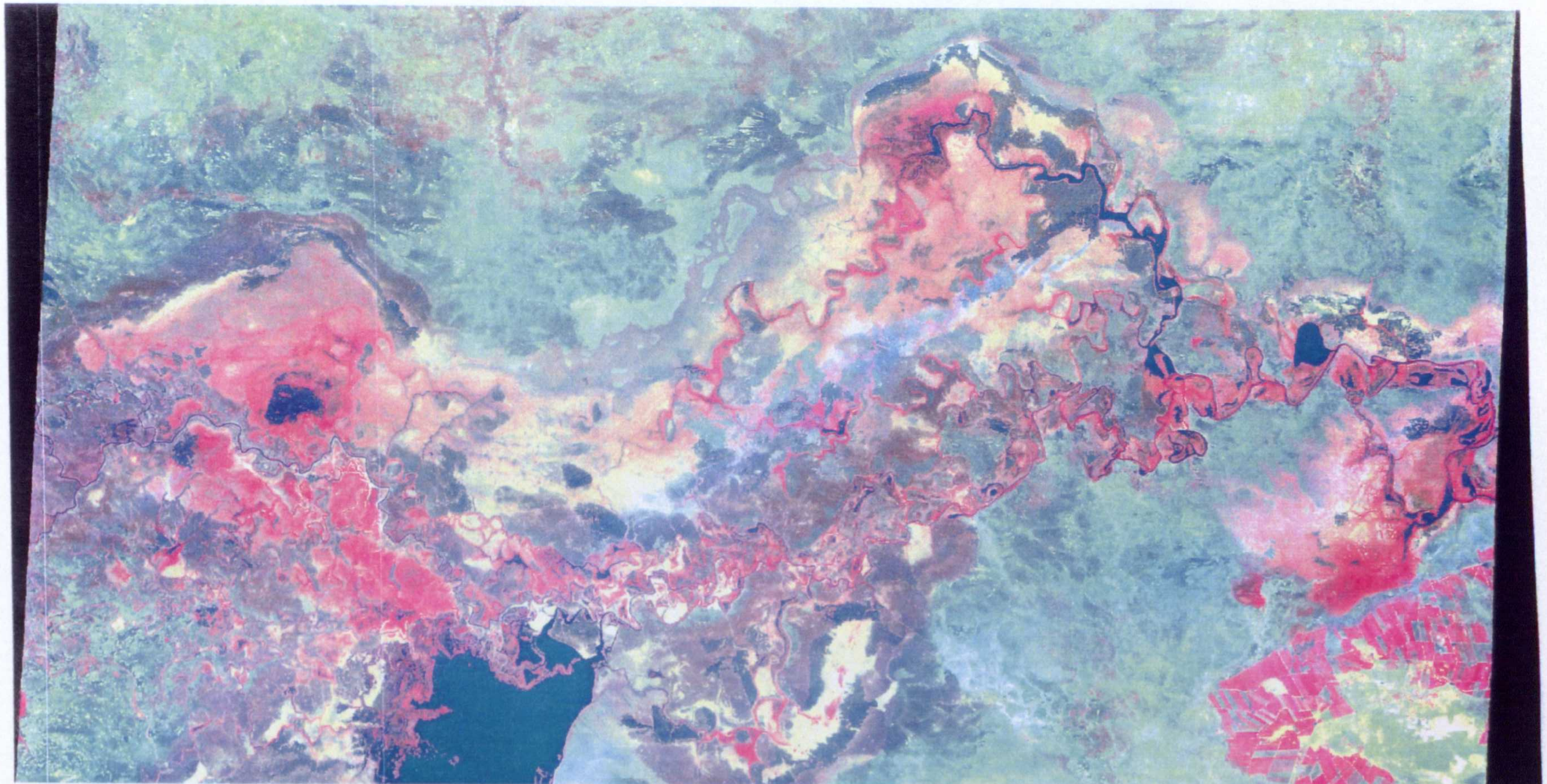


Figure 4.2 The 20 September 1994 Landsat TM image (Red = TM4, Green = TM3, Blue = TM2). This is the same scene as in Figure 4.1 but excluding most of the dry, wooded upland in the north (approximately 90 x 50 km in size). Notice the smoke across the center of the image.

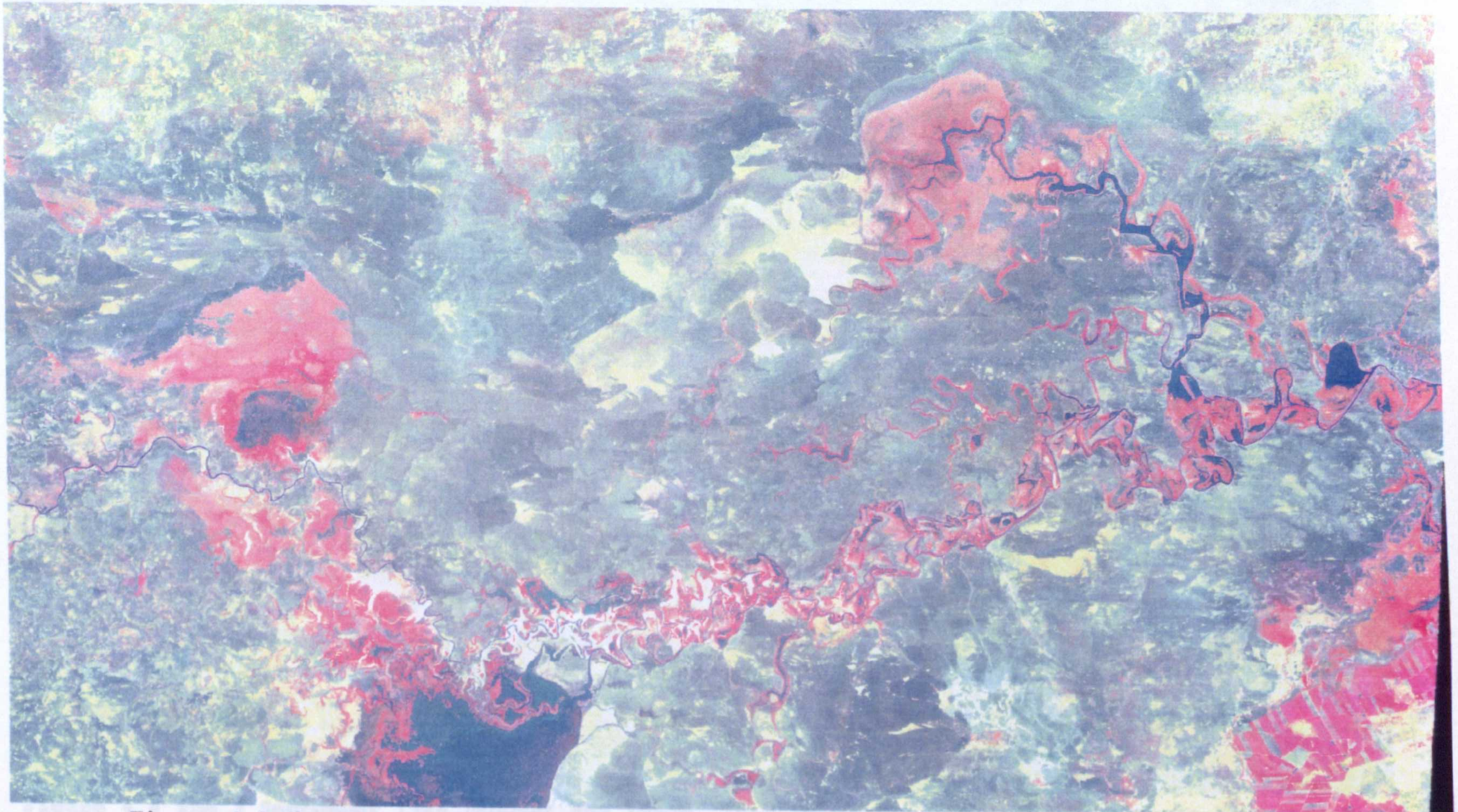


Figure 4.3 The 12 September 1991 Landsat TM image (Red = TM4, Green = TM3, Blue = TM2). This is the same scene as in Figure 4.2.

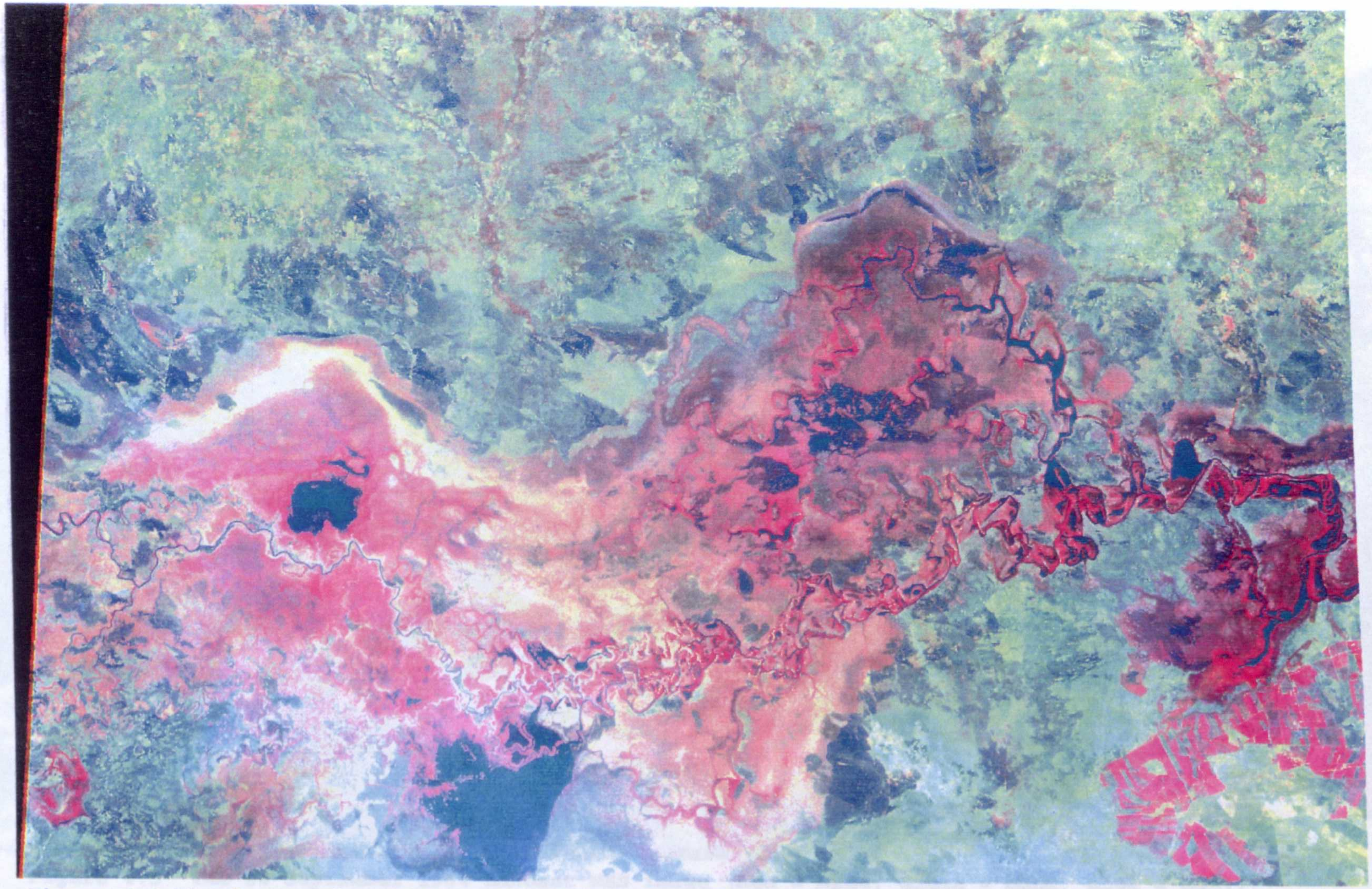


Figure 4.4 The 3 September 1988 Landsat MSS image. This is nearly the same scene as in Figure 4.1. Notice the late flood, similar to the situation in Figure 4.1. Compare the low spatial detail in this MSS image with the TM detail in Figures 4.2 and 4.3. Red = MSS4, Green = MSS2, Blue = MSS1.

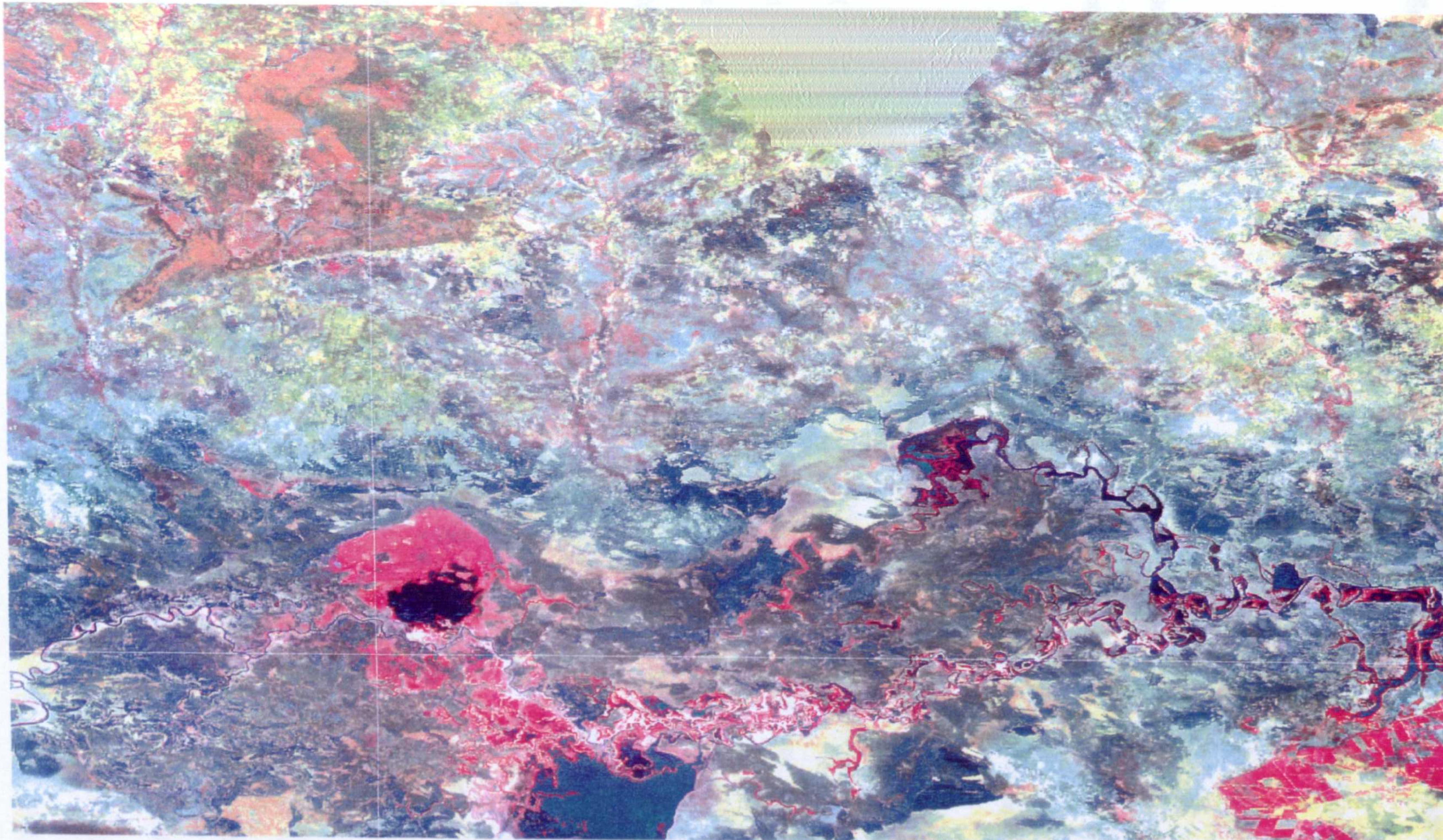


Figure 4.5 The 24 September 1984 Landsat MSS image (Red = MSS4, Green = MSS2, Blue = MSS1). This is nearly the same scene as in Figure 4.1. Notice the low spatial detail in this MSS image compared to the TM detail in Figures 4.2 and 4.3.

the full scene of Landsat 5 reference (track/frame) 172/71. For the MSS images only full scenes (same reference) could be bought from the earth receiving station in South Africa, from which the northwestern quadrant was subset. The thermal infrared TM band (Band 6, see Table 1.2) was not available on the 1994 image due to a technical problem. All MSS bands were available.

For use in the field, May-June 1991 panchromatic aerial photographs (the latest available) from three subsections of the study area (described in Section 4.6.1) were purchased. However, the photographs were found to convey too little variation in spectral information to be useful in land cover assessment. In addition they were from a different time of year (May-June) compared to the September satellite images, making them not directly comparable. The ensuing methodological procedures after the acquisition of the image data, and the interrelationships among them, are as summarised in Figure 4.6 (compare framework in Figure 4.6 with that in Figure 1.2). Details of the procedures are outlined in the sections below.

4.4 **Image Pre-processing**

Pre-processing of the images involved (1) image quality assessment, (2) atmospheric correction, (3) image co-registration, and (4) image normalisation. These will be addressed in turn below.

4.4.1 **Image Quality Assessment**

Initial univariate statistics were extracted for all the images using the image processing software. They are shown in Table 4.2. The more the scatter of values in a band (i.e. the higher the standard deviation and range), the more differentiation there is (Jensen, 1986). All the images were cloud free.

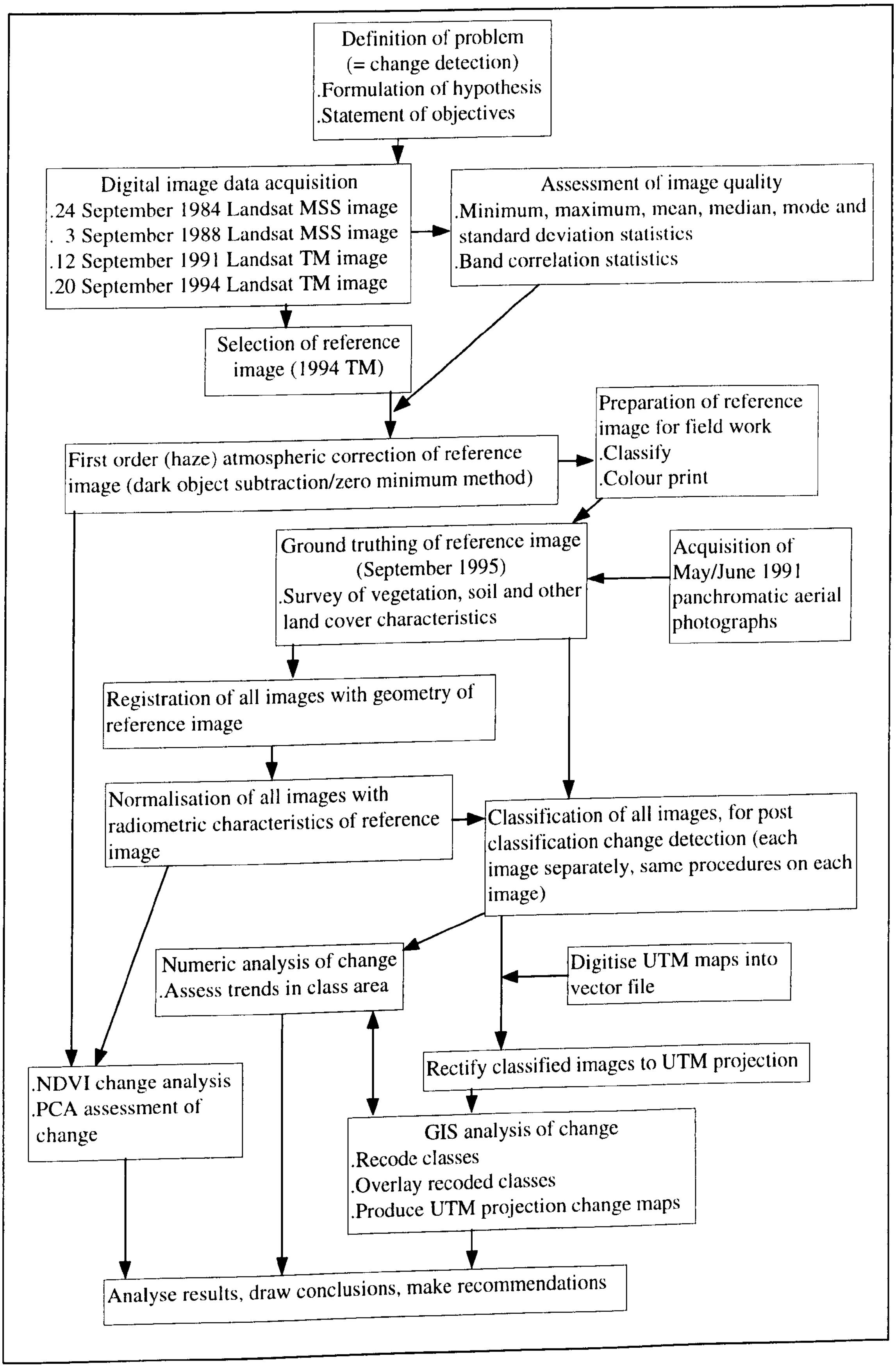


Figure 4.6 Flow diagram of methodological procedures.

Table 4.2 Image Data Univariate Statistics*

Image	Band	Minimum	Maximum	Mean	Median	Mode	Standard deviation
20 September 1994 Landsat TM	1	85	174	108.426	108	109	6.119
	2	31	82	43.739	44	44	4.401
	3	29	124	54.861	55	55	9.632
	4	15	132	53.040	52	47	15.088
	5	1	255	101.464	103	101	32.949
	7	0	255	61.862	64	66	20.643
12 September 1991 Landsat TM	1	83	145	98.212	98	98	4.584
	2	29	76	40.842	40	39	3.984
	3	31	118	53.561	53	49	9.031
	4	15	123	48.741	47	43	12.943
	5	6	255	94.787	95	91	29.390
	6	125	183	159.417	162	164	9.837
	7	0	255	52.264	54	56	16.581
3 September 1988 Landsat MSS	1	31	105	56.964	56	56	8.144
	2	21	110	54.866	54	53	11.710
	3	12	144	74.852	75	81	18.003
	4	0	157	76.154	77	76	22.007
24 September 1984 Landsat MSS	1	10	105	61.655	61	61	6.956
	2	5	131	64.866	63	58	12.763
	3	11	155	70.484	67	62	17.885
	4	12	157	67.169	64	62	20.377

*All statistics refer to reflectance, on a scale of 0-255 levels (8 bits).

Each image was examined for radiometric errors arising from sensor aberrations such as line dropout, line striping or line start problems (see Section 3.2.1.1.5). These problems were investigated visually on the digital image display screen.

(i) **Quality of 20 September 1994 TM Image**

There was one large fire on the ground at the time of image acquisition (near Luwato Lagoon, see Figure 2.1 for location) and two isolated smaller ones elsewhere in the image area. The large fire produced a plume of smoke which drifted across the area to the west as far as Lochinvar (see Figure 4.2). The smoke and generally high atmospheric scattering caused a high maximum value in TM band 1 (the Blue-Green band), while the fires caused the flame induced maximum possible readings of 255 (i.e. saturation) in bands 5 and 7 (mid infrared bands) (see Table 4.2). There was, therefore, temporary line dropout along scan lines just after fires in bands 5 and 7. In spite of these isolated cases the image was of good visual quality. It had a near normal distribution of values in bands 1, 2, and 3 (mean≈median≈mode), and large standard deviations in bands 5 and 7 because of the fire. There were no line start or line striping radiometric errors identified in any of the bands.

(ii) **Quality of 12 September 1991 TM Image**

As in the case of the 20 September 1994 TM image, this image had a flame induced maximum possible reading of 255 in bands 5 and 7 (mid infrared). There was, however, less smoke in the image scene, hence the lower maximum and minimum values in band 1. The fire was smaller and there were no line start, striping or dropout problems. Bands 1 and 2 had near normal distributions of data (mean≈median≈mode). The other bands had slightly skewed distributions but overall the image was of good quality.

(iii) **Quality of 3 September 1988 MSS Image**

The image was of good visual quality in spite of there being faint smoke over (Chunga Lagoon; Figure 4.4). It had near normal distribution of values in bands 1, 2 and 4 (where mean≈median≈mode) but a slightly skewed distribution in Band 3 (where mean≈median≠mode).

(iv) **Quality of 24 September 1984 MSS Image**

The image was of good visual quality and had no smoke interference, line start, line dropout or line striping problems. However, the distribution of values was slightly skewed in all the bands except for band 1 (where mean≈median=mode).

Multivariate statistics for all the images were computed and are shown in Table 4.3. Highly correlated bands usually carry redundant information, and using one of such bands instead of both may reduce the volume of data and save computation space and time (e.g. in classification). The lower the correlation between two bands the more independent they are (Jensen, 1986).

On the 1994 TM image, the visible bands 2 and 3 are, as expected, very highly correlated ($r = 0.936$). Bands 1 and 2, and 1 and 3 (also visible bands) are highly correlated too, but to a lesser degree ($r = 0.834$ and 0.735, respectively). In the visible region of the electromagnetic spectrum, therefore, band 1 is slightly independent of bands 2 and 3 (i.e. it contains information which is slightly independent of the contents of bands 2 and 3). Infrared bands 5 and 7 are very highly correlated ($r = 0.894$) but band 4 is slightly independent of bands 5 and 7. The infrared bands (4, 5 and 7) are slightly independent of the visible bands (1, 2 and 3), as expected, but the high

Table 4.3 Correlation Matrices of Image Data

(a) Correlation Matrix of 20 September 1994 TM Image Bands

	TM1	TM2	TM3	TM4	TM5	TM7
TM1	1.000					
TM2	0.834	1.000				
TM3	0.735	0.936	1.000			
TM4	0.428	0.703	0.651	1.000		
TM5	0.606	0.807	0.864	0.679	1.000	
TM7	0.555	0.684	0.767	0.368	0.894	1.000

(b) Correlation Matrix of 12 September 1991 TM Image Bands

	TM1	TM2	TM3	TM4	TM5	TM6	TM7
TM1	1.000						
TM2	0.897	1.000					
TM3	0.894	0.960	1.000				
TM4	0.647	0.811	0.781	1.000			
TM5	0.797	0.839	0.871	0.719	1.000		
TM6	0.053	-0.046	0.022	-0.292	0.212	1.000	
TM7	0.659	0.625	0.670	0.382	0.882	0.527	1.000

Table 4.3 continued - Correlation Matrices of Image Data

(c) Correlation Matrix of 3 September 1988 MSS Image Bands

	MSS1	MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.919	1.000		
MSS3	0.755	0.725	1.000	
MSS4	0.689	0.661	0.981	1.000

(d) Correlation Matrix of 24 September 1984 MSS Image Bands

	MSS1	MSS2	MSS3	MSS4
MSS1	1.000			
MSS2	0.949	1.000		
MSS3	0.823	0.806	1.000	
MSS4	0.760	0.738	0.981	1.000

correlation ($r = 0.864$) between bands 5 (mid infrared) and 3 (visible red) is surprising. It could be due to the dry nature of the land surrounding the wetland. The dry land is reddish-brown in colour (giving it high visible red reflectance) (see Figures 2.15, 2.18, 2.19, 2.22) and bare in some places (resulting in high mid infrared reflectance, from dry soil), which could have resulted in the high correlation between bands 3 and 5.

As on the 1994 TM image, the visible bands 2 and 3 on the 1991 TM image are very highly correlated, as expected (r = 0.960). Band 1 correlates highly with bands 2 and 3 (r = 0.897 and 0.894, respectively) and is less independent of the other visible bands than is the case on the 1994 TM image. The mid infrared bands 5 and 7 are highly correlated (r = 0.882), while the near infrared band 4 is independent of band 7 (r = 0.382) but less independent of band 5 (r = 0.719). There is a surprising high correlation between mid infrared band 5 and visible bands 1, 2 and 3 (r = 0.797, 0.839 and 0.871, respectively). The same explanation (i.e. predominance of reddish/yellowish dry land) proposed for the high correlation between bands 5 and 3 on the 1994 TM image can help explain this high correlation. The thermal infrared TM band (band 6) correlates negatively with TM2 (green) and TM4 (near infrared), possibly because at sites with healthy, green vegetation (and, therefore, high green and near infrared reflectance), shade cools the land, resulting in less thermal emission. The band has a low correlation with the other bands.

On the 1988 and 1984 MSS images, visible bands 1 and 2, and near infrared bands 3 and 4 are highly correlated (r = 0.919 and 0.981, respectively, on the 1981 image; 0.949 and 0.981, respectively, on the 1984 image), as expected. The near infrared bands 4 and 3 are generally independent of the visible bands 1 and 2, as expected. There are generally higher correlation values for the 1984 MSS image than for the 1988 MSS image, perhaps because on the latter image there was flood water (with low visible and infrared reflectance) in lower sections of the floodplain near Mazabuka (Figure 4.4).

4.4.2 **Atmospheric Correction**

The four general methods of atmospheric correction (Section 3.2.1.1) were considered for use, initially on the 1994 TM image (taken as the reference image), but atmospheric correction of the reference image was done using the dark object subtraction method. Because of the presence of freshly burnt grassland in the image scene (Figure 4.2), it was assumed that the reflectance from such areas should have been zero in visible and near infrared bands and hence the actual digital values over the burnt grassland were the result of atmospheric induced additive factors, especially haze. Using the image processing software, a model which subtracted the minimum value (Table 4.2) from each pixel's digital value in the respective band was built and used to produce a raster image, for the band, whose minimum value was zero. The values subtracted from the reference 1994 TM image bands are as shown in Table 4.4a. Bands 5 and 7 are not affected by haze (Jensen, 1986) and were, therefore, not corrected using this method. However, band 7 already had a minimum value of zero, and band 5 had a minimum value of 1, which is close to zero (see Table 4.2). The results of the atmospheric correction show that the haze was eliminated, as shown in Figure 4.7.

There were no targets whose ground reflectance was known to enable use of the radiance to reflectance conversion method, because no field work had been undertaken concurrently with the satellite overpass. Therefore, the radiance to reflectance conversion method was not used. Similarly, modeling methods would have required data on the meteorological and atmospheric conditions over the Kafue Flats at the time of data acquisition, such as aerosol composition, water vapour content, temperature,

Table 4.4 Atmospheric Correction Equations used to Correct Reference Image

(a) Dark Object Subtraction Method

TM Band	Subtraction from Band Pixel Values
1	TM1 - 85
2	TM2 - 31
3	TM3 - 29
4	TM4 - 15
5	None
7	None

(b) Regression Adjustment Method (attempted)

Water Body	Bands Regressed	Regression Equation	r^2 (%)	X - intercept (Bias)
Chinuka Pan	TM7, TM1	TM7 = -4.30 + 0.106TM1	3.2	40.566
	TM7, TM2	TM7 = 1.45 + 0.130TM2	1.1	-11.154
	TM7, TM3	TM7 = 2.10 + 0.110TM3	0.7	-19.091
	TM5, TM1	TM5 = 19.3 - 0.088TM1	1.9	218.573
	TM5, TM2	TM5 = 20.6 - 0.285TM2	4.7	72.281
	TM5, TM3	TM5 = 5.80 + 0.148TM3	1.0	-39.189
	TM4, TM1	TM4 = 10.4 + 0.076TM1	2.5	-137.384
	TM4, TM2	TM4 = 12.2 + 0.159TM2	2.7	-76.730
	TM4, TM3	TM4 = 12.5 + 0.149TM3	1.9	-83.893
Shalwembe Lagoon	TM7, TM1	TM7 = 1.55 + 0.031TM1	0.2	-49.679
	TM7, TM2	TM7 = 5.04 - 0.004TM2	0.0	1172.099
	TM7, TM3	TM7 = -6.06 + 0.276TM3	4.7	21.957
	TM5, TM1	TM5 = 12.5 - 0.033TM1	0.2	377.640
	TM5, TM2	TM5 = 9.69 - 0.020TM2	0.0	484.500
	TM5, TM3	TM5 = 0.91 + 0.203TM3	2.0	-4.480
	TM4, TM1	TM4 = 21.5 - 0.019TM1	0.4	-1155.914
	TM4, TM2	TM4 = 19.7 - 0.005TM2	0.0	3788.462
	TM4, TM3	TM4 = 15.2 + 0.108TM3	3.8	-144.741
Chunga Lagoon	TM7, TM1	TM7 = 10.7 - 0.070TM1	0.8	151.989
	TM7, TM2	TM7 = 7.01 - 0.092TM2	0.3	76.196
	TM7, TM3	TM7 = 7.87 - 0.127TM3	1.8	61.968
	TM5, TM1	TM5 = 6.80 + 0.008TM1	0.0	-850.000
	TM5, TM2	TM5 = 6.38 - 0.037TM2	0.0	-172.430
	TM5, TM3	TM5 = 8.09 - 0.018TM3	0.0	449.440
	TM4, TM1	TM4 = -13.5 + 0.138TM1	7.3	97.830
	TM4, TM2	TM4 = -27.6 + 1.380TM2	33.8	20.000
	TM4, TM3	TM4 = -10.1 + 0.890TM3	39.6	11.348

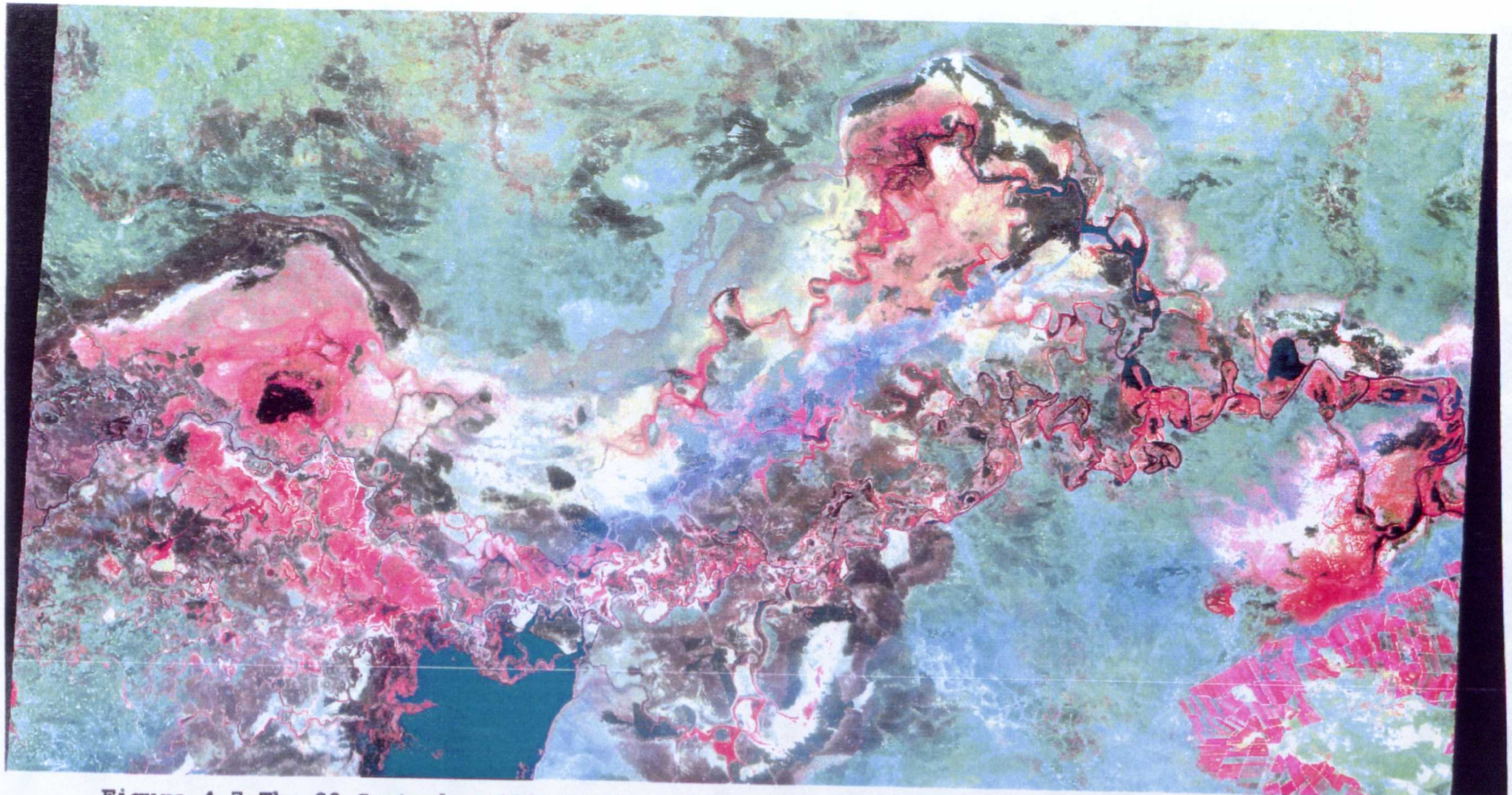


Figure 4.7 The 20 September 1994 Landsat TM image after atmospheric correction. The dark object subtraction atmospheric correction method was used. Compared to how it was before (Figure 4.2), the image is less hazy. Smoke was not eliminated by the correction. Red = TM4, Green = TM3, Blue = TM2.

humidity, pressure, and ozone content over each pixel location. These data were not available and consequently the method was not used.

The regression adjustment method was attempted, using the TM near and mid-infrared bands (Bands 4, 5 and 7) readings at three large water bodies in the study area (Chunga Lagoon, Shalwembe Lagoon and Chinuka Pan- see Figure 4.14 for location). The infrared band digital numbers for pixels on the water bodies were plotted against the corresponding visible band readings (Bands 1, 2 and 3) at the same pixels, one band pair at a time, to see which pairs gave the best results for use in atmospheric correction. The procedure was repeated for all three water bodies, 100 random pixels per water body. All the regression models were not significant (see Table 4.4b). The coefficients of determination (r^2) were all less than 0.5, meaning that more than 50% of the variation in the infrared band values was not accounted for by their regressions on the visible bands. The main reason for the poor regression results could have been because the lagoons are shallow and their surfaces have emergent and floating vegetation (e.g. water lilies and hyacinths; see Figure 4.8). Therefore, instead of having no infrared reflectance, the water bodies have infrared reflectance from the vegetation and bottom sediments. Due to the poor regression results the method was abandoned. Having corrected the reference image for first order atmospheric effects, the other images were indirectly corrected by the technique of image normalisation, as outlined in Section 4.4.4.

4.4.3 Image Co-Registration and Resampling

Accurate co-registration was needed to facilitate change detection and minimise change detection errors (see Section 3.2.1.4). A number of ground control targets were used to register all the other images to the geometry of the 1994 reference image. These included road junctions and river bends distributed in all sections of the scene. The results are summarised in Table 4.5. A nearest neighbour resampling algorithm was then used to resample the MSS images to a 30m x 30m pixel size like that of the TM images. The results show that the error (RMSE) was 0.43 of a pixel at the most (12.9m).

Figure 4.8 Water surface conditions on a lagoon on the Kafue Flats (on Luwato Lagoon, UTM grid 35 560401E, 8290070N, looking southwest from north bank, 27 September 1995, noon. In the back ground (top right corner) is smoke from an active fire in the water fringe vegetation zone). See also Figure 5.5.

Table 4.5 Image Co-registration and Resampling Error

Images Co-registered	Number of Ground Control Points	Output Pixel Size	Root Mean square Error (RMSE)
1984 MSS, 1994 TM	9	30m	0.35
1988 MSS, 1994TM	10	30m	0.43
1991 TM, 1994 TM	16	30m	0.28

4.4.4 **Image Normalisation**

The most recent image (20 September 1994) was chosen as the reference image because ground truthing was undertaken for this image. The radiometric characteristics of all the other images (in equivalent bands) were normalised to this image to minimise change detection errors arising from differences in atmospheric composition, illumination conditions, detector calibration (MSS versus TM), and astronomic and phase angle conditions (see Section 3.2.1.2) at the times of image acquisition on the five dates. The reference image was acquired at 07:28am local time, with a sun elevation angle of 48.81^0 and sun azimuth of 69.13^0 at the center (Table 4.1). The other images were acquired at slightly different times and sun angles (see Table 4.1), resulting in slightly different illumination conditions. Normalisation was undertaken to minimise any such differences (Schott *et al*, 1988; Eckhardt *et al*, 1990; Hall *et al*, 1991; Jensen *et al*, 1995; Lee and Marsh, 1995). Being near anniversary dates (Table 4.1), phenological differences were minimised. However, soil moisture conditions are also likely to have been different on the four dates as a result of annual variations in seasonal flooding (timing, duration, extent) and rainfall (see Figures 2.5 and 2.10).

Wet and dry normalisation targets (Table 4.6) were selected in accordance with the criteria outlined by Eckhardt *et al* (1990) (see Box 3.1). One of the wet normalisation targets is shown in Figure 4.9. The reflectance from the targets was considered to be non-changing and, therefore, any change in digital value between images was due to non target differences (e.g. atmospheric composition, illumination conditions, detector calibration, astronomic and phase angle differences). The assumption of no change is justified because irrigation reservoirs are maintained at near constant levels and the water is not stagnant. Artificial structures like concrete structures in Mazabuka are similarly non changing in reflectance.

Figure 4.9 An irrigation water storage reservoir on the Nakambala Sugar Estate, used as a normalisation target (UTM grid 35 574784E, 8246200N, looking west, 21 September 1995, morning). The reservoir is about 100m x 100m in size.

Table 4.6 Image Normalisation Targets Used

Target	20 September 1994 TM band values*			12 September 1991 TM band values			3 September 1988 MSS band values			24 September 1984 MSS band values		
	TM2	TM3	TM4	TM2	TM3	TM4	MSS1	MSS2	MSS4	MSS1	MSS2	MSS4
1. Irrigation reservoir 1	13	18	10	40	45	27	54	50	30	63	61	29
2. Irrigation reservoir 2	11	16	10	41	45	29	55	43	32	65	56	34
3. Irrigation reservoir 3	5	6	6	not covered by image			49	35	25	61	50	26
4. Irrigation reservoir 4	10	13	8	28	41	28	65	54	47	57	51	30
5. Bright artificial feature 1 (concrete at maize storage depot)	44	77	69	71	102	83	93	99	98	85	102	95
6. Bright artificial feature 2 (village area)	28	60	67	60	93	86	78	88	108	85	107	115
7. Irrigation reservoir 5	7	9	8	not covered by image			55	42	35	61	58	34
8. Irrigation reservoir 6	9	14	8	not covered by image			56	46	34	60	58	30
9. Irrigation reservoir 7	11	15	9	39	43	27	51	45	26	61	57	25
10. Bright artificial feature 3 (urban roofing)	33	64	66	not covered by image			88	92	95	94	113	103
11. Bright artificial feature 4	24	50	68	not covered by image			74	82	115	83	97	115
12. Irrigation reservoir 8	11	16	22	39	42	28	54	45	48	61	58	43
13. Irrigation reservoir 9	9	12	13	37	40	33	56	46	40	65	58	38
14. Bright feature	29	55	58	58	59	77	not clear			not clear		
15. Irrigation reservoir 10	8	13	13	38	41	30	not clear			not clear		
16. Irrigation reservoir 11	13	21	21	41	45	31	not clear			not clear		

*1994 TM values presented are averages from a 4 or 6 pixel area at target concerned on the atmospherically corrected image. Absolute values used in developing the equations in Table 4.7 differed from image to image according to pixel correspondence after co-registration. All values refer to reflectance on a scale of 0-255 levels (8 bits).

The targets' brightness values in the Green, Red and Near Infrared bands, which were present in both MSS and TM images (MSS1, 2, 4; TM2, 3, 4, respectively), were taken. The average value from a four pixel square per target (or 6 pixels for large targets) were used in the regression of the bands of the reference TM image (*y*-axis) against the equivalent MSS bands to be normalised (*x*-axis). Some of the targets were sometimes eliminated in order to get more significant regressions statistically (see Table 4.7). Therefore, not the same targets were used for each resulting equation.

Table 4.7 Image Normalisation Regression Equations Used

Image normalised with the 20 September 1994 TM reference image	Regression Equations	Coefficient of determination (r^2) (%)	Targets eliminated in deriving equation (see Table 4.6)
12 September 1991 TM	1994 TM2 = -28.5 + 1.00 1991TM2	99.1	4
	1994 TM3 = -28.8 + 1.02 1991TM3	99.9	5, 14, 16
	1994 TM4 = -21.2 + 1.09 1991TM4	99.8	12, 14, 16
3 September 1988 MSS	TM2 = -32.2 + 0.764MSS1	90.7	None
	TM3 = -25.8 + 0.892MSS2	98.8	4, 5, 6
	TM4 = -15.4 + 0.786MSS4	98.4	4, 5,10
24 September 1984 MSS	TM2 = -37.5 + 0.771MSS1	92.6	5, 6
	TM3 = -39.2 + 0.939MSS2	97.5	5, 6
	TM4 = -13.7 + 0.758MSS4	98.3	5, 6

Once the regression equations were determined, each of the bands on the respective dates was adjusted using the relevant equation to simulate the atmospherically corrected reference image and the conditions when the 1994 TM image was acquired.

A model was built which applied the regression equations on each pixel value in the respective band, to produce a raster image with adjusted values simulating those on the equivalent band on the reference image. The images resulting from the application of the normalisation equations in Table 4.7 are shown in Figures 4.10, 4.11 and 4.12.

In each equation, the subtraction component corrects for the difference in atmospheric path radiance (haze) between the dates, and the multiplication term corrects for the difference in detector calibration, sun angle, earth/sun distance, atmospheric attenuation, and phase angle between the dates (Jensen *et al*, 1995).

4.5 Preparation of Reference Image for Field Work

All pre-processing and further work concentrated on the southern 90 x 50 km subset of the quarter scenes, excluding the wooded upland area to the north (see Figure 4.2). Prior to field work, a supervised maximum likelihood classification of a Bands 4, 3, 2 (red, green, blue) false colour composite of the 1994 TM image (reference image) was performed using the spectral characteristics of the ground features for feature identification and training area selection (e.g. black areas for water, red for healthy/vigorous vegetation, etc.). The nomenclature of the classes was a modification of that used by Ringrose *et al* (1988) for the Okavango Delta, Botswana, which is a similar wetland system in southern Africa. Ten classes were used in this preliminary classification (Table 4.8) of the southern subset. The classified image was printed in colour at 1:178 000 for the 90 km x 50 km area, for use during ground truthing. This theoretical use of the comparative Okavango Delta wetland land cover classes in the preliminary classification was later found to have produced a lot of classification errors

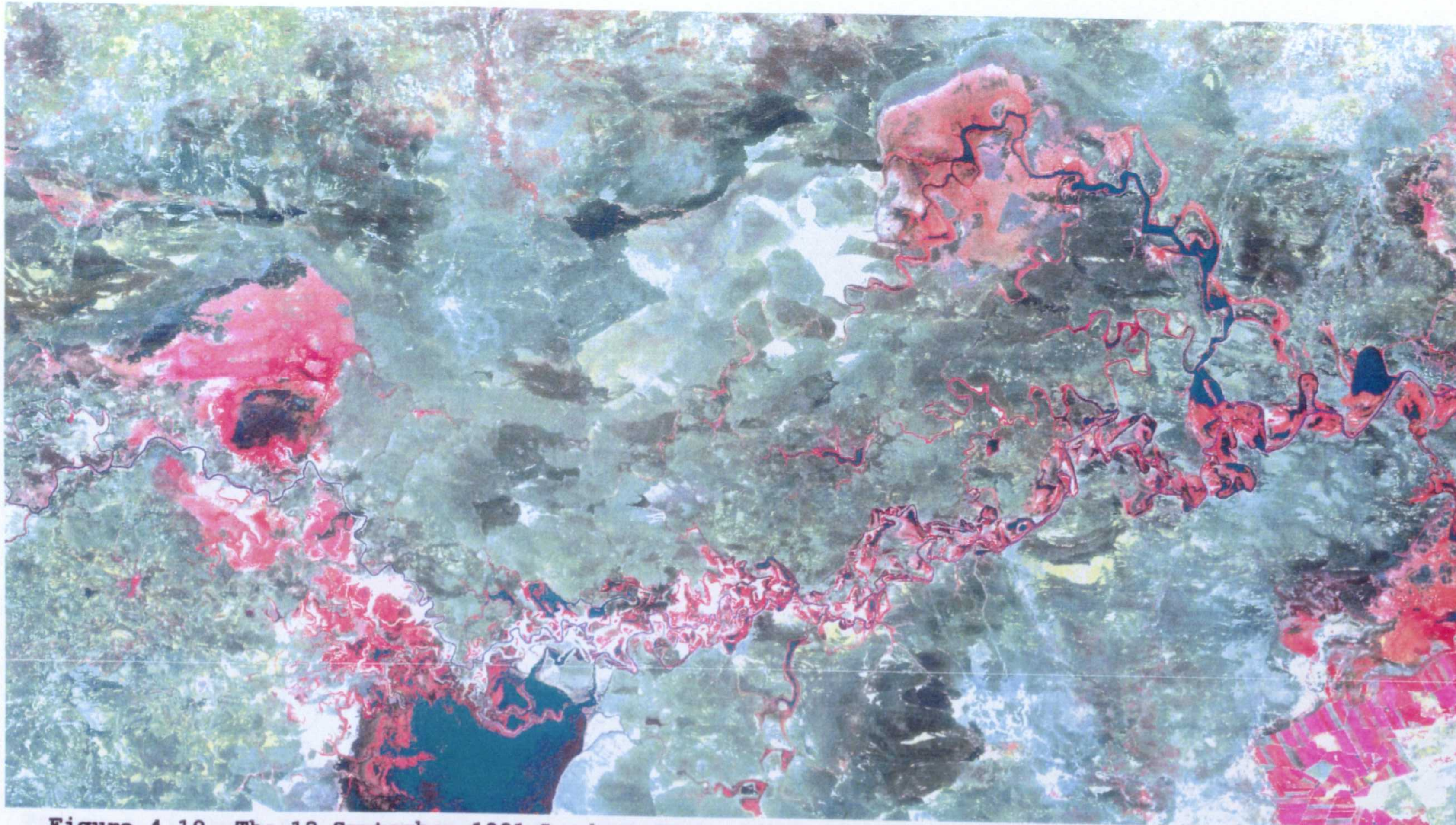


Figure 4.10 The 12 September 1991 Landsat TM image after normalisation with the atmospherically corrected 20 September 1994 Landsat TM reference image. Normalisation removed the haze from the image (compare with Figure 4.3). Red = TM4, Green = TM3, Blue = TM2.

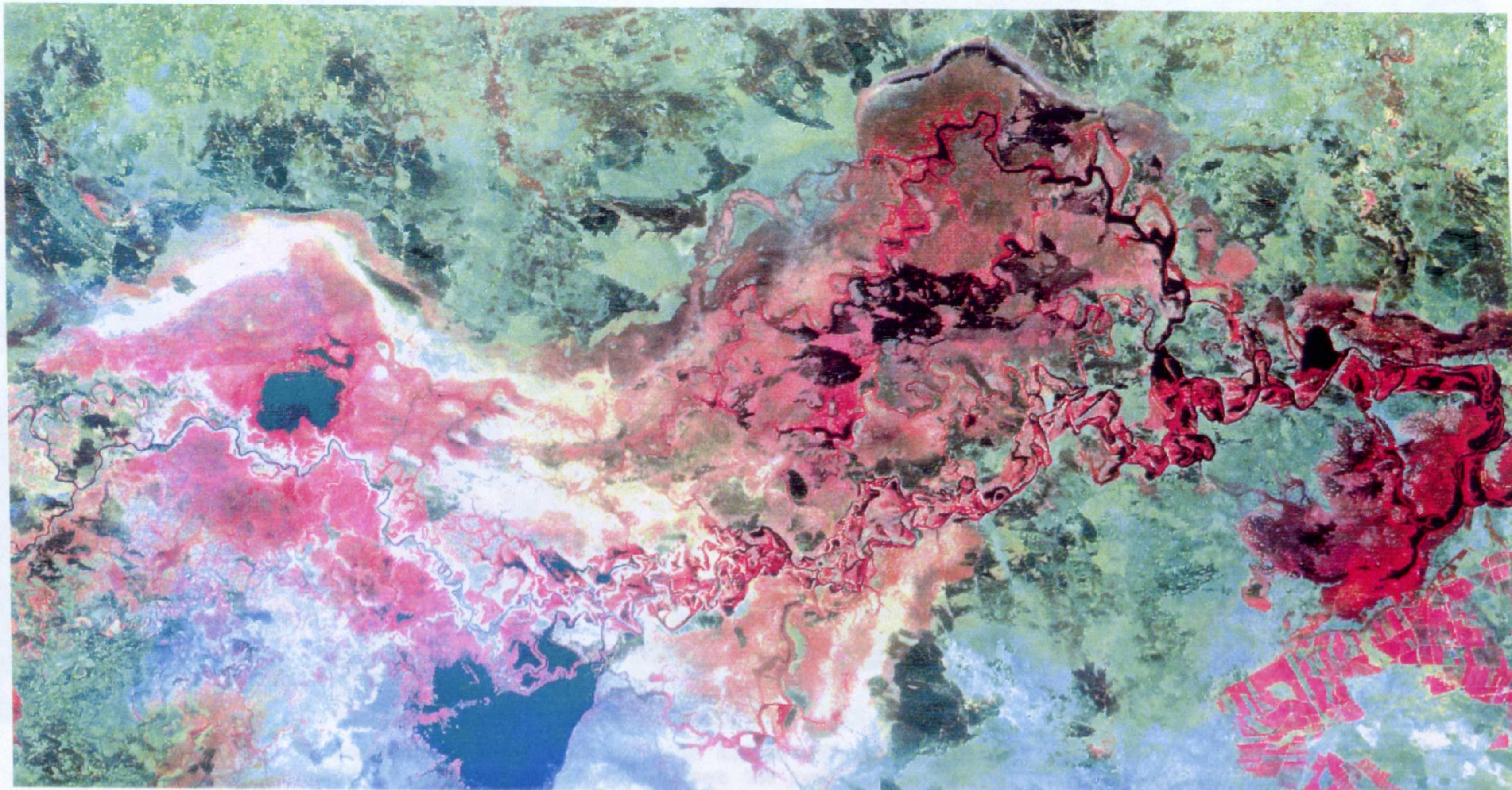


Figure 4.11 The 3 September 1988 Landsat MSS image after normalisation with the atmospherically corrected 20 September 1994 Landsat TM reference image. Normalisation removed haze from the image but the smoke in the lower left corner was not removed (compare with Figure 4.4). The image has been resampled to fit in the geometry of the reference image. Red = MSS4, Green = MSS2, Blue = MSS1.

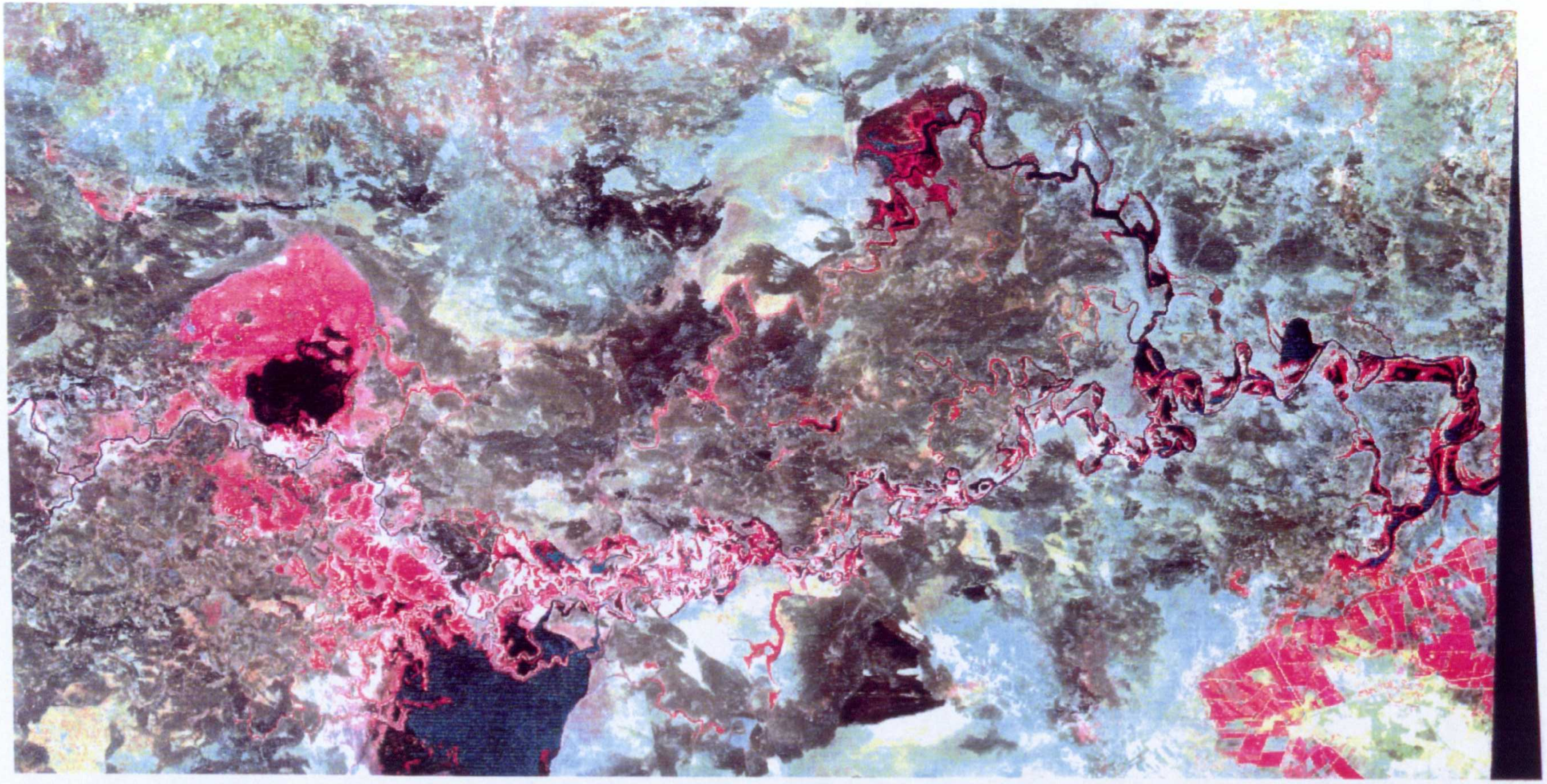


Figure 4.12 The 24 September 1984 Landsat MSS image after normalisation with the atmospherically corrected 20 September 1994 Landsat TM reference image. Normalisation removed haze from the image (compare with Figure 4.5). The image has been resampled to fit in the geometry of the reference image. Red = MSS4, Green = MSS2, Blue = MSS1.

after field verification. Because of the large error factor this preliminary classification has not been reproduced in this report. More relevant classes which were specific to the Kafue Flats were defined after field work and used in all ensuing classifications. These more accurate classified images will be illustrated in Section 4.7.

Table 4.8 Theoretically Derived Preliminary Classes on the Reference Image Prior to Field Work*

Class	Description
1. Open water	Lagoons, river, ox-bow lakes
2. Waterlogged dark soil	Clay, wet dark soil
3. Dry, dark soil	Clay, dry, bare dark soil
4. Actively growing riparian zone vegetation	River fringe, healthy vegetation including sugar cane
5. Less actively growing riparian zone vegetation	River fringe, stunted vegetation including sugar cane
6. Mixed vegetation in floodplain zone	Varied vegetation stands in floodplain, stunted by water shortage
7. Land based green vegetation	Woodland on fringe of wetland/floodplain
8. Other dry land	Undefined dry land
9. Sparse/dying vegetation	Very sparse, water stressed vegetation
10. Dry/dead vegetation	Mainly dry grass

*Names derived from comparative wetland work on the Okavango Delta, Botswana, by Ringrose *et al*, 1988.

4.6 Field Work

Field work was undertaken in September 1995, one year after the acquisition of the reference image. It was expected that the September 1995 conditions would not be exactly like those in September 1994 but it was anticipated that field work then would yield knowledge of the ground features being analysed. This knowledge would then be used when analysing archival images of the area by using known 1994 ground features to identify similar features on the archival images.

4.6.1 Ground Truthing Organisation and Procedure

The ground truthing was done in two stages, as summarised in Table 4.9. The first stage was reconnaissance surveying of the area covered by the image, on a four wheel drive vehicle, to examine the relationship between the satellite image classes (Table 4.8) and the land cover characteristics. Sites representative of most of the image classes were visited, mainly on the south bank floodplain of the Kafue River.

Stage two of the ground truthing survey involved semi-detailed surveying of the image area to generate details about the land cover characteristics. The important activities which needed to be undertaken in the field were:

1. Identifying land cover types
2. Determining vegetation density and speciation
3. Determining image classes that would relate to the land cover types.

Three geographical regions were chosen for the work: (1) Lochinvar, (2) northwest of Mazabuka, and (3) the area around Blue Lagoon National Park (Figure 4.13). The

Table 4.9 Summary of Ground Truthing Procedure

Stage	Activities (September 1995)
1	Reconnaissance surveying of area covered by image, on 4-wheel-drive vehicle, to examine relationship between classes on classified 20 September 1994 image and ground cover classes.
2	More detailed surveying: i. Choose three geographical locations for the semi-detailed work ii. Carry out traverse/transect, on 4-wheel-drive vehicle. Stop at sites typical of the land cover class, visually identified in the field, within the given image class. iii. Attempt generation of quantitative land cover information at each site using tape extended in 30-60m radius (extend further if necessary). In 4 main compass bearings (90^0 apart) record ground cover characteristics for given distance from site centre. Repeat if necessary until typical scene is characterised. Summarize land cover types from distance ranges into percentages. Technique was found to be too laborious, had only limited success and was substituted for by qualitative approach of mere description of visually identified land cover category (see vi. below). iv. Record location of site using GPS. Mark the site on 1:50 000 map and on 1:30 000 air photo if identified. v. Use air photos to "extend the view" beyond where traverse/transect was done (by stereo photo interpretation later in the laboratory). vi. At site record (as appropriate): a) Date b) Site no./GPS position c) Sample/slide/photo no. d) Satellite image class e) dominant (visually identified) ground cover class f) Tree height (estimated by tanget computation of height, from clinometer angle reading) g) Tree leaf type h) Grass height (estimate) i) Grass leaf type j) Grazing/browsing intensity (low→moderate→high→intense) k) Fire damage l) Ecotone (sharp or transitional?) m) Termite mounds (type) n) Soil sample no. o) Plant sample no.

choice of the areas was dictated by accessibility (roads) and availability of lodging facilities - the two most important factors in the vast wilderness of the Kafue Flats. In each of the areas traverses were carried out on a four wheel drive vehicle. Stops were made at sites typical of the observed (field defined) land cover classes irrespective of which satellite class the site corresponded to. At the sites an attempt was made at generating quantitative as opposed to qualitative vegetation description data (to avoid subjective descriptions - Treitz *et al*, 1992) using a 30m tape. The tape was extended in four compass directions (90^0 apart) to record the vegetation variation with distance along the tape in the first 30m and the radius was widened to 60m where necessary (TM resolution is 30m except in band 6)[1]. The procedure was repeated if necessary in an attempt to characterise the typical scene in the given land cover types. The technique had limited success because of the large variations within given land cover types. For example there was no `typical' woodland scene (examine Figures 2.16, 2.17). The qualitative approach of placing each site in a descriptive aspect of the broad land cover zone in which it occurred was more practical (woodland, termitaria zone, grassland, etc., - see Table 2.3 and Figures 2.15, 2.16, 2.17, 2.18, 2.19, 2.20, 2.21).

The location of each site where a stop was made was recorded using a Global Positioning System (GPS) with a potential accuracy of 12m when there is no selective availability (SA) military interference, or an error of 100m at the most when there is SA interference (according to the product's manufacturer)[*] . The site location was marked on the appropriate 1:50 000 topographic map and, if identified, on accompanying 1:30 000 May-June 1991 aerial photographs for stereo- and

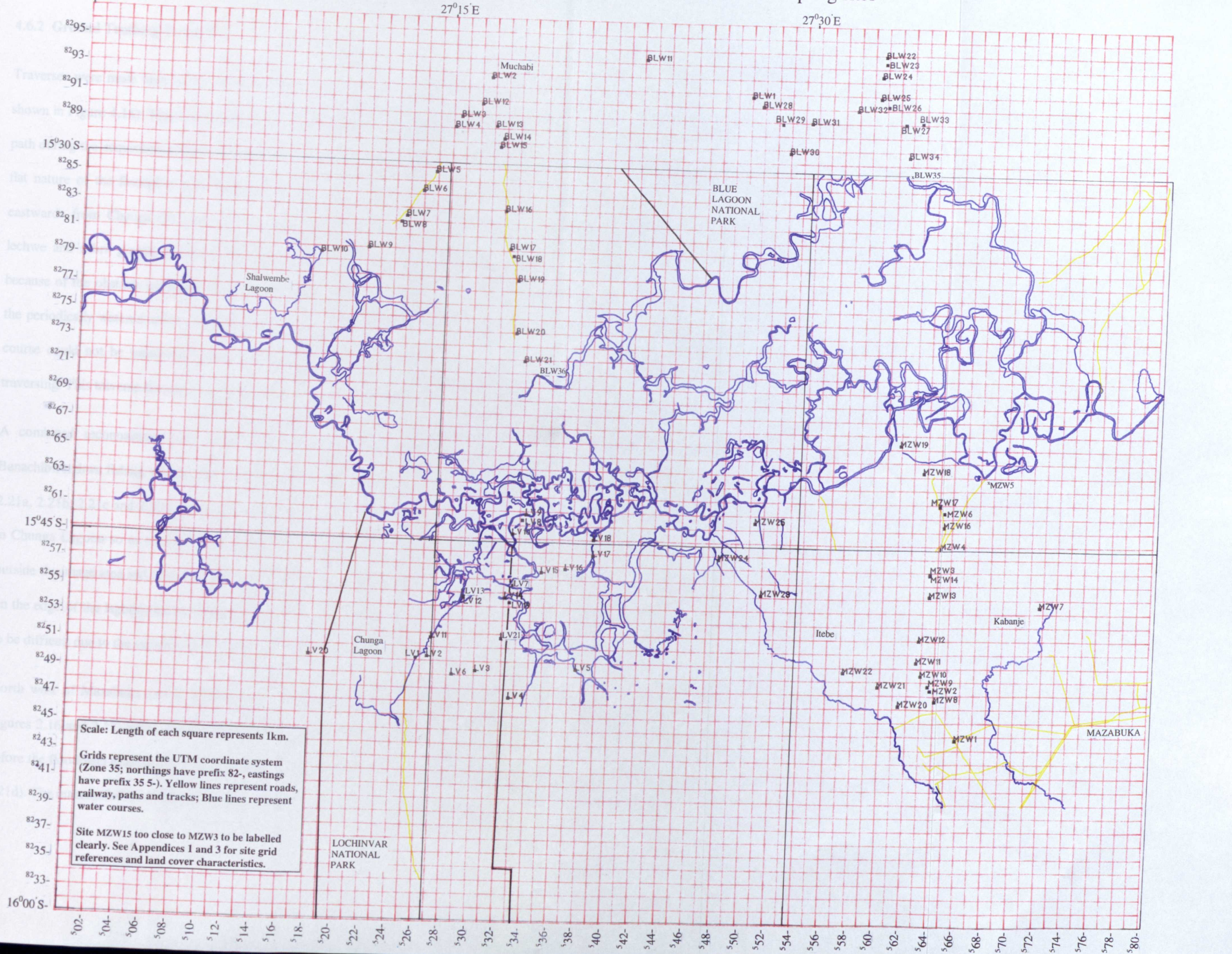
[1] Bryant, (1995) pers. comm., Department of Environmental Science, University of Stirling.
[*] Actual field accuracy about 42m.

monoscopic laboratory analysis later. It was hoped that the aerial photographs would `extend the view' beyond where the traverse observations were made.

The traverses were undertaken mainly parallel to bicycle and ox-cart paths used by fishermen to transport fish from the Kafue River fishery. Colour print and slide photographs were taken at most of the sites for future reference. At sites with notable soil exposure, 10cm surface soil samples were taken (using a hand spade) for laboratory analysis to determine the texture and organic matter content in order to obtain a general indication of the likely reflectance characteristics of the soil. A total of 29 samples were collected, code labeled, stored in air tight plastic sample bags and analysed in the Department of Soil Science of the University of Zambia, three weeks later. The results are summarised in Appendix 1. Soil colour was recorded on site using Munsell Colour Charts. The dominant (visually identified) plant species at the site was named using accompanying photographs prepared by the FAO (1968, Vol. IV). Where field identification was not possible or doubted, plant samples were collected, code labeled, placed in a paper press for storage, and (three weeks later) given to a plant taxonomist in the Department of Biology, University of Zambia for identification.

The other site detail recorded is as shown in Table 4.9. The information was recorded in order to understand better the environmental setting of the site. Eighty two sites from all the traverses were described in detail (Figure 4.13). The descriptions are summarised in Appendix 1 and Column 2 of Appendix 3. It soon became apparent that the pattern of land cover classes was similar in both south and north bank areas. This limited the number of sites described in detail because no distinctly new land cover types were emerging.

Figure 4.13 Location and distribution of field sampling sites



4.6.2 **Ground Truthing Traverses**

Traverses were made both in the north and south banks sides of the Kafue River (as shown in Figure 4.14). Traverses A and B in Lochinvar attempted to follow the flight path during the acquisition of the accompanying 1991 air photographs. Because of the flat nature of the floodplain (see Figures 2.19a and 2.29), it was possible to drive eastwards from Chunga (Traverse A) and Hippo Corner (Traverse B) across the lechwe and zebra grazed grassland. Traverse A could not be extended farther east because of the obstacle presented by dense *Sesbania* reeds (e.g. see Figure 2.21e) in the periodically watered water course. East of Hippo Corner (Traverse B), a straight course could not be maintained due to a large active grassland fire at the time of traversing. This traverse diverted northeast to Namatusi fishing village (Figure 4.14).

A combined reconnaissance and semi detailed survey visit was made towards Banachibwembwe fishing village prior to undertaking Traverses A and B (see Figures 2.21a, 2.21b, 2.21c and 2.30). Traverse C aimed at avoiding the obstacle of the water in Chunga Lagoon so as to make observations in the west. Most of the traverse fell outside the image area and, therefore, no site recording was undertaken along it except on the edge of the lagoon (Site LV20 in Figure 4.13). Traversing farther west proved to be difficult due to the vastness of the lagoon (see Figure 2.29).

North west of Mazabuka and in the Blue Lagoon area there is woodland (e.g. see Figures 2.16 and 2.17) which opens up into the termitaria zone (e.g. see Figure 2.18) before the floodplain grassland (e.g. see Figure 2.19) and then the river (e.g. see Figure 2.21d). The inaccessibility of the (thorny) mixed woodland to vehicles prevented the

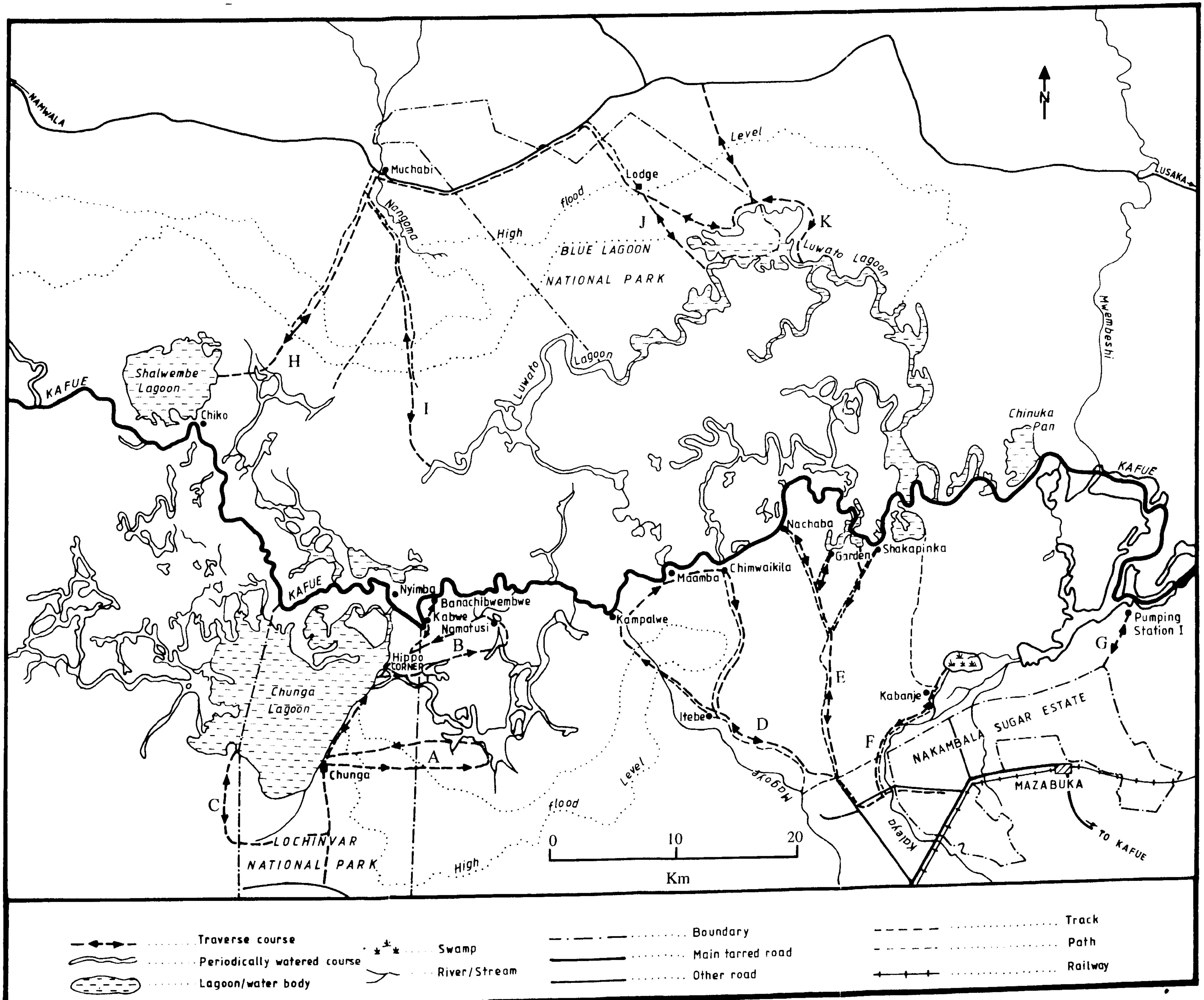


Figure 4.14 Ground truthing traverses undertaken on the Kafue Flats

use of straight traverses. The traversing undertaken, therefore, followed paths and tracks entering the floodplain.

Traverse D went through the woodland from Mazabuka towards the settled and cultivated area at Itebe, on route to the floodplain and fishing villages at Kampalwe, Maamba, Chimwaikila and back to Mazabuka (Figure 4.14). Similar zonation was encountered along Traverse E towards Shakapinka, Garden and Nachaba fishing villages. Traverse F headed towards the settled and cultivated area at Kabanje, terminating at the swamp north of Kabanje. Traverse G passed through the cane fields on the Nakambala Sugar Estate (see Figure 2.25) towards the irrigation water Pumping Stations 1 and 2, terminating at Pumping Station 1 (see Figures 2.26 and 2.27).

In the Blue Lagoon area there was a more limited number of access paths and tracks across the woodland into the floodplain. Traverse H started at the settled and cultivated area of Muchabi, turning west on the floodplain (see Figures 2.15, 2.16, 2.17, 2.19(b), and 2.22) towards Shalwembe Lagoon (see Figure 2.20). Similar zonation as that in Traverse D was observed along Traverse I when moving from Muchabi along Nangoma River towards the beginning of Luwato lagoon on the zebra and lechwe grazing areas of the floodplain. Observations were made parallel to the main road between Muchabi and Blue Lagoon Lodge, across Blue Lagoon National Park. Traverse J headed southwards from the lodge to Luwato Lagoon (see Figures 2.23 and 4.8) and Traverse K terminated where Luwato lagoon begins to turn south east, having started near the main gravel road to Lusaka.

4.6.3 Land Cover Classes Identified in the Field

Representative sites for most of the classes into which the 1994 image was preliminarily classified (Table 4.8) were visited for verification and re-definition of the classes. The main problem was in pin pointing exactly where on the classified image print (1:178 000) a particular site was. Care was taken to visit representative sites of all the classes in all the three geographical areas (see Section 4.6.1) where the ground truthing was undertaken. After field verification of the initial classes, it was found that the more appropriate classes should be as shown in Table 4.10. The classes in Table 4.10 are a summary of the land cover characteristics observed in the field (see column 2 of Appendix 3). The woodland categories refer to woodland either in full leaf or in various stages of spring leafing.

4.7 Change Detection Method

The principal change detection technique used was Classification Comparisons (see Section 3.2.2.4) (Lillesand and Kiefer, 1994; Jensen, 1986; Milne, 1988; Muchoney and Haack, 1994; Howarth and Wickware, 1981; Jakubauskas *et al*, 1990; Dale *et al*, 1996). The normalised and co-registered 3-band images from the four dates (see Sections 4.4.3 - 4.4.4) were classified separately. The Classifications Comparisons method was preferred to the other change detection techniques outlined in Section 3.2.2 because it not only indicates where change has occurred but also the nature of the change (i.e. from one specified land cover category to another). Techniques like Image Differencing and Image Ratioing can show where change has occurred in terms of increased or decreased reflectance but this change still has to be related to the ground cover categories producing it, which requires some form of land cover

Table 4.10 Field Defined Land Cover Classes on the Kafue Flats

Class	Sub classes
1. Open water	i. deep, without plant cover (river, ox-bow lakes, lagoons)
	ii. deep/shallow, with floating or partly submerged plants (mainly lagoons and ox-bow lakes)
	iii. shallow (lagoons, ox-bow lakes)
2. Water reeds and water fringe vegetation	i. dense, vigorously growing
	ii. less dense, disturbed by fire, cattle grazing or water stress
3. Dry stream, lagoon or pan bed	
4. Grassland	i. open, dry/green, intensively grazed grassland
	ii. open, dry, moderately grazed or grazing free grassland
	iii. tall, red/brown dry reeds
5. Sparse green floodplain vegetation	i. drought resistant, ungrazed
	ii. emerging after heavy grazing or burning
6. Termitaria zone	i. grassland termitaria with isolated shrubs
	ii. tree termitaria with dry grass
	iii. termitaria without trees or grass
7. Burnt areas	i. old burning with little black ash and with bare soil
	ii. recent burning with a lot of black ash
8. Exposed dry soil (with or without short grass)	i. associated with human settlement /cultivation areas
	ii. associated with game/cattle trampling, browsing/grazing
9. Woodland	i. degraded, mixed, with short shrubs
	ii. dense mixed woodland with dry grass
	iii. sparse mixed woodland with dry grass
	iv. *Acacia* woodland/thicket with dry grass
	v. *Albizia* woodland with dry grass
	vi. *Mopane* woodland with dry grass

categorisation. In addition, since they rely solely on a comparison of reflectance values at each pixel, they are highly susceptible to the radiometric and geometric errors outlined in Section 3.2.1. Other techniques such as change in vegetation indices (NDVI, PCA, Tasseled Cap change) also still require that the change be interpreted in terms of the land cover characteristics causing it, which requires some form of land cover categorisation. They can indicate where change has occurred, but interpreting this change still has to be undertaken with respect to the land cover types causing it. If these land cover types are not known, the interpretation becomes difficult. Change detection using the NDVI and PCA spectral enhancement techniques was, however, undertaken as a supplement.

In the classification process, each image was subjected to the same classification procedures. A supervised maximum likelihood classifier was used on each image, and the same number of classes used in each case. The initial gathering of signatures was done using an unsupervised classification technique because using the field sampling sites as supervised classification training sites resulted in more classification errors than when signature clustering was done in an unsupervised way. The clusters (signatures) generated were later edited by collecting signatures at selected training areas for the clusters, depending on the amount of error in the unsupervised classification. The class signature statistics used in the classification process were the minimum, maximum, mean and standard deviation values. Each respective unsupervised classification (to gather signatures) on each of the five images was set to 20 maximum iterations, to stop at 0.999 convergence threshold (i.e. 99.9% convergence). This means that as soon as 99.9% or more of the pixels stay in the same cluster between one iteration and the next, the utility should stop processing. In other words, as soon as 0.1% or fewer of the pixels change clusters between iterations, the utility should stop processing, which prevented it from running indefinitely (ERDAS Inc., 1994).

Image classification is inherently an iterative process, so starting with a trial run of 9 classes per image (to try and depict the main field-defined classes shown in Table 4.10), the number of classes per classification trial was progressively increased. It was found that 15 classes produced more meaningful variation in the vegetation cover classes, nearly as much variation as on the original image (see Figures 4.15, 4.16, 4.17 and 4.18; compare with Figures 4.7, 4.10, 4.11 and 4.12, respectively). Compared to the wetland classes derived from work by Ringrose *et al* (1988) on the Okavango Delta (Table 4.8), the classes were more relevant to the Kafue Flats. The 15 classes resulted from the 9 main field defined classes because some of the subclasses in Table 4.10 were delineated by the classification procedures. They depict a hierarchy of vegetation density and vigour (and therefore wetness/dryness). Dense (hydrophytic) wetland vegetation is the clearest wetland diagnostic feature (Tammi, 1994; Section 1.7). Table 4.11 summarises the resulting 15 classes used, but details of the reflectance characteristics of the 15 classes are outlined in Chapter 5. Beyond 15 classes there were too many dry land cover classes for meaningful interpretation because of the difficulty of assigning meaningful class names.

The combination of supervised and unsupervised signature gathering techniques was found to be more accurate in reproducing the variation on the original images than either technique alone. The convergence levels reached to produce the 15 classes were 0.991 for the 1984 MSS image, 0.987 for the 1988 TM, 0.984 for the 1991 TM, and 0.990 for the 1994 TM image.

Table 4.11 Image Interpretation Classes Used

Class	Land cover characteristics
1. Open water	Water without plant cover (in river, lagoons, ox-bow lakes)
2. Dense, very vigorous water reeds/ water fringe vegetation	Dense, very vigorous wetland vegetation (grass, reeds, shrubs)
3. Dense, vigorous water reeds/ water fringe vegetation	Dense, vigorous wetland vegetation (grass, reeds, shrubs)
4. Less dense, stressed water reeds/ water fringe vegetation	Medium to low density/vigour wetland vegetation (grass, reeds, shrubs); dense woodland in full leaf
5. Sparse, stressed water reeds/ water fringe vegetation	Sparse or low vigour wetland vegetation (grass, reeds, shrubs); moderately dense woodland in full leaf
6. Mixed green grassland/ woodland vegetation	Mixture of sparse green and dry grass, and/or dry grass with sparse trees in leaf
7. Sparse green grassland/ woodland vegetation	Mixture of sparse green and dry grass, and/or dry grass with scattered trees in full or emerging spring leaf
8. Very sparse green grassland/ woodland vegetation	Mixture of very sparse green and dry grass, and/or dry grass with very scattered trees in full or emerging spring leaf
9. Very sparse green vegetation/ termitaria with isolated trees	Mainly dry grass with very scattered trees in full or partial spring leaf in termitaria zone; also grassland with very faint greenness
10. Emergent vegetation in shallow water or after burning	Emergent vegetation in shallow water (especially in lagoons and water body fringes); new grass flush among (old) black soot in burnt areas
11. Dry grassland and termitaria zone without trees	Dry grassland (with little soil exposure); mixture of treeless termitaria zone (termite mounds) and dry grass
12. Dry land with leafless plant structures (woodland/grassland)	Leafless woodland, with bare soil and dry grass patches
13. Exposed, trampled dry soil with surface debris	Exposed, dry greyish/brown soil with plant litter
14. Bare, compacted dry soil	Exposed, dry greyish/brown soil
15. Burnt area or muddy, dark surface	Freshly burnt areas (with black soot), dark wet clay (on fringes of water bodies or mud in drying up areas)

The area covered by each of the classes on each of the images was calculated and trends in the classes evaluated. The original classes were later regrouped into fewer classes, some of which were overlaid and mapped in a GIS framework to assess spatial changes.

4.8 **Creation of Vector Maps for Image Rectification**

For use in image rectification, 1:50 000 topographic maps of the study area, produced by the Survey Department of the Government of Zambia (Sheets 1527C1, 1527C2, 1527C3, 1527C4, 1527D1, 1527D3) were digitised and a vector file created for use in locating the field sites described in the field and for which GPS readings were taken (Figure 4.13). The maps were in UTM (Universal Transverse Mercator) projection, Zone 35 (south of equator). Only processed images were rectified to this projection, to avoid the introduction of further errors on the original images (unrectified images are more *spectrally* correct than rectified ones; ERDAS Inc., 1994). The classified, rectified images are shown in Figures 4.15, 4.16, 4.17 and 4.18.

Figure 4.15 The classified 20 September 1994 TM (reference) image, rectified to the UTM map projection. Prior to classification, the image was atmospherically corrected. Compare with Figure 4.7.

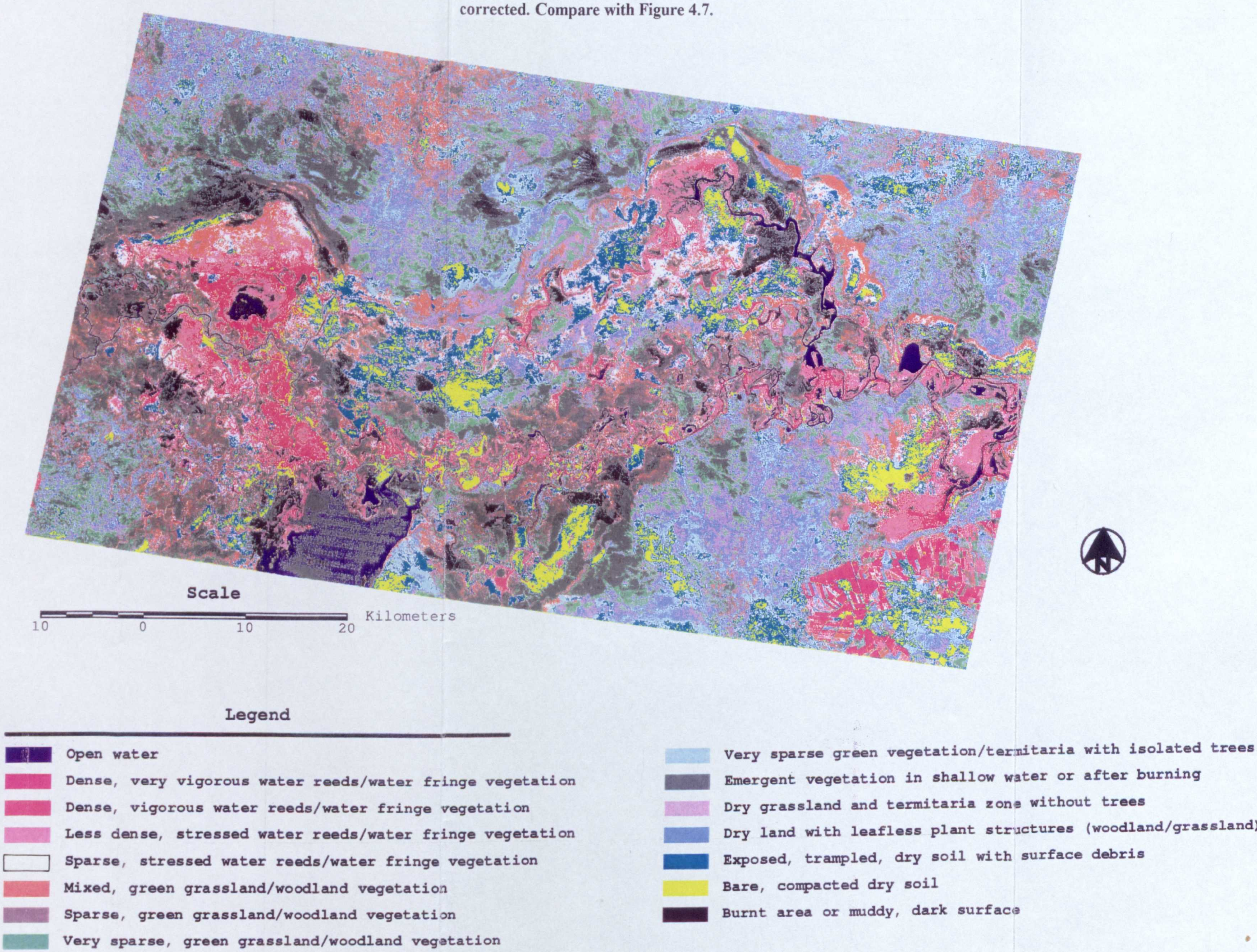
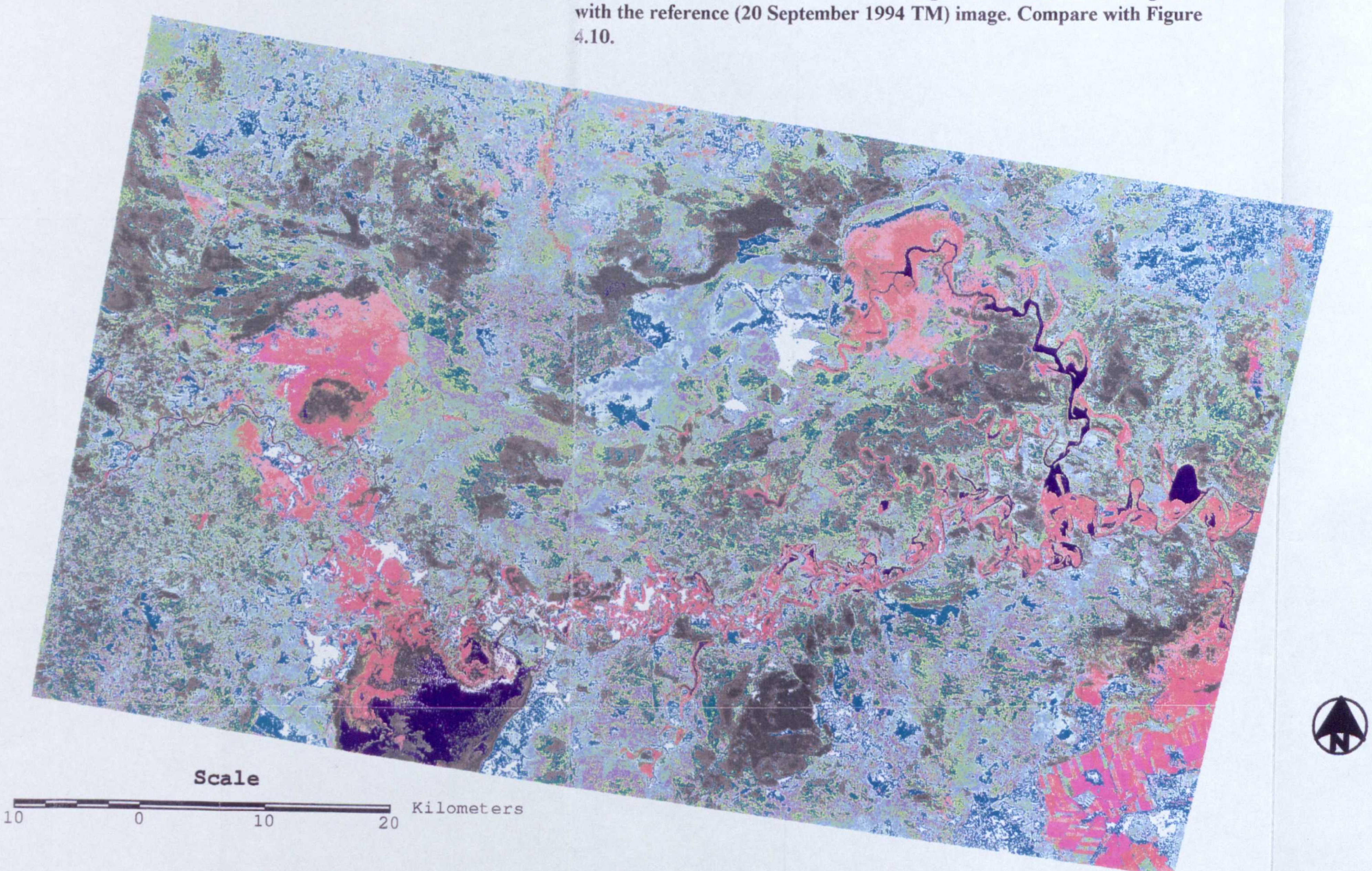


Figure 4.16 The classified 12 September 1991 TM image, rectified to the UTM map projection. Prior to classification, the image was normalised and registered with the reference (20 September 1994 TM) image. Compare with Figure 4.10.



Legend

- Open water
- Dense, very vigorous water reeds/water fringe vegetation
- Dense, vigorous water reeds/water fringe vegetation
- Less dense, stressed water reeds/water fringe vegetation
- Sparse, stressed water reeds/water fringe vegetation
- Mixed green grassland/woodland vegetation
- Sparse, green grassland/woodland vegetation
- Very sparse green grassland/woodland vegetation
- Very sparse green vegetation/termitaria with isolated green trees
- Emergent vegetation in shallow water or after burning
- Dry grassland and termitaria zone without trees
- Dry land with leafless plant structures (woodland/grassland)
- Exposed, trampled dry soil with surface debris
- Bare, compacted dry soil
- Burnt area or muddy, dark surface

Figure 4.17 The classified 3 September 1988 MSS image, rectified to the UTM map projection. Prior to classification, the image was registered and normalised with the reference (20 September 1994 TM) image. White areas on water bodies are unclassified (error) pixels. Compare with Figure 4.11.

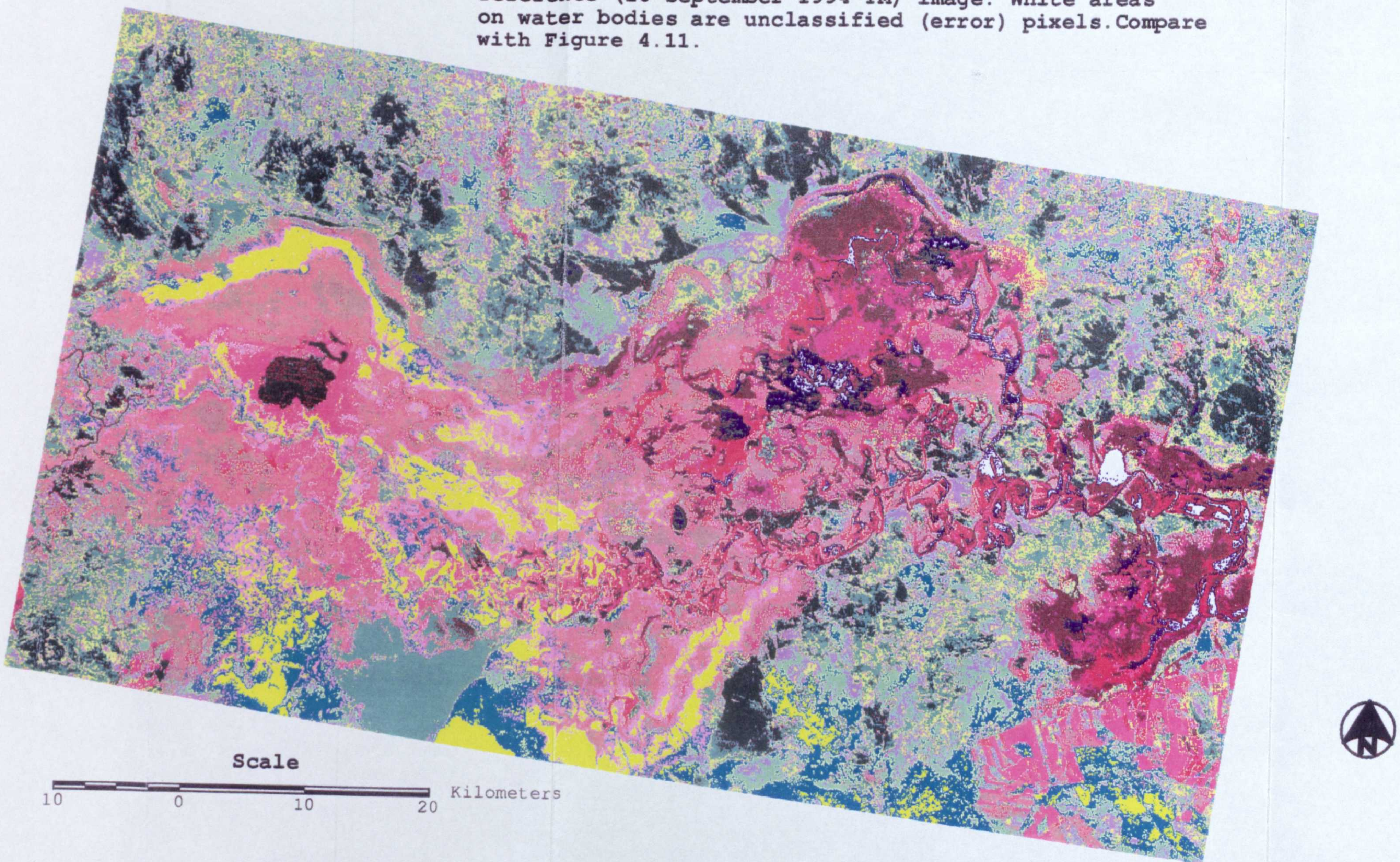
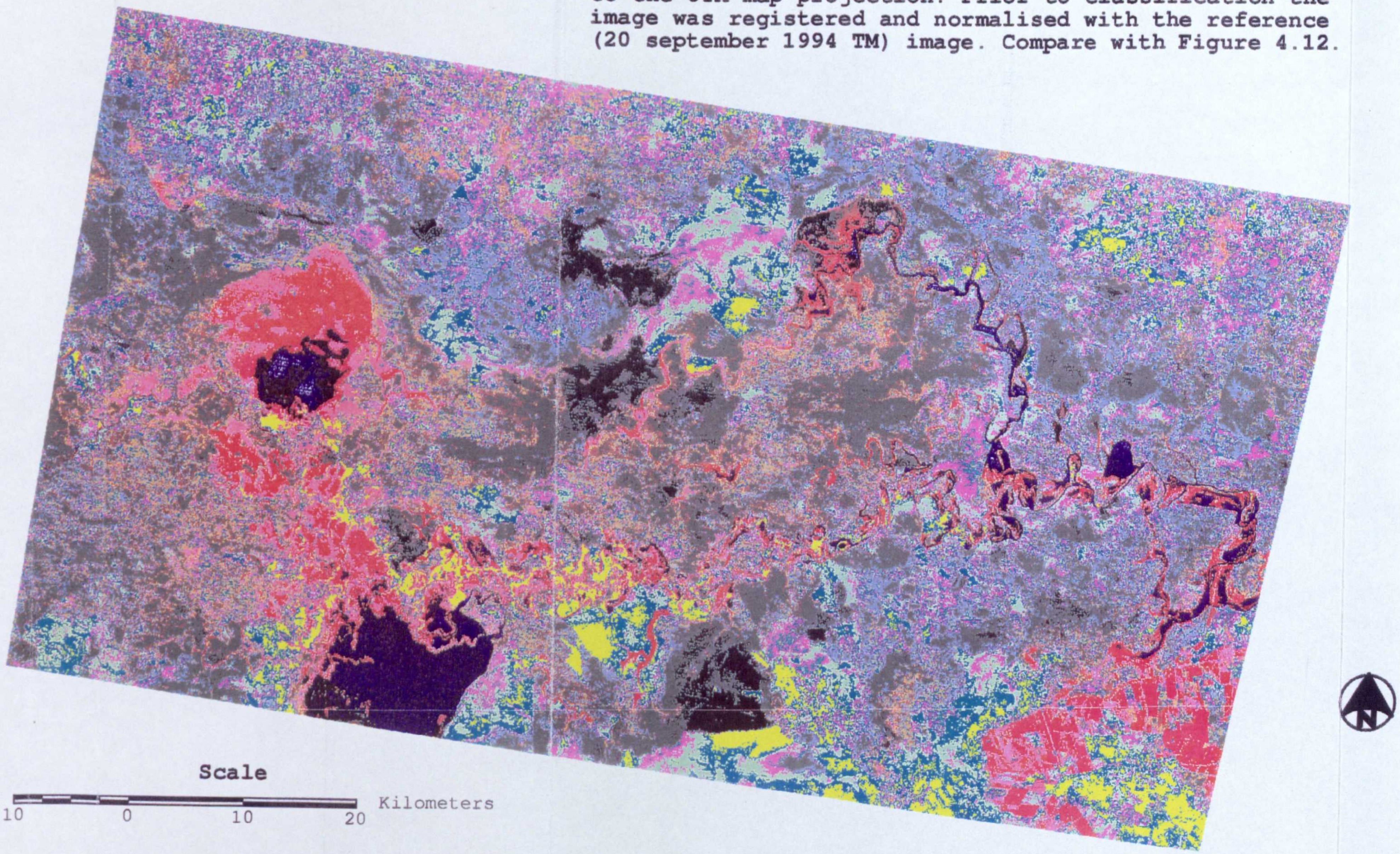


Figure 4.18 The classified 24 September 1984 MSS image, rectified to the UTM map projection. Prior to classification the image was registered and normalised with the reference (20 september 1994 TM) image. Compare with Figure 4.12.



Scale

10 0 10 20 Kilometers

Legend

- Open water
- Dense, very vigorous water reeds/water fringe vegetation
- Dense, vigorous water reeds/water fringe vegetation
- Less dense, stressed water reeds/water fringe vegetation
- Sparse, stressed water reeds/water fringe vegetation
- Mixed, green grassland/woodland vegetation
- Sparse, green grassland/woodland vegetation
- Very sparse, green grassland/woodland vegetation
- Very sparse, green vegetation/termitaria with isolated trees
- Emergent vegetation in shallow water or after burning
- Dry grassland and termitaria zone without trees
- Dryland with leafless plant structures (woodland/grassland)
- Exposed, trampled dry soil with surface debris
- Bare, compacted dry soil
- Burnt area or muddy, dark surface

Chapter 5

IMAGE INTERPRETATION AND THEMATIC INFORMATION EXTRACTION

5.1 Introduction

This chapter details the characteristics of the digital image interpretation categories resulting from the classification of the normalised and co-registered images as described in Section 4.7. The significance of the accuracy of the image classification results is briefly assessed.

5.2 Image Interpretation Classes

On each image, 15 classes were used in the classification (Table 4.11), starting with the reference image (1994 TM). It was assumed that the 15 classes existed on the earlier images as well, although in different relative sizes and spatial location. This means that there was no new land cover class in 1994 that did not exist in 1984, and that all the land cover classes that existed in 1984 still existed in 1994 in some form (qualitative/quantitative). The characteristics of the 15 classes are outlined below. The wetness (and, consequently, green vegetation content) decreases from Class 1 to Class 15. The class spectral signatures (see Figure 5.1 and Appendix 2) on the other images were compared to those on the reference image to find their equivalent. The names of the classes were derived from the descriptions of the field sites whose GPS positions were recorded (see Appendix 3) and located on classified images rectified to the UTM projection (see Section 4.8).

Class 1 - Open Water

The class included deep or shallow water largely free from vegetation cover, in the main river, lagoons, oxbow lakes and pans (see Figures 2.21a, 2.21b, 2.21c, 2.21d, 2.29 and 4.8). The class spectral signature was characterised by low green, red and near infrared reflectance (see Figure 5.1 and Appendix 2; also Figure 1.3).

Class 2 - Dense, Very Vigorous Water Reeds/Water Fringe Vegetation

Included in this class were stands of dense, very vigorous vegetation that thrives in very wet conditions, like *Cyperus papyrus, Typha domingensis, Polygonum senegalense, Vossia cuspidata, Phragmites mauritianus* and sugar cane (see Figure 5.2; also Figures 2.20, 2.21a, 2.21b, 2.21c, 2.21d and 2.25). The spectral signature of the class was characterised by very high near infrared reflectance and relatively low red and green reflectance (see Figure 5.1 and Appendix 2).

Class 3 - Dense, Vigorous Water Reeds/Water Fringe Vegetation

This class was like Class 2 but the vegetation reflected less near infrared radiation either because it was in less than prime growth stage or because of stress due to less water or physical disturbances like grazing (see Figure 5.2).

Class 4 - Less Dense, Stressed Water Reeds/Water Fringe Vegetation

This class was like Class 3 but the vegetation had less near infrared reflectance. Dense woodland in some stands fell in this class. The water reeds and water fringe vegetation in this class was more stressed either by less water or more severe disturbance by grazing or even fire (see Figure 5.3).

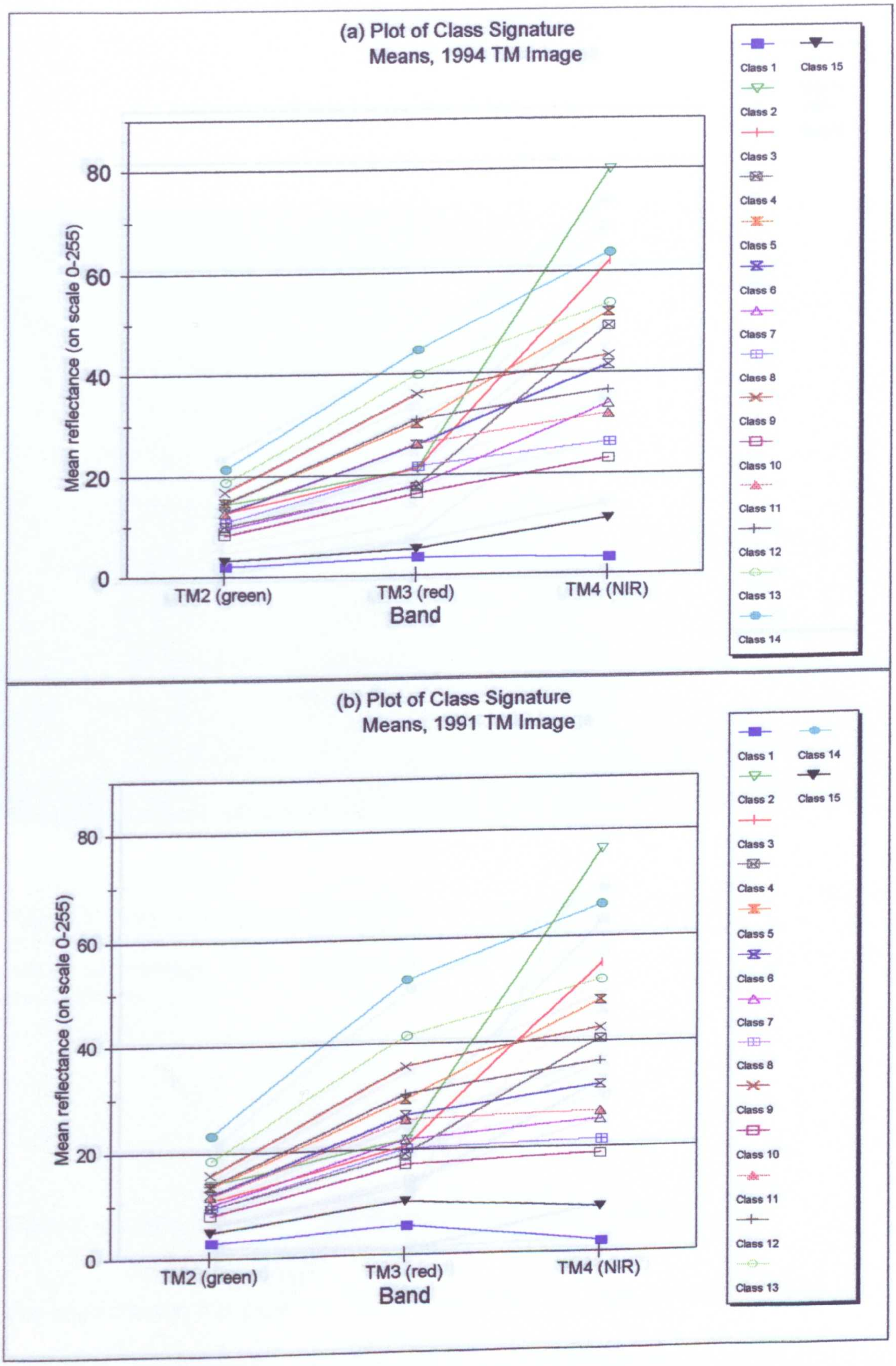


Figure 5.1 Plots of class spectral signature means (see text for class descriptions). For TM images, green = TM2 (0.52-0.60μm), red = TM3 (0.63-0.69μm), near infrared = TM4 (0.76-0.90μm). For MSS images, green = MSS1 (0.50-0.60μm), red = MSS2 (0.60-0.70μm), near infrared (NIR) = MSS4 (0.80-1.1μm).

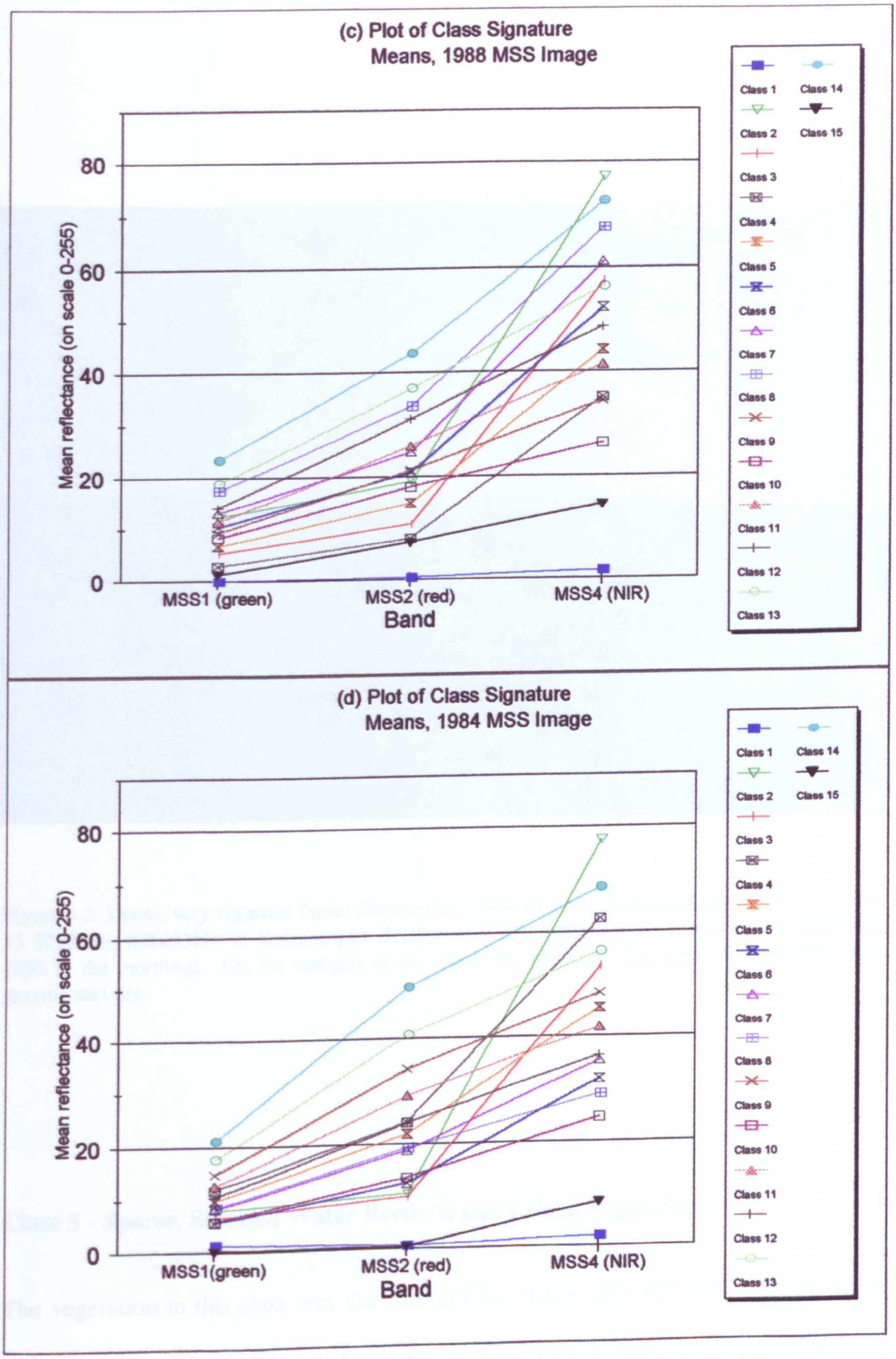


Figure 5.1 (continued) Plots of class spectral signature means (see text for class descriptions). For TM images, green = TM2 (0.52-0.60μm), red = TM3 (0.63-0.69μm), near infrared = TM4 (0.76-0.90μm). For MSS images, green = MSS1 (0.50-0.60μm), red = MSS2 (0.60-0.70μm), near infrared (NIR) = MSS4 (0.80-1.1μm).

Figure 5.2 Dense, very vigorous *Typha Domingensis* reeds in a marsh on the Kafue Flats (UTM grid 35 571744E, 8254536N; at Kabanje just Northwest of Mazabuka, looking Northwest, 9 September 1995 in the morning). On the margins of the marsh the reeds are less dense, disturbed by cattle grazing and fire.

Class 5 - Sparse, Stressed Water Reeds/Water Fringe Vegetation

The vegetation in this class was like that in Class 4 but with increased red and green reflectance (see Figure 5.1 and Appendix 2) from the dry grass and exposed dry soil among the sparse vegetation. The higher proportion of dry soil in Class 5 resulted in

(a)

(b)

Figure 5.3 Less dense and sparse wetland reeds on the Kafue Flats (a) Sparse *Typha domingensis* reeds bordering Luwato Lagoon (UTM grid 35 **560**401E, 82**90**070N looking west, 27 September 1995 at noon). The reeds are near a fishing camp and are annually opened up by cutting and burning by man (see also Figures 4.8 and 5.8b). (b) Less dense *Typha domingensis* reeds bordering a lagoon at Namatusi (UTM grid 35 5**38**523E, 82**59**102N, looking east, 19 September 1995 at noon).

higher near infrared reflectance. Woodland stands which were not reflecting enough near infrared radiation to be included in Class 4 were included in this class.

Class 6 - Mixed Green Grassland/Woodland Vegetation

This class mainly included green floodplain grassland vegetation growing in the moist floodplain left by the retreating flood, and also woodland in leaf (see Figure 5.4). The vegetation in the class had less near infrared or more red reflectance than that in Class 5, either because it was not dense enough (especially in the case of woodland) or because of water stress (especially in the case of grasses, water reeds and other water fringe vegetation) or high grazing pressure (in the case of grasses and reeds eaten by cattle and game). Very young sugar cane also fell in this class.

Class 7 - Sparse, Green Grassland/Woodland Vegetation

This class had composition similar to Class 6 but with higher visible red reflectance (see Figures 5.1 and 5.4, also Appendix 2) because of a higher proportion of dry reddish/brown grass and exposed dry soil. The high red reflectance is especially highlighted by the MSS images.

Class 8 - Very Sparse Green Grassland/Woodland Vegetation

The land cover included in this class had more dry grass, dry trees and exposed dry land (among the little green vegetation) than that in Class 7. The spectral signature was characterised by higher red reflectance (and slightly more green) than in Class 7 (see Figure 5.1 and Appendix 2), coming from the dry reddish/brown features and soil (see Figure 5.4).

(a)

(b)

Figure 5.4 Mixed woodland in spring among dry grass in Blue Lagoon National Park (a) Near Blue Lagoon Lodge (UTM grid 35 **549**043E, 82**91**808N looking south, 28 September 1995 in the afternoon) (b) At UTM grid 35 **541**141E, 82**94**348N looking Northwest, 26 September 1995, 07:30 am. Depending on the reflectance characteristics as detected by the MSS and TM sensor, such woodland was classified into either class 6, 7, 8 or 9 together with grass or reed stands with similar spectral signatures. Site (a) was placed in Class 6 while Site (b) was placed in Class 8. Compare colours with those in Figures 2.15, 2.16, 2.17, 2.18 and 2.22.

Class 9 - Very Sparse Green Vegetation/Termitaria With Isolated Trees

This class included drying grass in the floodplain as well as the dry grass-isolated green trees combination in the termitaria and woodland zones. The spectral signature was therefore characterised by higher visible red and green reflectance, from the reddish/brown dry grass and leaves, than in Class 8 (see Figure 5.1 and Appendix 2).

Class 10 - Emergent Vegetation in Shallow Water or After Burning

This class included sparse vegetation (grass, sedges, reeds) in shallow water (flood water, lagoons, ox-bow lakes or river edges) as well as the fresh, scanty vegetation shoots in dry grass stands subjected to early burning (June/July), resulting in the growth of fresh grass in the period leading up to the image acquisition time in September (spring). These two land cover types were spectrally similar because water, like the black soot in burnt areas, has low reflectance in the near infrared and visible regions of the electromagnetic spectrum. The similarity was enhanced by the shallow nature of some of the water bodies (except river), whose water was laden with suspended clay particles similar in reflectance characteristics to the exposed soil in burnt areas (compare Figures 5.5 and 5.8a). With the green, red and near infrared bands used in the time series (see Section 4.4.4), emergent vegetation in shallow water (see Figure 5.5) was difficult to separate from that emerging after burning (see Figure 5.8a).

Figure 5.5 Partly submerged *Polygonum senegalense* (foreground, right), sedges, *Typha domingensis* reeds (background, top right corner) and floating small plants on Luwato Lagoon (UTM grid 35 560401E, 8290070N, 27 September 1995 at noon).

Class 11 - Dry Grassland and Termitaria Zone Without Trees

This class included dry, tall (20cm - 1.5m) unburnt reddish brown and yellow grass either in the floodplain or termitaria-grassland zone where green vegetation was absent or too scanty to be included in Class 9 (see Figure 5.6). Some woodland stands with dry leaves (among dry grass) and with dry reddish brown structures, such as dry seed pods (see Figure 5.4b), also fell in this class.

(a)

(b)

Figure 5.6 Examples of colour variations in dry grassland on the Kafue Flats (a) Red coloured, ungrazed dry floodplain grass south of Namatusi (UTM grid 35 5**38**542E, 82**57**918N, 19 September 1995, noon, looking east) (b) Brown/yellowish grass (predominantly *Setaria sphacelata*) in the treeless termitaria zone south of Muchabi (UTM grid 35 5**24**962E, 82**84**342N, 25 September 1995, afternoon, looking south west). See also Figure 2.19.

Class 12 - Dry Land With Leafless Plant Structures (Grassland/Woodland)

This class included dry areas not distinctly reddish/brown enough to be included in Class 11. Leafless woodland in areas with exposed dark clay bare patches, as well as scanty tall grasses in similar areas, tended to fall in this class. The interaction of shadows from the tall, leafless woodland trees (or grass reeds) with the dark clay bare patches probably made this class spectrally distinct from either Class 11 or Class 13.

Class 13 - Exposed, Trampled Dry Soil With Surface Debris

This class included dry, bare soil surfaces with scanty, dry grass and tree cover (see Figure 5.7). The land cover type occurred either in game and cattle grazing areas or in human settlement areas. The interaction of surface debris and greyish/brownish clay-loam soils made the surfaces have a predominantly light green colour which appeared light bluish on a Red-Green-Blue false colour composite image (where red represents near infrared, green represents red and blue represents green reflectance).

Class 14 - Bare, Compacted Dry Soil

This class was spectrally distinct from either Class 11, 12 or 13 because it had high reflectance in the near infrared, red and green regions of the electromagnetic spectrum, which made it appear white on a false colour composite image. It was clearly dry with no apparent green vegetation cover (compare this interpretation with the reflectance curves in Figure 1.3). Its dry grass was too short and scanty to be in class 11, but the surface was too bare to be included in Class 13. This resulted in high visible (red +

(a)

(b)

Figure 5.7 Game trampled, compacted soil land cover types in Lochinvar National Park (a) With thorny *Acacia* trees, near Chunga Lagoon (UTM grid 35 525699E, 8250254N looking south east, 18 September 1995, morning) (b) Bare, with scanty, ungrazed drying herbs, just east of Chunga Lagoon (UTM grid 35 526544E, 8250392N, looking east, 18 September 1995, morning). Both sites in the photos are heavily trampled by lechwe.

green) and near infrared reflectance, from the dry soil surface. About this `white zone', Turner (1982) points out that the land cover class was at first interpreted as grass whose leaves and inflorescence had turned brown but still maintained a high infrared reflectance because the stem remains green, adding that the zone moves downslope during the dry season and has a grass cover which is eventually burnt over. Turner (1982) adds that the white colour may be partly due to a growth of algae developed after the grass has began to die down and the soil is exposed. It was thought that this would increase the infrared reflectance, while the visible appearance is light coloured because of the light yellow leaves of the grass. When the algae die the infrared reflectance again declines, and then the area is usually burnt but it was noted that the burning always stops at the edge of the white area, showing that the grasses are too green to burn. According to Turner (1982) this explanation is not entirely satisfactory because the new growth of algae would probably reduce the reflectance in the visible bands, but instead both visible and infrared are extremely high in the white zone. Another possibility is that as the soil dries out, its infrared reflectance increases due to the presence of certain minerals such as Calcium Carbonate and Gypsum (Turner, 1982).

Class 15 - Burnt Area Or Muddy, Dark Surface

This class included primarily burnt areas not old enough to have the characteristics of Class 10 because of a black soot cover. Areas in this class (see Figure 5.8) appeared black on the false colour composite image, but less so than water (Class 1). It was sometimes difficult to separate burnt areas from water, especially deep, open water which has a nearly similar spectral signature (see Figure 5.1 and Appendix 2). When it

(a)

(b)

Figure 5.8 Examples of land cover types created by fire on the Kafue Flats (a) *Compositae* herb among unburnt grass stems in the termitaria-floodplain transition zone south of Muchabi (UTM grid 35 5**23**417E, 82**82**027N, 25 September 1995). The herb is quite frequent per unit area in some places (b) Burnt *Typha domingensis* reeds in Blue Lagoon National Park (UTM grid 35 5**53**490E, 82**90**044N looking Southeast, 28 September 1995, mid morning). Such burnt reeds could be classified as dry grass (Class 11 or Class 12) but may not have been present at this site at image acquisition time.

occurred on the periphery of water bodies where the water would not be expected to be deep, this class characterised muddy, dark clay surfaces without vegetation cover.

5.3 Assessment of Classification Accuracy

Following rectification of the classified reference (20 September 1994 TM) image to the UTM projection, a digital UTM vector file (created as described in Section 4.8) with 82 field sampling sites (Figure 4.13) was draped over the image to investigate the accuracy of the classification of the field sites. Because there is usually some geometric error during rectification, not one but four pixels at each digitised site were investigated to see the classification. The reference image was rectified to the UTM projection with Root Mean Square Error (RMSE) of 0.48 (Table 5.1), which means that each pixel in the rectified image was 0.48 of a pixel (14.4m) away from its true UTM position. In addition, the GPS accuracy was potentially 12m at best (see Section 4.6.1) but about 42m in the field[1], making the total possible deviation of each site from its true UTM position at least 56m (nearly two pixels), hence the need to investigate the four pixels around the site.

The results, summarised in Appendix 3, show that 75 of the 80 `error free sites'[2] were placed in classes whose names characterised the site field descriptions (i.e. all except LV9, LV10, MZW22, BLW6 and BLW16), giving a classification accuracy of 93.7%. When determining whether or not the class assigned to a site was acceptable, the site

[1] The estimated actual accuracy of the GPS in the field was 42m because it gave the UTM co-ordinates of Site MZW1 in Appendix 3 (a road junction site which is clear on a 1:50 000 map) as 65782E, 44851N (excluding the UTM easting and northing prefixes). On a 1:50 000 map the site is at 6575E, 4480N. This deviation is about 32m (easting) and 51m (northing), an average of 41.5m (or 42m).

[2] After image rectification, some of the sites described in the field turned out to be just outside the reference image's cover by a few hundred meters.

Table 5.1 Magnitude of Error in Rectifying Classified Images to the UTM Map Projection

Classified image	Pixel size after rectification	Total Root Mean Square Error
1994 TM	30m	0.48
1991 TM	30m	0.75
1988 MSS	30m	0.38
1984 MSS	30m	0.95

description (column 2 in Appendix 3) was related to the vegetation/aridity hierarchy of the classes as described in Section 5.2. See the `Comments' column in Appendix 3 for specific justification for acceptance or rejection of an assigned class for each site. This assessment was not undertaken for the other images because no ground truthing information was available. However, the classification technique (see Section 4.7) demonstrated enough accuracy to be reliable (see Figures 4.15 - 4.18). Although unable to assign each site to its absolute ground cover zone (without confusing floodplain with woodland green vegetation for example), the classification was able to cluster areas with similar density (and/or vigour) of green vegetation cover or dry land types (an inherent problem in remote sensing is lack of unique spectral signatures - Lillesand and Kiefer, 1994). This was done by analysing their reflectance statistics using a maximum likelihood classifier which assigns a pixel to the class it is most likely to belong to using class signature mean, standard deviation, minimum and maximum value statistics (Jensen, 1986; ERDAS Inc., 1994). The classifier is the most accurate and requires that the data be normally distributed (ERDAS Inc., 1994). The class signature data in this case were normally distributed except for Classes 1 (Open water) and 15 (Burnt area or muddy, dark surface). Although the field site descriptions were mainly qualitative rather than quantitative (see Table 4.9 and Appendix 3), there was broad agreement between field site descriptions and image cover classes for the sites.

5.3.1 Classification Accuracy Assessment Statistics

In order to assess the classification accuracy of features other than the field sample sites, and to assess the accuracy of each of the 15 classes, 255 random pixels (equalised per class, i.e. 17 per class) on the reference (1994) classified image were examined. Ideally these should have been points for which there was known ground cover information for reference (ERDAS Inc., 1994), but inaccessibility of the study area, costs and lack of up to date aerial photographs or maps meant that the reference information was mainly the points' reflectance characteristics as depicted on the original false colour composite image (compared to class signatures) and also the context of their location and the knowledge of the area derived from ground traverses (see Figure 4.14). The May-June 1991 panchromatic aerial photographs (the latest available) were of little use as surrogate ground truth reference data because:

- The contrast of features was too poor for detailed land cover interpretation. Colour photographs would have been more useful for this.
- The photographs covered only sections, and not all, of the area. Only the sections of the Kafue Flats where ground truthing was undertaken (see Section 4.6.1) were covered by the photographs, but the random points generated were from all over

the image area. This made the photographs inadequate as reference data for the 255 random points.

- The photographs were taken in 1991, 3 years before the reference image was acquired. In addition, there was still flood water on the flood plain at the time of photo acquisition. The two facts meant that the difference between the features as they were on the image and photo acquisition dates was large.

The random points were generated using 3x3 pixel windows and, for each window, when a clear majority of 6 class values existed, the class value with the majority was taken as the centre pixel. Therefore the random points were at homogenous sites.

The error matrix generated is shown in Table 5.2, together with the classification accuracy estimates. Congalton (1991) has defined the classification accuracy assessment techniques used as follows (see also Box 5.1):

1. *Producer's accuracy* indicates the probability of a reference pixel being correctly classified and is a measure of omission error. It is called producer's accuracy because the producer of the classification is interested in how well a certain area can be classified.

2. *User's accuracy* on the other hand indicates the probability that a pixel classified on the image actually represents that class on the ground, and is a measure of commission error. It can, therefore, be called *Class accuracy*.

The overall accuracy from the error matrix generated (see Table 5.2) was 72.55%. The source of the majority of classification inaccuracy was Classes 10, 11, 12, 13 and 14; with accuracies of 59%, 47%, 65%, 59% and 59% respectively. In Class 10 (emergent

(i) **Overall Accuracy** = $\frac{\text{total (correctly) classified pixels}}{\text{total number of pixels in error matrix}}$

(ii) **Producer's Accuracy** = $\frac{\text{total (correctly) classified pixels in class}}{\text{total number of pixels in the class as derived from the reference data (i.e. column total)}}$

(iii) **User's Accuracy** = $\frac{\text{total (correctly) classified pixels in class}}{\text{total number of pixels that were classified in the class}}$

(iv) **Kappa Coefficient**

KAPPA is a discrete multivariate technique of use in accuracy assessment. The result of performing a KAPPA analysis is a KHAT statistic, which is a measure of agreement or disagreement. KHAT is computed as follows:-

$$\text{KHAT} = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} * x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+} * x_{+i})} \qquad (5.1)$$

Where:-

r is the number of rows in the matrix
x_{ii} is the number of observations in row i and column i, respectively
x_{i+} and x_{+i} are the marginal totals of row i and column i, respectively
N is the total number of observations

From Table 5.2:

$$\text{KHAT} = [(255 \times 185) - 4335] \div (255)^2 - 4335 = 0.7059$$

Box 5.1 Definitions of Classification Accuracy Assessment Statistics (After Congalton, 1991).

vegetation in shallow water or after burning) there was some confusion with Classes 8 and 9 (sparse green vegetation classes), which can be expected because some emerging vegetation in shallow water or in burnt patches begins to have the reflectance

Table 5.2 Classification Error Matrix for Reference (1994) TM Image

(Rows refer to classified pixels, columns refer to reference pixels. See text for class names and descriptions, and Box 5.1 for definition of statistics).

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	class total	class (user's) accuracy (%)
1	**16**	0	0	0	0	0	0	0	0	0	0	0	0	0	1	17	94
2	0	**14**	3	0	0	0	0	0	0	0	0	0	0	0	0	17	82
3	0	3	**12**	2	0	0	0	0	0	0	0	0	0	0	0	17	71
4	0	0	3	**13**	1	0	0	0	0	0	0	0	0	0	0	17	76
5	0	0	0	1	**14**	0	0	0	2	0	0	0	0	0	0	17	82
6	0	0	0	1	3	**12**	0	1	0	0	0	0	0	0	0	17	71
7	0	0	0	0	1	2	**14**	0	0	0	0	0	0	0	0	17	82
8	0	0	0	0	0	0	0	**15**	0	1	1	0	0	0	0	17	88
9	0	0	0	0	1	0	1	0	**13**	0	0	1	1	0	0	17	76
10	1	0	0	0	0	0	1	2	2	**10**	0	1	0	0	0	17	59
11	0	0	0	0	0	4	1	1	2	0	**8**	1	0	0	0	17	47
12	0	0	0	0	0	0	0	0	3	0	2	**11**	1	0	0	17	65
13	0	0	0	0	3	0	0	0	3	0	1	0	**10**	0	0	17	59
14	0	0	0	0	3	0	0	0	1	0	0	0	3	**10**	0	17	59
15	1	0	0	0	0	0	0	0	0	3	0	0	0	0	**13**	17	76
column total (pixels)	18	17	18	17	26	18	17	19	26	14	12	14	15	10	14	255	
producer's accuracy (%)	89	82	67	76	54	67	82	79	50	71	67	79	67	100	93		

Overall accuracy = 185/255 = 72.55%
Adjusted overall accuracy (see text) = 80%
Overall accuracy for field sites = 93.7%
Mean class (user's) accuracy = 72.47%
KHAT (Kappa coefficient) overall = 0.7059 (i.e. 70.59%)

characteristics of sparse vegetation (there is slight overlap in the range of their signature values in some bands - see Appendix 2). For Classes 11, 12, 13 and 14, the main source of inaccuracy was faint smoke (in localised, small areas, see Figures 4.7 and 4.8) from at least three active fires at the time of acquisition of the 1994 image. The smoke could not be eliminated by the atmospheric correction performed (see Section 4.4.2; Figures 4.7 and 4.11). When the smoke occurred over sparse green vegetation (Classes 5, 6, 7 or 8), the pixels were classified either as Class 11, 12, 13 or 14 depending on the intensity of visible (red or green) reflectance. If Classes 10, 11, 12, 13 and 14 are excluded, the overall classification accuracy using the error matrix in Table 5.2 becomes 80%. The classification technique was, therefore, accurate in terms of the reflectance from the pixels affected by faint smoke, and can, therefore, be said to have been reliable. The other classes all had user's accuracies greater than 70%.

There was some confusion, in many of the classes, between one class and those immediately bordering it in the wetness/greenness hierarchy, as can be expected when there is slight overlap in the ranges of values in the class signatures (see Appendix 2). The overall Kappa coefficient of 0.7059 means that the classification process was avoiding 70.59% of the errors that a completely random classification would generate.

5.3.2 Significance of the Accuracy Assessment Procedure and Results

Congalton (1991) points out that a critical assumption of classification accuracy assessment techniques is that the error matrix is truly representative of the entire classification. He stresses four issues for consideration when generating the error matrix:

1. Ground (reference) data should be available.

2. The classification scheme should have the following provisions:-

   (a) any area to be classified should fall into one and only one category.
   (b) every area should be included in the classification.
   (c) a hierarchical nature.

3. The sample size should be statistical, but what is statistically sound should be balanced with what is practical.

4. Whether the sample used is random, stratified random or equalised random.

The 255 pixels (points) used to generate the error matrix in Table 5.2 were truly representative of the entire classification because they were an equalised random sample, 17 points per class. Although ground data were not available for all of them due to the constraints of inaccessibility, high costs of generating ground data and lack of up to date maps or aerial photographs, the context in which the points occurred, their reflectance characteristics compared to class signatures, and knowledge of the area from the ground truthing traverses served as surrogate reference data. The errors of omission were largest for Classes 9 and 5 (see Table 5.2), meaning that the surrogate data were not adequate for distinguishing sparse, stressed water reeds/water fringe vegetation from very sparse green vegetation/termitaria with isolated trees. For the other classes, producer accuracy was greater than 66%, making the surrogate data fairly adequate for distinguishing these classes.

The classification scheme used assigned each area to one and only one class and, except for very deep, clear water pixels with zero readings in all the three bands used (green, red, near infrared), all pixels were classified (e.g. see Figure 4.17). Zero value pixels were not classified because they were like the image background zeros. Classifying the zeros would have resulted in classifying the image background as well, thereby introducing more errors. However, the 15 classes used (see Section 5.2) were in a wetness/greenness hierarchy. The error matrix generated is, therefore, valid from the view points of Congalton's (1991) considerations (1), (2) and (4).

The requirement that a statistical sample size be used was more difficult to satisfy. Congalton (1991) advises that a good rule of thumb is to collect at least 50 samples for each vegetation and land use category in the error matrix, and if the matrix has more than 12 classes, at least 75-100 samples per class should be used. This would have meant using up to 100 sample points per class, or a total of 1500 points for the 15 classes. This sample size was overwhelming in practice. Jensen (1986) reports the use of the following equation, determined from the formulas for the binomial probability theorem, to calculate the ideal number of sample points:-

$$N = 4(p)(q^{-})/E^{2} \quad (5.2)$$

where: p is the expected percent accuracy

q^{-} is the difference between 100 and p

E is the allowable error

N is the number of points to be sampled

With an expected overall classification accuracy of 85% and an allowable error of 5%, the number of sample points for reliable results, from this formula, should have been 204. The 255 random points are, therefore, acceptable for reliable results, according to this formula.

Acceptable overall classification accuracy depends on predetermined criteria depending on the phenomena being studied (Congalton, 1991; Jensen, 1986). For example, the overall accuracy of land use maps for earth resource management should generally be 85%, and the accuracy must be approximately equal for most categories (Jensen, 1986). From Table 5.2, the overall accuracy of 73% (adjusted to 80%) is close to this and probably acceptable for purposes of mapping the green vegetation content and dryness of the Kafue Flats. With the exception of dry land classes (Classes 10, 11, 12, 13, 14), class accuracy was over 70%. Green vegetation was recognised as green vegetation by the classifier, with slight confusion of the density/vigour status due to slight overlap in the signature value ranges (see Appendix 2) and the presence of faint plumes of smoke at the time of acquisition of the image.

The overall accuracy of 73-80% (and KHAT value of 70.59%) is similar to values reported by other workers. Jensen *et al* (1995) report 81% (with KHAT 73.5%), and Sader *et al* (1991) report 70%. Comparing quantitative (TWINSPAN) to qualitative (subjective) field data gathering techniques and their resulting classification accuracies, Treitz *et al* (1992) report overall accuracies of 70-76% (KHAT 71-77%) from subjective techniques, and 55-61% (KHAT 53.1-58.6%) from quantitative techniques. They conclude that generally applied, objective quantitative analysis of field plot vegetation does not presently offer any advantages over subjective field-plot information for classification of remotely sensed data because the data needed take longer to collect but do not give superior validation accuracies. Sader *et al* (1991) comment that 100% accuracy is unrealistic, and that 70% at regional level could be good enough in the context of cost of alternative ground surveys.

The accuracy assessment performed, therefore, adequately estimates the accuracy of classification and the omission and commission errors in classifying the four images. The errors vary among the four images because the environment was not 100% similar on the five dates but normalisation and using near anniversary dates attempted to minimise temporal differences.

Chapter 6

CHANGE DETECTION RESULTS

6.1 Introduction

This chapter presents the results of the change detection analysis performed on the multi-temporal image data. The first part of the chapter outlines the results from the Classification Comparisons change detection method. In the second part of the chapter supplementary change detection results from the Normalised Difference Vegetation Index (NDVI) and Principal Component Analysis (PCA) techniques are outlined.

6.2 Land Cover Trends in the Whole Study Area

The sizes of the areas covered by each of the land cover classes into which the images were classified for change detection analysis (Section 5.2) are shown in Table 6.1, together with percentages of change in each of the respective classes between successive image dates. The largest area of the Kafue Flats and nearby woodland common to all images was used, because the images were co-registered.

From Table 6.1, the classes fluctuated in size between successive image dates, with no class showing a consistent trend of either increasing or reducing in area of coverage on the ground. The figures for Classes 1 and 15 are unreliable because of non uniqueness of spectral signatures of deep, open water and freshly burnt areas on one hand, and some stands of emergent vegetation in water and fresh shoots or unburnt green vegetation in burnt areas on the other (see Sections 5.2 and 5.3).

Table 6.1 Area of Land Cover Classes on the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

Class	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) ÷ 10 000m^{2}ha^{-1}]				%Change between successive image dates		
	24 September 1984	3 September 1988	12 September 1991	20 September 1994	1984-1988	1988-1991	1991-1994
1	9 556.9	7 690.2	8 247.6	6 564.9	-19.5	7.2	-20.4
2	4 994.9	11 915.7	4 280.2	4 959.5	138.6	-64.1	15.9
3	17 153.7	13 684.1	12 934.5	15 305.3	-20.2	-5.5	18.3
4	13 690.0	23 741.2	18 150.8	19 564.8	73.4	-23.5	7.8
5	20 207.4	27 996.3	17 501.1	30 429.5	38.5	-37.5	73.9
6	24 236.7	35 294.1	48 776.9	35 849.9	45.6	38.2	-26.5
7	30 823.4	36 794.1	45 521.0	31 514.5	19.4	23.7	-30.8
8	37 392.4	27 419.4	45 592.7	38 839.0	-26.7	66.3	-14.8
9	45 588.9	39 746.2	35 559.4	38 288.1	-12.8	-10.5	7.7
10	86 767.9	52 804.5	48 204.1	62 345.9	-39.1	-8.7	29.3
11	39 267.0	41 772.2	37 039.1	45 915.1	6.4	-11.3	24.0
12	40 368.2	38 254.3	45 784.0	39 159.4	-5.2	19.7	-14.5
13	31 760.8	27 484.7	28 099.5	34 401.3	-13.5	2.2	22.4
14	14 763.3	21 289.3	13 156.9	19 463.2	44.2	-38.2	47.9
15	18 710.3	29 394.5	26 433.0	12 680.4	57.1	-10.0	-52.0
Total	435 280.8	435 280.8	435 280.8	435 280.8			

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 15 = Burnt area or muddy, dark surface

The classes shown in Table 6.1 were regrouped and recoded as shown in Table 6.2, in order to see if consistent trends would emerge and for analysis of any emerging trends in a GIS frame work. Determining trends was necessary in order to establish whether or not the large inter image changes observed (Table 6.1) fitted in a particular long term pattern and, therefore, whether or not the wetland was undergoing a degradation trend. The new land cover categories are broader, with more distinct spectral signatures. For example, there was very little confusion between pixels in classes assigned to the dense green vegetation category and those in the dry grassland, woodland and exposed soil category (see Table 5.2).

Table 6.2 Recoded Land Cover Class Categories

(a) New class categories

Category		Old classes included (see Table 6.1)
1	Open water	1
2	Dense green vegetation	2, 3, 4
3	Sparse green vegetation	5, 6, 7
4	Very sparse green vegetation	8, 9, 10
5	Dry grassland, woodland, exposed soil	11, 12, 13, 14
6	Burnt or muddy area	15

(b) Size of area covered by new class categories: September 1984, 1988, 1991 and 1994

		Area covered by class (hectares) [Area = (No. pixels x 30m x 30m) + 10 000m^{2}ha^{-1}]				**% Change between successive image dates**		
Category		**20 Sept. 1984**	**3 Sept. 1988**	**12 Sept. 1991**	**20 Sept. 1994**	**1984-1988**	**1988-1991**	**1991-1994**
1	**Open water**	**9 556.9**	**7690.2**	**8 247.6**	**6 564.9**	**-19.5**	**7.2**	**-20.4**
2	**Dense green vegetation**	**35 838.6**	**49 341.0**	**35 365.5**	**39 829.6**	**37.7**	**-28.3**	**12.6**
3	**Sparse green vegetation**	**75 267.5**	**100 084.5**	**111 799.0**	**97 793.9**	**33.0**	**11.7**	**-12.5**
4	**Very sparse green vegetation**	**169 749.2**	**119 970.1**	**129 356.2**	**139 473.0**	**-29.3**	**7.8**	**7.8**
5	**Dry grassland, woodland, exposed soil**	**126 159.3**	**128 800.5**	**124 079.5**	**138 939.0**	**2.10**	**-3.7**	**12.0**
6	**Burnt or muddy area**	**18 710.3**	**29 394.5**	**26 433.0**	**12 680.4**	**57.1**	**-10.1**	**-52.0**
	Total	**435 280.8**	**435 280.8**	**435 280.8**	**435 280.8**			

From Table 6.2, the sizes of the new land cover categories do not show consistent increasing or decreasing trends either, as illustrated in Figure 6.1.

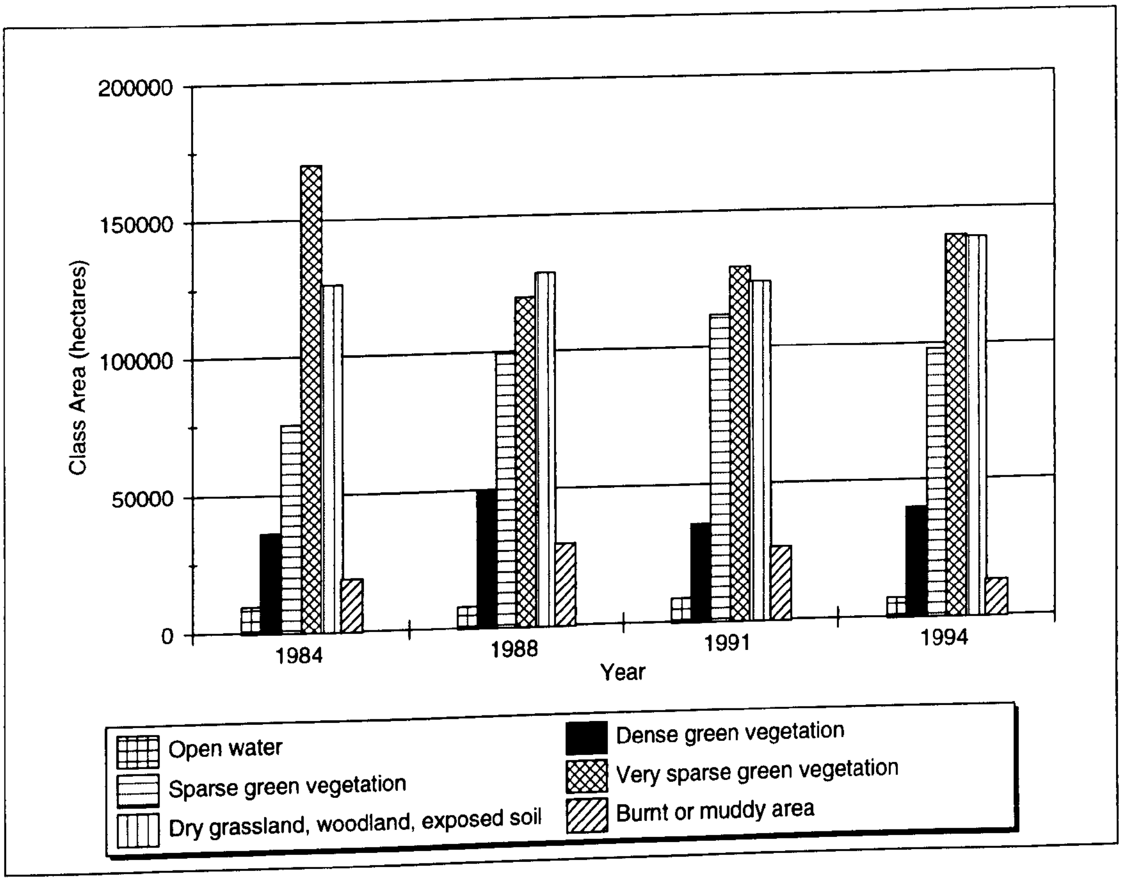


Figure 6.1 Trends in area of recoded land cover classes on the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

During the time of the year when the images were acquired (dry season), a distinct characteristic of the Kafue Flats which distinguishes the area as a wetland is the dense, green vegetation which the surrounding upland does not have except in isolated woodland stands (sparse green vegetation found on the flood plain is also present in the surrounding woodland). To see where spatial extent of this category of land cover was changing, dense green vegetation (see Table 6.2a) from the 1984, 1988, 1991 and

1994 images was recoded as 1, 2, 3 and 4, respectively, and all other classes on the respective images recoded to zero. These unique codes enabled overlaying of the maps of dense green vegetation from the respective years in a GIS framework to produce a change map. The resulting change map (Figure 6.2) shows that there was loss of dense green vegetation in upstream parts of the study area west and north-west of Nyimba. Areas downstream of Nyimba are affected by backing up of water from the Kafue Gorge dam (see Section 2.7.1) and appear to have undergone very little change.

Sparse green vegetation on the images was recoded as 5, 6, 7 and 8 for 1984, 1988, 1991 and 1994 images, respectively, to enable overlaying of the raster images in a GIS framework. The resulting change map for sparse vegetation (Figure 6.3) shows that areas from which 24 September 1984 dense green vegetation was lost (Figure 6.2) were covered by sparse green vegetation on 20 September 1994. Most of this degradation of dense green vegetation occurred upstream of Nyimba. Very sparse green vegetation appears to have increased consistently from 1988 to 1994, whereas burnt land reduced consistently in the same period (Table 6.2b, Figure 6.1). The area covered by dry grassland, woodland and exposed soil was highest in 1994, and, with the exception of a slight reduction in 1991, was increasing in the period leading up to 1994.

Statistically, however, these trends are not significantly linear (Table 6.3). The equation for Class 1 (Open water) has a high coefficient of determination (r^2) but is unreliable because of confusion of spectral signature of water with that of burnt land (see Section 5.2).

Figure 6.2 A change detection map of September dense green vegetation on the Kafue Flats. The map is an overlay of dense green vegetation thematic files from the 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994 images.

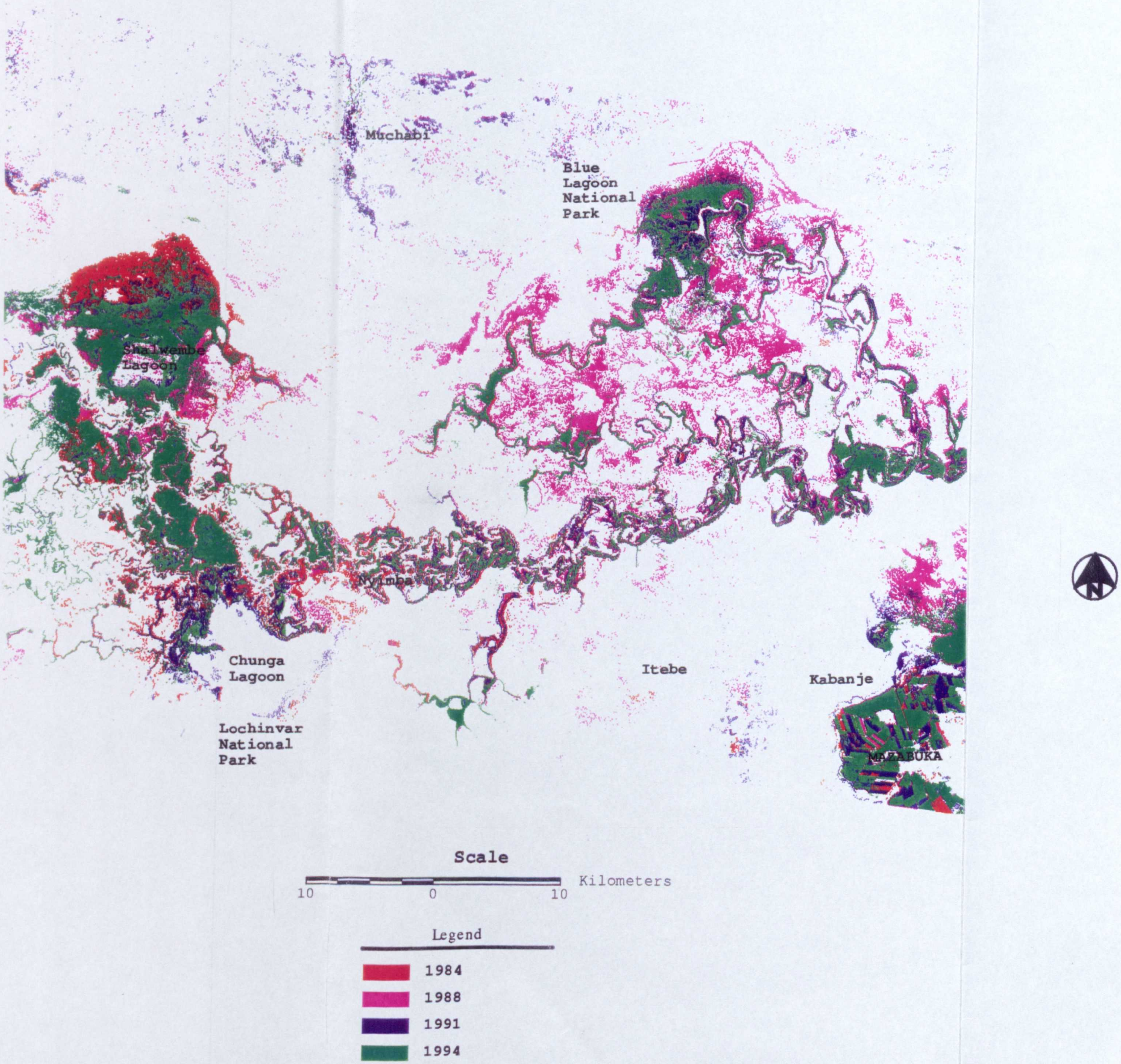


Figure 6.3 A change detection map of September sparse green vegetation on the Kafue Flats. The map is an overlay of sparse green vegetation thematic files from the 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994 images.

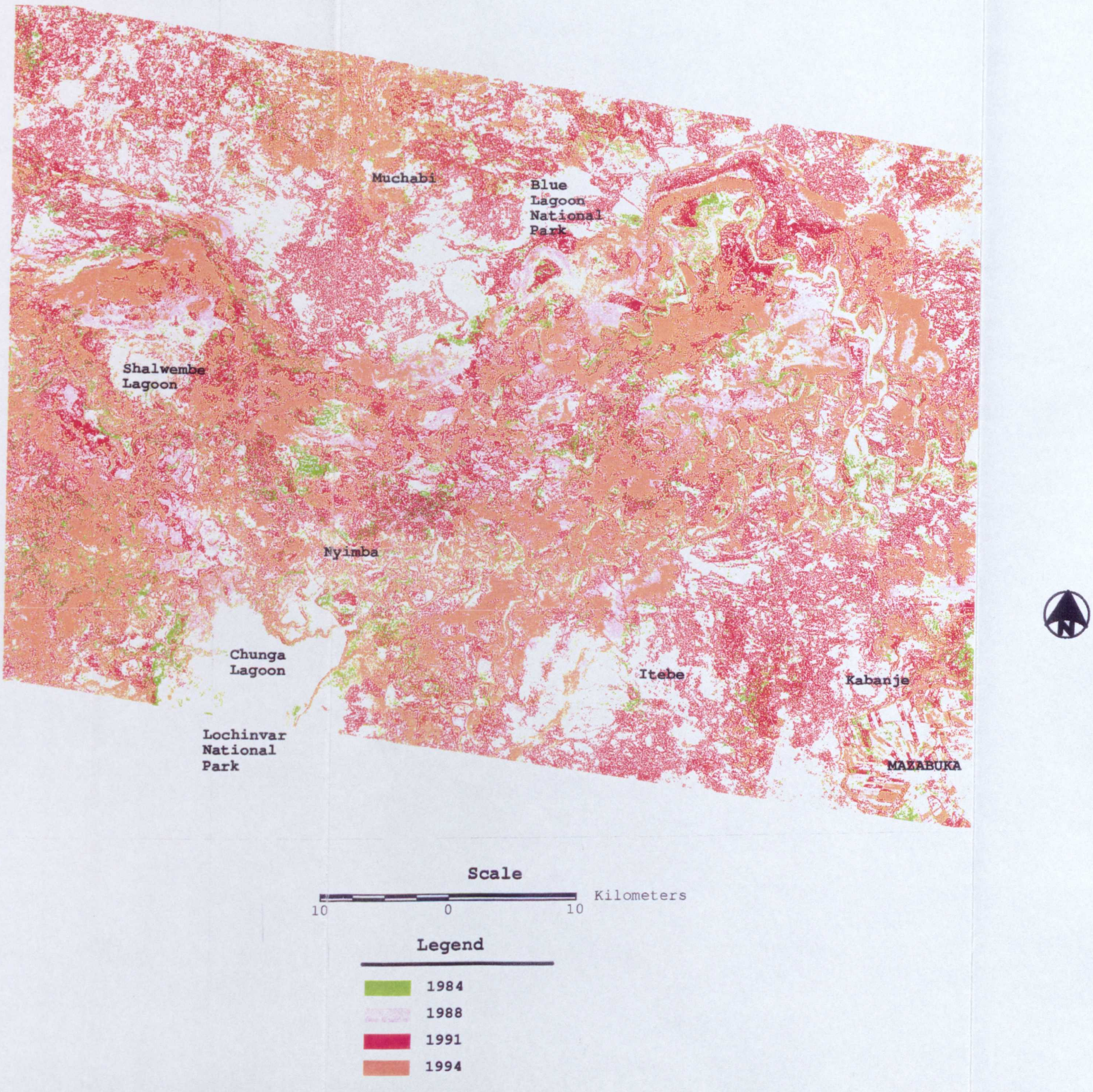


Table 6.3 Regression Analysis of Changes in Land Cover Classes on the Kafue Flats: September 1984, 1988, 1991 and 1994

(a) Original Classes

Regression Equation	Coefficient of Determination (r^2) (%)	Probability	Significance (at 5% level)[1]
Class 1 = 522 664 - 259 Year*	79.0	0.111	not significant
Class 2 = 372 420 - 184 Year	04.8	0.782	not significant
Class 3 = 444 465 - 216 Year	24.3	0.507	not significant
Class 4 = -822 249 + 423 Year	19.0	0.564	not significant
Class 5 = -1 214 312 + 623 Year	18.6	0.568	not significant
Class 6 = -3 026 349 + 1539 Year	42.9	0.345	not significant
Class 7 = -746467 + 393 Year	06.1	0.752	not significant
Class 8 = -1 186 683 + 615 Year	12.3	0.650	not significant
Class 9 = 1 672 145 - 821 Year	68.5	0.172	not significant
Class 10 = 5 186 880 - 2576 Year	40.9	0.360	not significant
Class 11 = -850 916 + 448 Year	25.3	0.497	not significant
Class 12 = -190 835 + 116 Year	02.2	0.853	not significant
Class 13 = -386 684 + 210 Year	07.6	0.724	not significant
Class 14 = -395 425 + 207 Year	05.3	0.769	not significant
Class 15 = 1 056 670 - 520 Year*	08.6	0.706	not significant

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 15 = Burnt area or muddy, dark surface

[1] The null hypothesis is that the slope of the regression is not significantly different from zero (i.e. the regression is not significantly linear). If the calculated probability (of this being true) is greater than 5% (0.05), the null hypothesis is accepted and it is concluded that the regression's slope does not significantly differ from zero and, therefore, the regression equation is not statistically significant at 5%. If the calculated probability is less than 5%, the null hypothesis is rejected.

* Unreliable due to confusion of spectral signature between freshly burnt areas and deep, clear water pixels

Table 6.3 Regression Analysis of Changes in Land Cover Classes on the Kafue Flats, September 1984, 1988, 1991 and 1994

(b) Recoded Classes (see Table 6.2)

Regression Equation	Coefficient of Determination (r^2) (%)	Probability	Significance (at 5% level)[1]
Category 2 = -5 371 + 23 Year	0	0.985	not significant
Category 3 = -4 987 134 + 2 555 Year	51.1	0.285	not significant
Category 4 = 5 672 326 - 2 781 Year	30.3	0.450	not significant
Category 5 = -1 823 874 + 982 Year	40.6	0.363	not significant

(Equations for Categories 1 and 6 as in Table 6.3a for Classes 1 and 15, respectively).

Where:

Category 1 = Open water
Category 2 = Dense green vegetation
Category 3 = Sparse green vegetation
Category 4 = Very sparse green vegetation
Category 5 = Dry grassland, woodland, exposed soil
Category 6 = Burnt or muddy area

6.3 Land Cover Trends in Subsections of the Study Area

The lack of significant trends in land cover change in the entire study area (Section 6.2) may have been because of offsets by way of losses in a particular land cover class in one part of the study area and gains in the class in other parts. To see if there were any consistent trends in localised sections, the images were divided into four contiguous subsections (Figure 6.4) which were analysed separately. The subsections were:

1. Blue Lagoon West, chosen in order to isolate the upstream area which showed the largest losses in dense green vegetation (Figure 6.2).
2. Blue Lagoon, chosen in order to isolate Blue Lagoon National Park and surrounding grazing land.

[1] See Footnote 1 on the previous page.

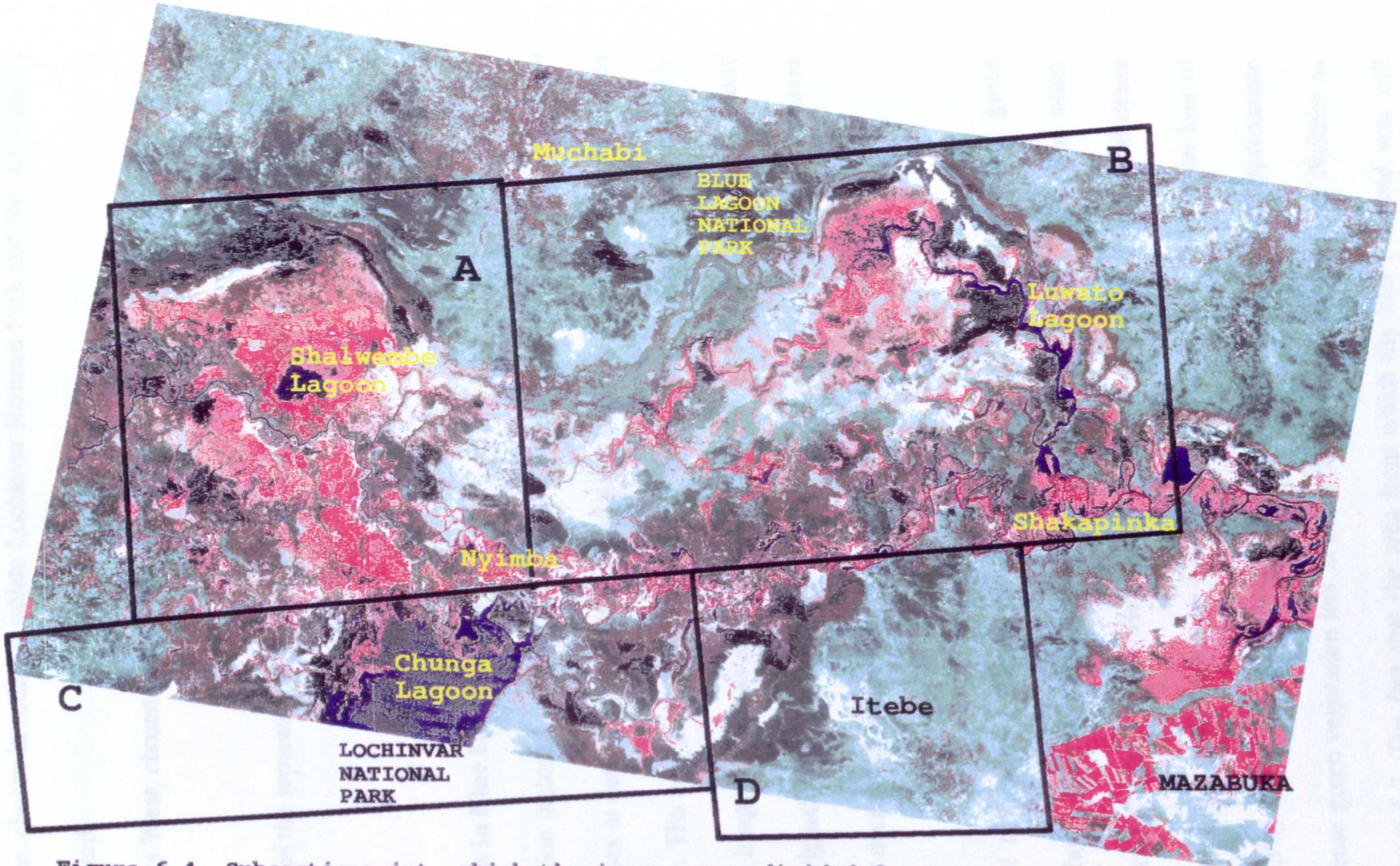


Figure 6.4 Subsections into which the images were divided for separate analysis of change: A. Blue Lagoon West, B. Blue Lagoon, C. Lochinvar, D. Mazabuka West. The illustration is on the classified, rectified 20 September 1994 image (Figure 4.15), using the colours on the original image (Figure 4.7) except for water (in blue).

3. Lochinvar, chosen in order to isolate Lochinvar National Park and the surrounding grazing land.
4. Mazabuka West, chosen in order to isolate a predominantly woodland area.

The results of the separate analyses of change, for the subsections, will be presented in turn.

6.3.1 **Trends in Blue Lagoon West**

This subsection included the area west and north-west of Nyimba (Figure 6.4) which revealed losses in dense green vegetation and gains in sparse green vegetation (Figures 6.2 and 6.3). The area covered by the original and recoded land cover classes (Table 6.2a) on the image dates is as shown in Table 6.4. As in the case of the entire study area, the original land cover classes in this subsection do not show consistent increasing or decreasing trends between successive image dates (Table 6.4a).

The areas of the recoded classes are as shown in Table 6.4b. Very sparse green vegetation shows a consistent decreasing trend between 1984 and 1994. The other classes underwent mixed trends. However, compared to 19 493.2 hectares of dense green vegetation in 1984, there were only 16 899.7 hectares in 1994, a total loss of 2 593.5 (13.3%) in spite of gains in the intervening period. This is the approximate amount of dense green vegetation lost in the area west and north-west of Nyimba as shown in Figure 6.2. The fact that the area from which the loss occurred was still without dense green vegetation in 1994 in spite of gains in the intervening period indicates that the gains were in downstream areas, perhaps in lagoons with falling water levels, leaving sufficiently moist areas for dense vegetation to thrive in. Sparse green vegetation increased by 3 879.4 hectares (18.7%) from 20 767.4 hectares in 1984 to 24 646.8 hectares in 1994, following increases and decreases in the intervening period. The Changes are illustrated in Figure 6.5.

Table 6.4 Area and Trends in Area of Land Cover Classes in the Blue Lagoon West Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(a) Original Land Cover Classes

	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) ÷ 10 000m^{2}ha^{-1}]				% Change between successive image dates		
Class	**24 Sept. 1984**	**3 Sept. 1988**	**12 Sept. 1991**	**20 Sept. 1994**	**1984-1988**	**1988- 1991**	**1991-1994**
1	**1 372.7**	**20.5**	**110.3**	**560.2**	**-98.5**	**438.2**	**407.7**
2	**1 606.5**	**6 834.6**	**989.2**	**1 361.5**	**235.4**	**-85.5**	**37.6**
3	**10 020.7**	**606.0**	**5 238.8**	**8 154.1**	**-94.0**	**764.5**	**55.6**
4	**7 866.0**	**829.7**	**3 372.7**	**7 384.1**	**-89.5**	**306.5**	**118.9**
5	**5 945.0**	**1 260.6**	**5 026.1**	**9 569.6**	**-78.8**	**298.7**	**90.4**
6	**6 570.2**	**9 558.8**	**9 964.7**	**7 888.6**	**45.5**	**4.2**	**-20.8**
7	**8 252.2**	**17 112.1**	**9 418.1**	**7 188.8**	**107.4**	**-45.0**	**-23.7**
8	**5 091.6**	**14 097.2**	**8 328.3**	**4 793.6**	**176.9**	**-40.9**	**-42.4**
9	**4 040.1**	**2 972.7**	**4 353.1**	**2 469.6**	**-26.4**	**46.4**	**-43.3**
10	**13 525.2**	**4 562.2**	**8 402.9**	**11 517.8**	**-66.3**	**84.2**	**37.1**
11	**3 732.3**	**2 934.6**	**8 170.7**	**4 408.0**	**-21.4**	**178.4**	**-46.1**
12	**6 036.1**	**3 878.0**	**7 328.8**	**3 197.3**	**-35.8**	**89.0**	**-56.4**
13	**2 954.5**	**4 423.5**	**3 733.7**	**5 848.0**	**49.7**	**-15.6**	**56.6**
14	**2 380.5**	**9 498.6**	**2 832.5**	**3 484.2**	**299.0**	**-70.2**	**23.0**
15	**2 247.6**	**3 052.1**	**4 371.3**	**3 815.8**	**35.8**	**43.2**	**-12.7**
Total	**81 641.2**	**81 641.2**	**81 641.2**	**81 641.2**			

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 15 = Burnt area or muddy, dark surface

Table 6.4 Area and Trends in Area of Land Cover Classes in the Blue Lagoon West Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(b) Recoded Land Cover Classes

Category		Area covered by class (hectares) [Area = (No. pixels x 30m x 30m) ÷ 10 000m²ha⁻¹]				% Change between successive image dates		
		24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	1984-1988	1988-1991	1991-1994
1	Open water	1 372.7	20.5	110.3	560.2	-98.5	438.2	407.7
2	Dense green vegetation	19 493.2	8 270.3	9 600.7	16 899.7	-57.6	16.1	76.0
3	Sparse green vegetation	20 767.4	27 931.5	24 409.0	24 646.8	34.5	-12.6	1.0
4	Very sparse green vegetation	22 656.9	21 632.1	21 084.3	18 781.2	-4.5	-2.5	-10.9
5	Dry grassland, woodland, exposed soil	15 103.4	20 734.7	22 065.6	16 937.5	37.3	6.4	-23.2
6	Burnt or muddy area	2 247.6	3 052.1	4 371.3	3 815.8	35.8	43.2	-12.7
	Total	81 641.2	81 641.2	81 641.2	81 641.2			

6.3.2 Trends at Lochinvar

The Lochinvar subsection included Chunga Lagoon, the lagoon and river fringe dense reeds immediately north (near Nyimba) and west, and the floodplain area to the east of Chunga Lagoon but west of Itebe (Figure 6.4). The area covered by the land cover classes is as shown in Table 6.5.

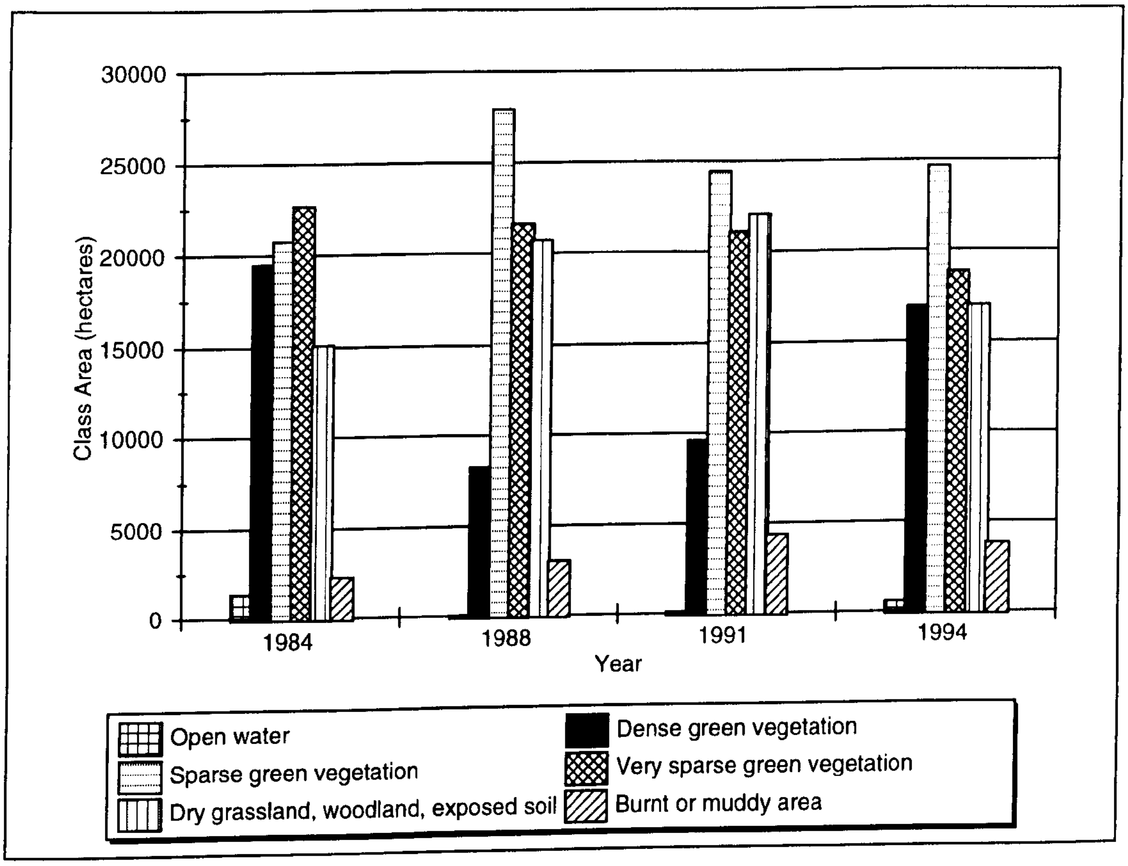


Figure 6.5 Trends in area of recoded land cover classes in the Blue Lagoon West subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

The area covered by the land cover classes fluctuated from year to year. The 1988 image showed faint smoke over Chunga Lagoon (see Figure 4.11), which resulted in the spectral signature of the water being distorted towards that of features highly reflective in the visible region of the electromagnetic spectrum and, consequently, very little water was delineated. The spectral signature of the flood plain west and east of the lagoon was similarly distorted into non-vegetated categories (dry grassland, woodland, exposed soil), even though there was sparse green vegetation (compare Figures 4.17 and 4.11).

Table 6.5 Area and Trends in Area of Land Cover Classes in the Lochinvar Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(a) Original Land Cover Classes

Class	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) + 10 000m²ha⁻¹] 24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	% Change between successive dates 1984-1988	1988- 1991	1991-1994
1	5504.0	*6.7	4 394.6	3 524.3	*-99.9	*	-19.8
2	212.0	428.2	69.4	39.3	102.0	-83.8	-43.1
3	1 694.0	302.0	856.1	487.4	-82.2	183.5	-39.9
4	1 554.6	300.5	1 942.4	1 264.4	-80.7	546.4	-34.9
5	1 830.8	527.7	579.1	2 091.6	-71.2	9.7	261.2
6	1 928.9	2 310.5	3 465.1	3 159.3	19.8	50.0	-8.8
7	1 971.9	5 021.9	2 925.4	4 942.4	154.7	-41.7	68.9
8	2 147.0	6 579.0	3 396.2	2 403.7	206.4	-43.4	-29.2
9	3 203.4	763.8	2 863.5	2 102.6	-76.2	274.9	-26.6
10	6 722.7	7 829.2	3 447.4	11 912.6	16.5	-56.0	245.6
11	2 016.8	1 252.4	3 604.6	1 520.4	-37.9	187.8	-57.8
12	1 745.9	2 488.8	3 733.0	678.2	42.6	50.0	-81.8
13	4 273.3	7 821.7	3 122.1	3 297.9	83.0	-60.1	5.6
14	3 224.2	6 834.2	3 186.5	2 801.3	112.0	-53.4	-12.1
15	4 355.6	206.5	4 392.8	1 980.1	-95.3	2 027	-54.9
0	10 743.2	10 455.2	11 150.0	10 922.8			
Total	53 128.3	53 128.3	53 128.3	53 128.3			

(*unreliable - see text)

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 15 = Burnt area or muddy, dark surface
Class 0 = Image background and Zero value pixels in burnt areas

Table 6.5 Area and Trends in Area of Land Cover Classes in the Lochinvar Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991and 20 September 1994.

(b) Recoded Land Cover Classes

Category		Area covered by class (hectares) [Area = (No. pixels x 30m x 30m) ÷ 10 000m²ha⁻¹]				% Change between successive image dates		
		24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	1984-1988	1988-1991	1991-1994
1	Open water	5 504.0	*6.7	4 394.6	3 524.3	*-99.9	*	-19.8
2	Dense green vegetation	3 460.6	1 030.7	2 867.9	1 791.1	-70.2	178.2	-37.5
3	Sparse green vegetation	5 731.6	7 860.1	6 969.6	10 193.3	37.1	-11.3	46.3
4	Very sparse green vegetation	12 073.1	15 171.9	9 707.2	16 418.9	25.7	-36.0	69.1
5	Dry grassland, woodland, exposed soil	11 260.2	18 397.2	13 646.2	8 297.8	63.4	-25.8	-39.2
6	Burnt or muddy area	4 355.6	206.5	4 392.8	1 980.1	-95.3	2 027	-54.9
	Background and zeros	10 743.2	10 455.2	11 150.0	10 922.8			
	Total	53 128.3	53 128.3	53 128.3	53 128.3			

(*unreliable - see text)

The area of dense green vegetation was highest in 1984 (3 460.6 hectares), but only 1 791.1 hectares were present in 1994. Although there was a mixture of increase and decrease in this vegetation category in the period between, this loss amounted to 1 669.5 hectares (48.2%). Sparse green vegetation increased by 4 461.7 hectares (77.8%) from 5 731.6 hectares in 1984 to 10 193.3 hectares in 1994, after a mixed trend intervening period, and very sparse green vegetation increased by 4 345.8 hectares (36%) in the same period. These changes are illustrated in Figure 6.6.

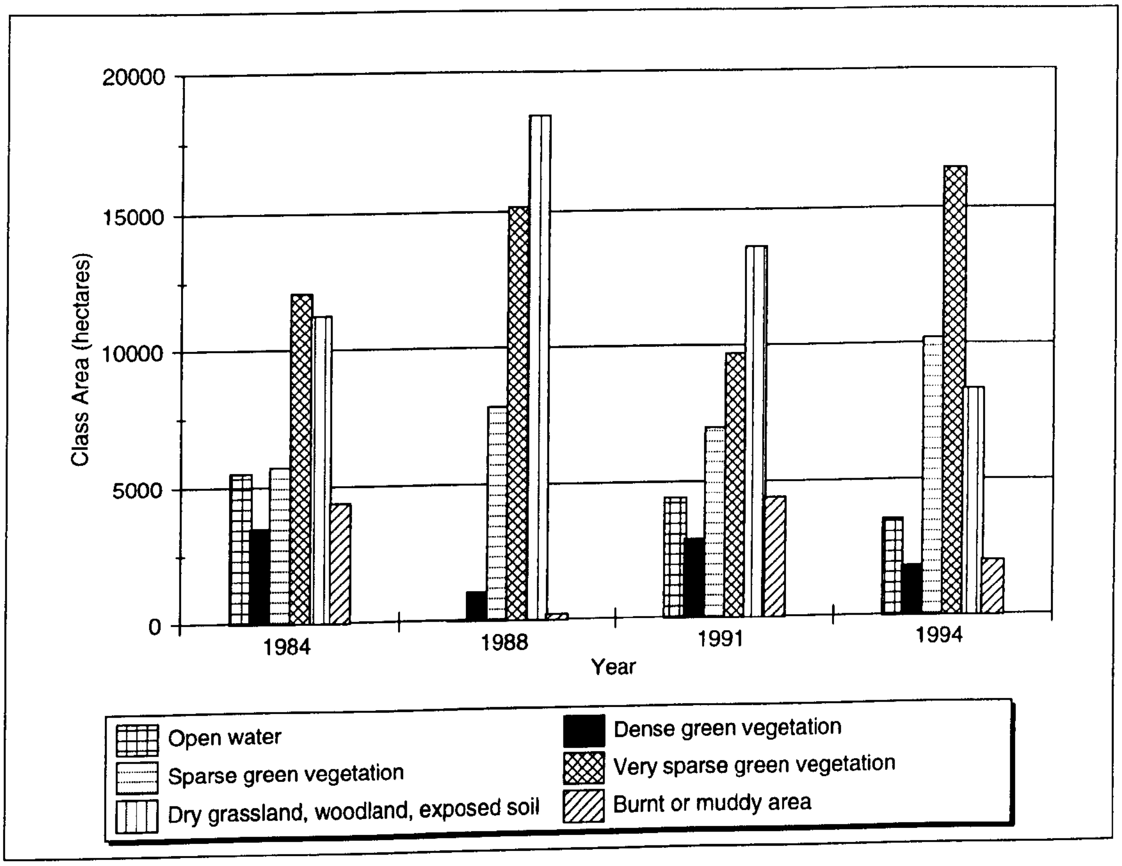


Figure 6.6 Trends in area of recoded land cover classes in the Lochinvar Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

6.3.3 Trends in the Blue Lagoon Area

The Blue Lagoon subsection stretched from the woodland area just south of Muchabi, across the flood plain and dense water fringe vegetation zone around Luwato Lagoon in the east, across the flood plain down to Shakapinka (north-west of Mazabuka) and west in the river and lagoon zone east of Nyimba (Figure 6.4). The area of cover of each of the land cover classes is shown in Table 6.6.

Table 6.6 Area and Trends in Area of Land Cover Classes in the Blue Lagoon Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(a) Original Land Cover Classes

Class	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) ÷ 10 000m²ha⁻¹] 24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	% Change between successive image dates 1984-1988	1988-1991	1991-1994
1	2 239.7	4 693.8	2 571.3	2 113.3	109.6	-45.2	-17.8
2	428.9	1 262.6	167.9	891.2	194.4	-86.7	430.8
3	3 421.9	10 147.0	3 303.7	3 525.6	196.5	-67.4	6.7
4	1 305.2	16 344.7	8 030.2	7 359.8	1 152	-50.9	-8.3
5	5 294.3	20 741.8	6 402.5	13 970.7	291.8	-69.1	118.2
6	10 579.1	16 345.1	15 676.4	13 031.4	54.5	-4.1	-16.9
7	10 078.5	8 571.4	16 918.7	9 559.4	-15.0	97.4	-43.6
8	13 323.6	3 659.0	17 538.0	12 628.9	-72.5	379.3	-28.0
9	14 732.2	12 792.7	10 040.6	10 847.0	-13.2	-21.5	8.0
10	38 440.4	13 308.4	18 740.2	17 727.3	-65.4	40.8	-5.4
11	13 095.8	12 408.3	12 124.1	15 769.4	-5.2	-2.3	30.1
12	12 840.8	6 826.0	13 504.8	11 105.8	-46.8	97.8	-17.8
13	6 796.0	1 601.6	5 979.2	13 925.5	-76.4	273.3	132.9
14	2 192.1	1 290.0	2 573.8	5 843.2	-41.2	99.5	127.0
15	8 401.4	11 404.2	9 727.5	5 000.1	35.7	-14.7	-48.6
0	216.6	1989.9	87.9	87.9			
Total	143 386.5	143 386.5	143 386.5	143 386.5			

Where: Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 15 = Burnt area or muddy, dark surface
Class 0 = Zero value pixels

As in the case of the Blue Lagoon West and Lochinvar subsections, the land cover classes in the Blue Lagoon subsection do not show consistent increasing or decreasing trends in area of cover. Dense green vegetation increased by 6 620.6 hectares (128%)

Table 6.6 Area and Trends in Area of Land Cover Classes in the Blue Lagoon Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(b) Recoded Land Cover Classes

Category	Area covered by class (hectares) [Area = (No. pixels x 30m x 30m) ÷ 10 000m^2ha^{-1}] 24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	% Change between successive image dates 1984-1988	1988-1991	1991-1994
1 Open water	2 239.7	4 693.8	2 571.3	2 113.3	109.6	-45.2	-17.8
2 Dense green vegetation	5 156.0	27 754.3	11 501.8	11 776.6	438.9	-58.6	2.4
3 Sparse green vegetation	25 951.9	45 658.3	38 997.6	36 561.5	75.9	-14.6	-6.2
4 Very sparse green vegetation	66 495.6	29 760.1	46 318.5	41 203.2	-55.2	55.6	-11.0
5 Dry grassland, woodland, exposed soil	34 925.3	22 125.9	34 181.9	46 643.5	-36.6	55.5	36.5
6 Burnt or muddy area	8 401.4	11 404.2	9 727.5	5 000.5	35.7	-14.7	-48.6
Background and zeros	216.6	1989.9	87.9	87.9			
Total	143 386.5	143 386.5	143 386.5	143 386.5			

from 5 156 hectares in 1984 to 11 776.6 hectares in 1994, while sparse green vegetation increased by 10 609.6 hectares (40.9%) from 25 951.9 to 36 561.5 hectares (Table 6.6b). The main decrease in the same time period was in very sparse green vegetation which covered 66 495.6 hectares in 1984 but 41 203.2 hectares in 1994, a reduction of 25 292.4 hectares (38%). In the intervening period the area covered by the classes underwent both an increase and a decrease (Figure 6.7).

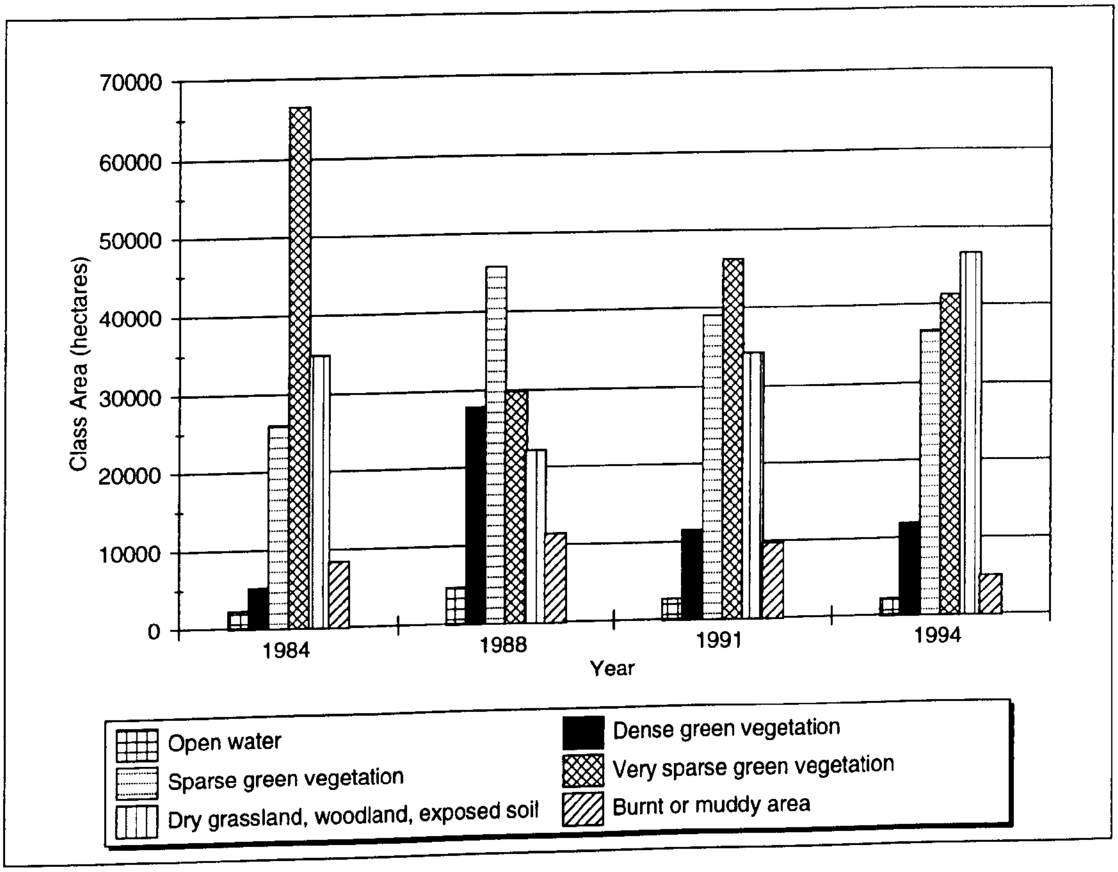


Figure 6.7 Trends in area of recoded land cover classes in the Blue Lagoon subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

6.3.4 Trends in Mazabuka West

The Mazabuka West subsection mainly included the woodland area from Itebe to just west of the Nakambala Sugar Estate and part of the flood plain to the north, as far as the river and water fringe vegetation zone around Maamba (Figure 6.4). The area covered by the land cover classes is as shown in Table 6.7.

The lack of consistent trends of either increase or decrease in the area of cover, observed for predominantly flood plain areas (Sections 6.3.1 - 6.3.3) is noticeable for this subsection predominantly consisting of woodland in early spring leaf but with dry grass (Figure 6.8).

Table 6.7 Area and Trends in Area of Land Cover Classes in the Mazabuka West Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(a) Original Land Cover Classes

Class	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) ÷ 10 000m^{2}ha^{-1}] 24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	% Change between successive image dates 1984-1988	1988- 1991	1991-1994
1	27.4	43.9	29.4	23.9	60.2	-33.0	-18.7
2	25.6	201.8	53.2	39.9	688.3	-73.6	-41.6
3	243.5	556.8	311.8	182.2	128.7	-44.0	-41.6
4	341.0	442.4	337.5	275.2	29.7	-23.7	-18.5
5	594.7	598.1	478.6	605.7	0.6	-20.0	26.6
6	822.8	1 529.3	4 399.6	1 220.9	85.9	187.7	-72.2
7	1 548.2	1 709.2	4 887.2	1 714.0	10.4	185.9	-64.9
8	4 029.4	1 982.4	5 289.9	4 783.1	-50.8	166.8	-9.6
9	5 987.8	4 186.6	3 327.2	5 882.0	-30.1	-20.5	76.6
10	8 009.9	6 179.0	4 228.4	6 223.1	-22.9	-31.6	47.2
11	3 841.3	4 707.3	5 344.9	6 842.1	22.5	13.5	28.0
12	3 715.6	7 421.8	3 943.1	7 773.3	99.7	-46.9	97.1
13	6 139.3	5 199.5	3 962.7	2 987.0	-15.3	-23.8	-24.6
14	2 805.5	2 478.5	1 238.6	2 005.2	-11.7	-50.0	61.89
15	3 208.4	4 101.2	3 474.4	769.4	27.8	-15.3	-77.9
0	92.3	94.7	126.5	105.6			
Total	41 433.0	41 433.0	41 433.0	41 433.0			

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 15 = Burnt area or muddy, dark surface
Class 0 = Image background and Zero value pixels in burnt areas

Table 6.7 Area and Trends in Area of Land Cover Classes in the Mazabuka West Subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

(b) Recoded Land Cover Classes

		Area covered by class (hectares) [Area = (No. pixels x 30m x 30m) ÷ 10 000m^{2}ha^{-1}]				% Change between successive image dates		
Category		24 Sept. 1984	3 Sept. 1988	12 Sept. 1991	20 Sept. 1994	1984-1988	1988-1991	1991-1994
1	Open water	27.4	43.9	29.4	23.9	60.2	-33.0	-18.7
2	Dense green vegetation	610.1	1 201.0	702.5	497.3	98.9	-41.5	-29.2
3	Sparse green vegetation	2 965.7	3 836.6	9 765.4	3 540.6	29.4	154.5	-63.7
4	Very sparse green vegetation	18 027.4	12 348.5	12 845.5	16 888.6	-31.5	4.0	31.5
5	Dry grassland, woodland, exposed soil	16 501.7	19 807.1	14 489.3	19 607.6	20.0	-26.8	35.3
6	Burnt or muddy area	3 208.4	4 101.2	3 474.4	769.4	27.8	-15.3	-77.9
	Background and zeros	92.3	94.7	126.5	105.6			
	Total	41 433.0	41 433.0	41 433.0	41 433.0			

6.3.5 Trends at Large lagoons

Square areas enclosing Chunga and Shalwembe Lagoons (Figure 6.4), the biggest lagoons on the Kafue Flats, were examined for land cover changes. The results are summarised in Tables 6.8 and 6.9.

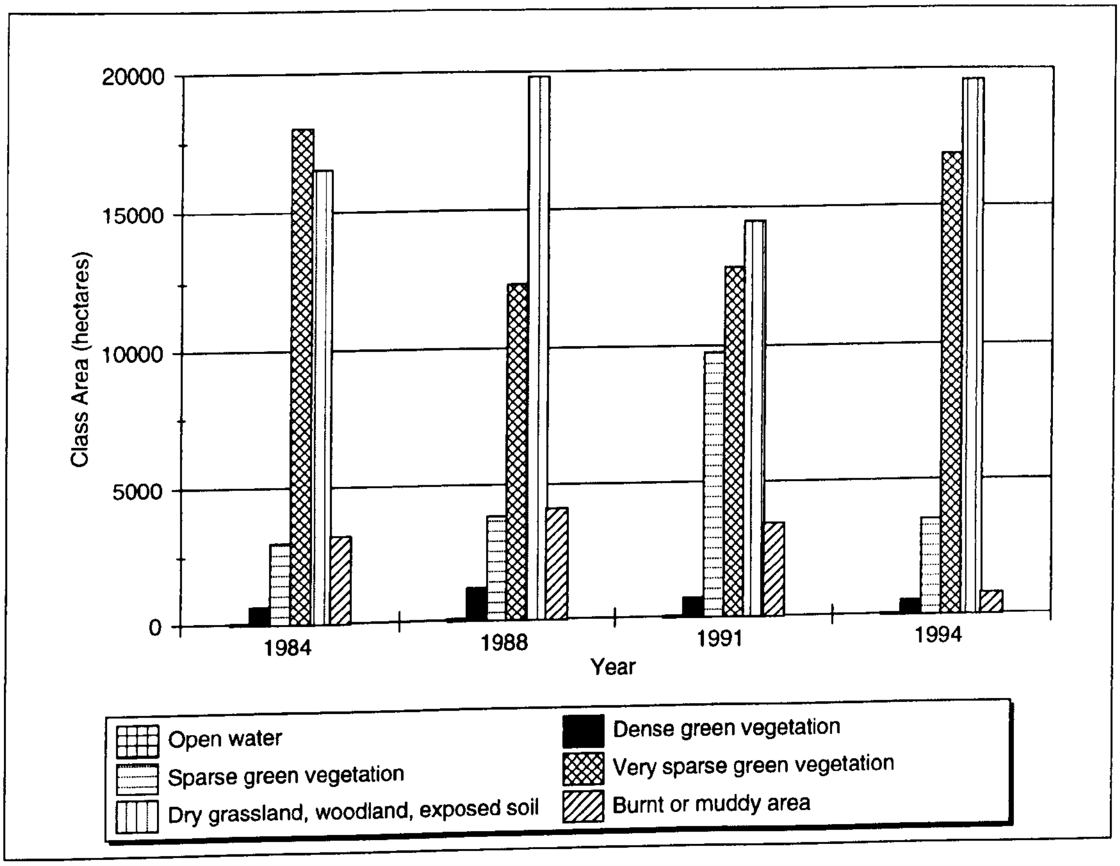


Figure 6.8 Trends in area of recoded land cover classes in the Mazabuka West subsection of the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

Apart from the 3 September 1988 image conditions (when there was smoke over the lagoon and surrounding dry ground - see Figure 4.11) the amount of water in Chunga lagoon seems to have been reducing between 1984 and 1994 (see Table 6.8). There appears to have been reduction in dense, very vigorous water reeds/water fringe vegetation (Class 2) and an increase in emergent vegetation in shallow water (Class 10). The pattern at Shalwembe Lagoon is not clear but the lagoon had less water and surrounding dense, very vigorous green vegetation (Class 2) in September 1994 than it did in September 1984 (see Table 6.9). The amount of water reeds and water fringe vegetation categories (Classes 3 and 4) also seems to have increased in the same period.

Table 6.8 Area and Trends in Area of Land Cover Classes around Chunga Lagoon on the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) ÷ 10 000m^{2}ha^{-1}]				**% Change between successive image dates**		
Class	**24 Sept. 1984**	**3 Sept. 1988**	**12 Sept. 1991**	**20 Sept. 1994**	**1984-1988**	**1988- 1991**	**1991-1994**
1	**5 525.3**	***0.0**	**4 357.1**	**3 496.4**	***-100**	***∞**	**-19.8**
2	**292.7**	**638.7**	**126.8**	**93.5**	**118.2**	**-80.1**	**-26.3**
3	**1 825.7**	**6.8**	**1 149.4**	**739.5**	**-99.6**	**16 803**	**-35.7**
4	**2 150.2**	**151.3**	**1 947.4**	**1 262.1**	**-93.0**	**1 187**	**-35.2**
5	**1 143.0**	**107.4**	**497.2**	**756.8**	**-90.6**	**362.9**	**52.2**
6	**965.7**	**554.1**	**688.7**	**847.0**	**-42.6**	**24.3**	**23.0**
7	**457.1**	**1 791.3**	**576.6**	**1 328.9**	**292.0**	**-67.8**	**130.5**
8	**95.0**	**2 022.1**	**345.9**	**370.0**	**2 029**	**-82.9**	**7.0**
9	**1 013.8**	**484.4**	**898.1**	**933.1**	**-52.2**	**85.4**	**3.9**
10	**609.4**	***7 566.8**	**1 480.9**	**7 544.6**	***1 142**	**-80.4**	**409.5**
11	**490.0**	**710.0**	**325.9**	**260.4**	**44.9**	**-54.1**	**-20.1**
12	**244.5**	**1 142.5**	**796.7**	**201.1**	**367.3**	**-30.3**	**-74.8**
13	**1 054.1**	**3 832.2**	**1394.6**	**1 021.1**	**263.6**	**-63.6**	**-26.8**
14	**1 249.5**	**2 306.9**	**2 557.2**	**984.1**	**84.6**	**10.9**	**-61.5**
15	**4 166.6**	**62.7**	**4 016.7**	**1 372.3**	**-98.5**	**6 306**	**-65.8**
0	**930.3**	**835.7**	**1 053.7**	**1 002.0**			
Total	**22 212.9**	**22 212.9**	**22 212.9**	**22 212.9**			

(*unreliable - see Section 6.3.2)

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 15 = Burnt area or muddy, dark surface
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 0 = Image background and zero value pixels

Table 6.9 Area and Trends in Area of Land Cover Classes around Shalwembe Lagoon on the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994.

Class	Area covered by class (ha) [Area = (No. pixels x 30m x 30m) ÷ 10 000m²ha⁻¹]				% Change between successive image dates		
	1984	1988	1991	1994	1984-1988	1988- 1991	1991-1994
1	1 140.9	0.0	31.8	402.8	-100	∞	1 167
2	735.8	2 026.7	555.8	504.2	175.4	-72.6	-9.3
3	943.9	157.0	1 659.8	1 885.7	-83.4	957.2	13.6
4	743.6	505.5	835.9	1 411.4	-32.0	65.4	68.8
5	112.2	103.3	408.6	343.0	-7.9	295.5	-16.1
6	192.0	363.3	223.2	117.2	89.2	-38.6	-47.5
7	40.4	740.1	206.7	411.3	1 732	-72.1	99.0
8	1.6	187.1	65.3	7.2	11 594	-65.1	-89.1
9	21.9	12.5	51.3	0.6	-42.9	309.6	-98.8
10	33.8	51.8	531.5	142.8	53.3	926.1	-73.1
11	23.4	5.4	62.6	5.9	-76.9	1 059.3	-90.6
12	12.8	4.7	141.4	0.4	-63.3	2 908.5	-99.7
13	31.3	4.5	128.7	26.6	-85.6	2 760.0	-79.3
14	47.3	48.2	181.9	114.8	1.9	277.4	-36.9
15	1 569.3	1 527.6	653.2	362.1	-2.7	-57.2	-44.6
0	87.5	0.0	0.0	1.7			
Total	5 737.7	5 737.7	5 737.7	5 737.7			

Where:

Class 1 = Open water
Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Class 6 = Mixed green grassland/woodland vegetation
Class 7 = Sparse green grassland/woodland vegetation
Class 8 = Very sparse green grassland/woodland vegetation
Class 9 = Very sparse green vegetation/termitaria with isolated trees
Class 10 = Emergent vegetation in shallow water or after burning
Class 11 = Dry grassland and termitaria zone without trees
Class 12 = Dry land with leafless plant structures (woodland/grassland)
Class 15 = Burnt area or muddy, dark surface
Class 13 = Exposed, trampled dry soil with surface debris
Class 14 = Bare, compacted dry soil
Class 0 = Zero value pixels

6.4 Change Detection Using Spectral Enhancement Techniques

Inter-image changes in the spectral characteristics of the image series were examined using the Normalised Difference Vegetation Index (NDVI) and Principal Component Analysis (PCA) spectral enhancement techniques. The results are presented in turn.

6.4.1 Normalised Difference Vegetation Index (NDVI) Changes

The Normalised Difference Vegetation Index (NDVI) compares the amount of infrared with visible red reflectance as follows:

$$\text{NDVI} = \frac{\text{Near Infrared - Red}}{\text{Near Infrared + Red}} \quad \text{or} \quad \frac{\text{MSS4 - MSS2}}{\text{MSS4 + MSS2}} \quad \text{or} \quad \frac{\text{TM4 - TM3}}{\text{TM4 + TM3}} \qquad (6.1)$$

NDVI values range between 1 and -1. Values greater than one indicate a predominance of near-infrared reflecting features (mainly healthy, green vegetation but also dry grass and soil - see Figure 1.3) over visible red reflectors (for example, reddish/brown dry grass and dry soil). Values less than one indicate a predominance of visible red reflectors and zero values indicate equal near-infrared and visible red reflectance (Lillesand and Kiefer, 1994; Jensen, 1986; ERDAS Inc., 1994). Figure 6.9 illustrates the use of the NDVI spectral enhancement technique in highlighting areas, and assessing vigour, of green vegetation cover. Many studies have used the NDVI for vegetation monitoring (e.g. Townshend and Justice, 1986; Hielkema *et al*, 1986; Justice *et al*, 1986; Justice and Hiernaux, 1986). The frequencies of NDVI values from each of the normalised images are shown in Figure 6.10. On the 24 September 1984 image most of the NDVI values were above 1, with a peak frequency around 0.25 (Figure 6.10a). There was a similar pattern on the 3 September 1988 image but the number of pixels at the peak frequency of 0.25 is less than that for the 1984 image

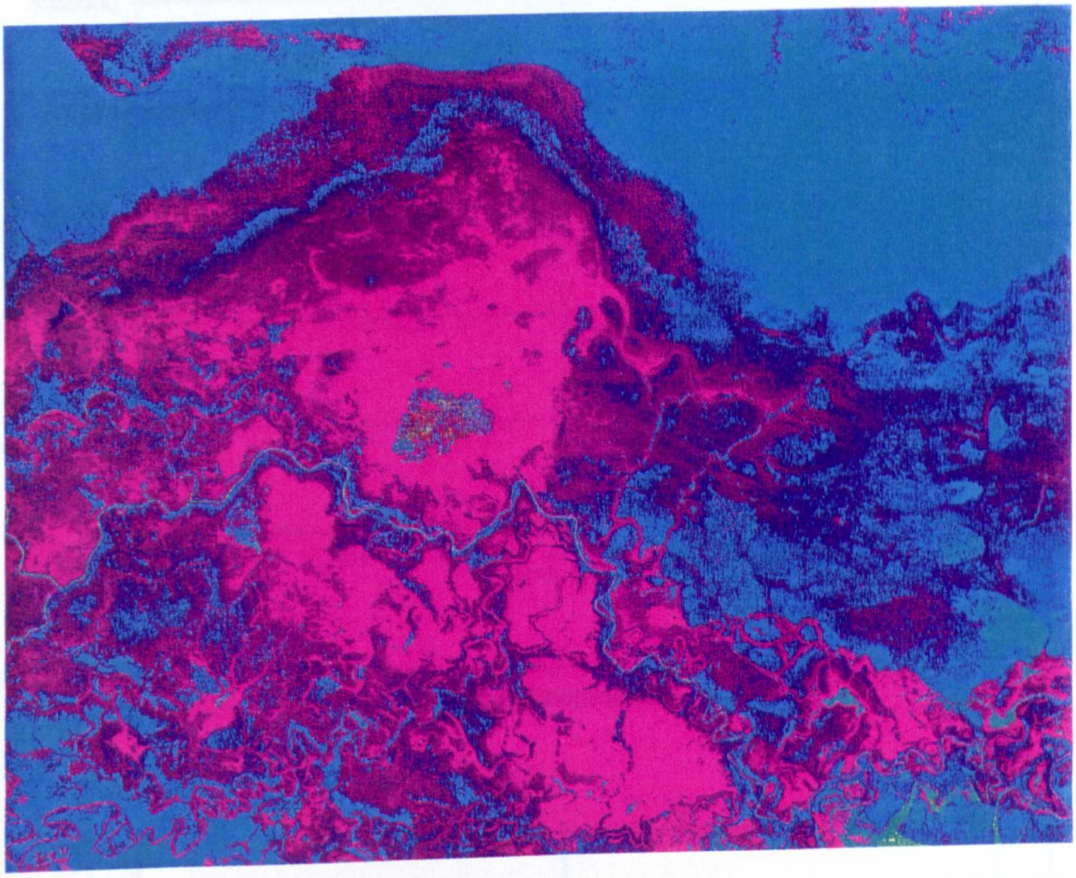


Figure 6.9 An NDVI image of the wetland area north west of Nyimba (the Blue Lagoon West subsection in Figure 6.4). The image was derived from the atmospherically corrected 20 September 1994 TM image. The NDVI values, ranging from -1.000 to 0.992, have been colour coded (density sliced) such that yellow represents the lowest value (-1.000) and red represents the highest (0.992). The colour hierarchy is in the order red (highest NDVI), blue, green, yellow (lowest NDVI). Dense, vigorous vegetation appears red (high NDVI) but there is some confusion with dry soil/dry grass on the margin of the wetland north of Shalwembe Lagoon (compare with Figure 6.4 or 4.15). Dry land appears blue while water and burnt areas (with very low NDVI) appear green/yellow.

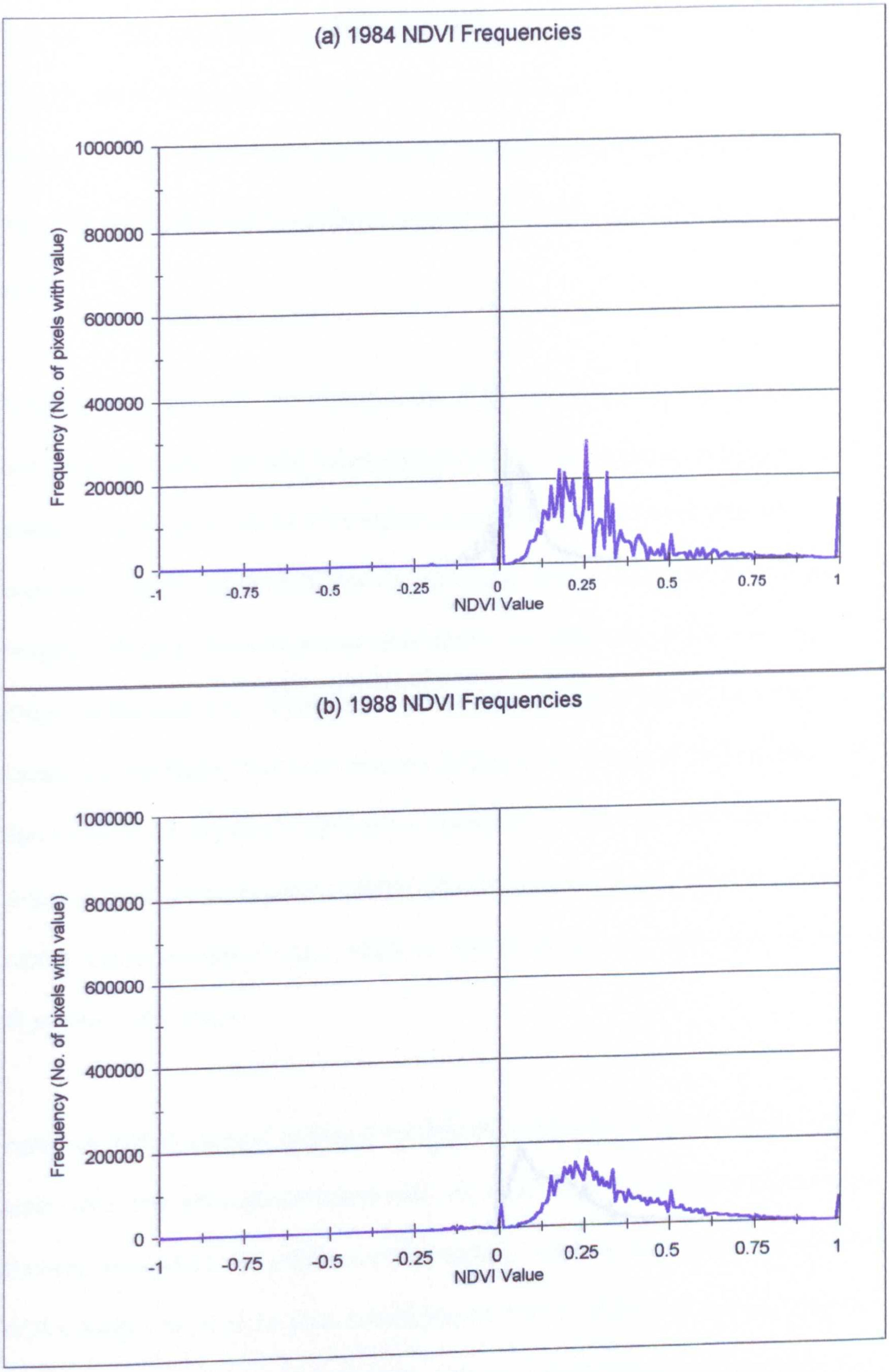


Figure 6.10 Frequency of Normalised Difference Vegetation Index (NDVI) values on the 24 September 1984 MSS, 3 September 1988 MSS, 12 September 1991 TM and 20 September 1994 TM images of the Kafue Flats.

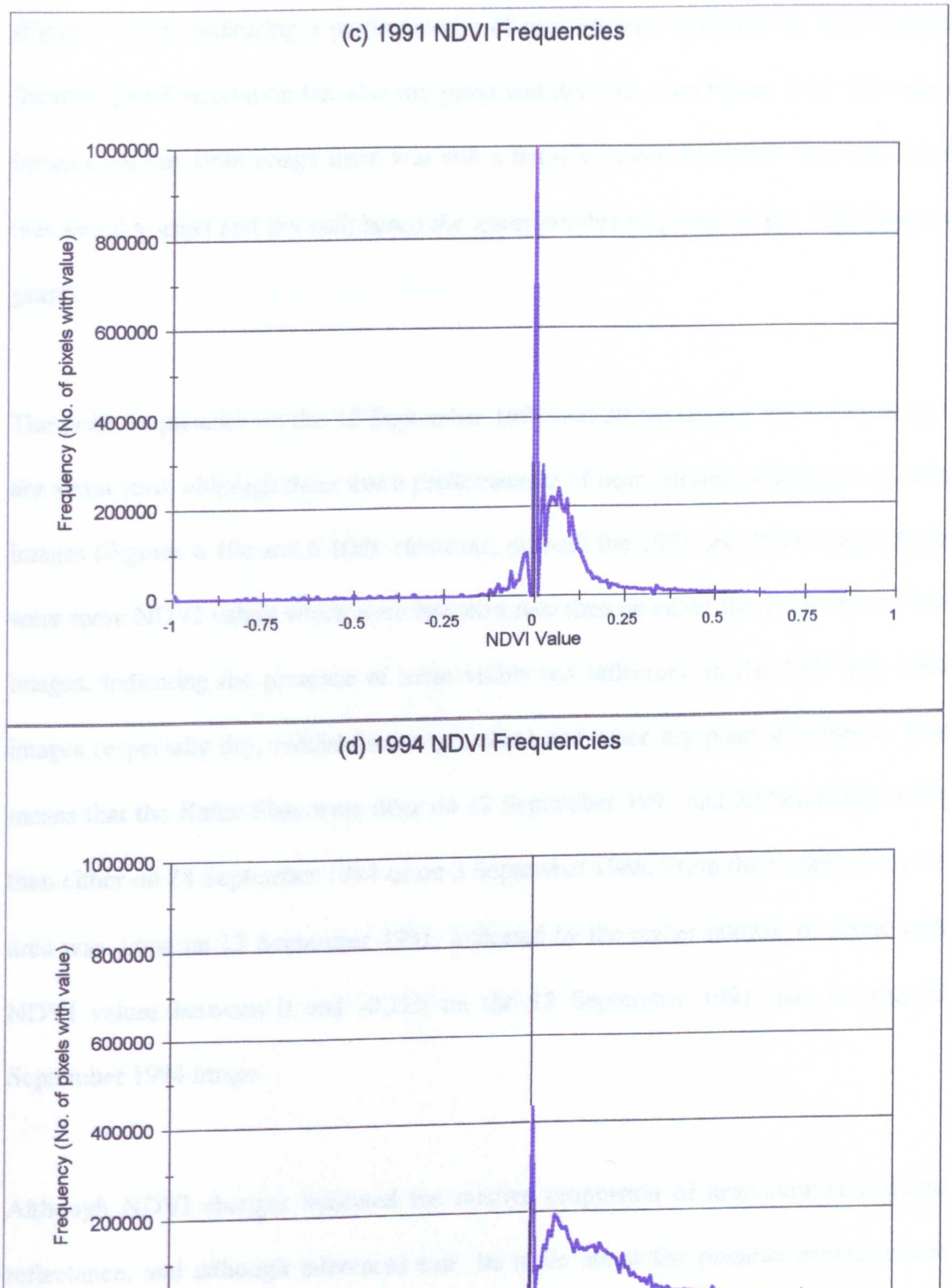


Figure 6.10 (*continued*) Frequency of Normalised Difference Vegetation Index (NDVI) values on the 24 September 1984 MSS, 3 September 1988 MSS, 12 September 1991 TM and 20 September 1994 TM images of the Kafue Flats.

(Figure 6.10b), indicating a predominance of near-infrared reflectors on both images (healthy green vegetation but also dry grass and dry soil - see Figure 1.3). However, because on the 1988 image there was still a flood in lower floodplain sections, there was less dry grass and dry soil; hence the lower number of pixels on the 1988 image's graph.

The peak frequencies on the 12 September 1991 and 20 September 1994 TM images are about zero, although there was a predominance of near-infrared reflectance on both images (Figures 6.10c and 6.10d). However, on both the 1991 and 1994 images there were more NDVI values which were less than zero than on either the 1988 or the 1984 images, indicating the presence of more visible red reflectors on the 1991 and 1994 images (especially dry, reddish/brown grassland and other dry plant structures). This means that the Kafue Flats were drier on 12 September 1991 and 20 September 1994 than either on 24 September 1984 or on 3 September 1988. From the images used, the area was driest on 12 September 1991, indicated by the higher number of pixels with NDVI values between 0 and -0.125 on the 12 September 1991 than on the 20 September 1994 image.

Although NDVI changes indicated the relative proportion of near-infrared and red reflectance, and although inferences can be made about the possible ground cover features from which the reflectance was coming, mapping the change between two NDVI images by pixel by pixel subtraction of NDVI values between the respective images resulted in images predominantly with zero values. Other resulting values were more difficult to interpret. For example, a pixel with an NDVI value of 1 on the second NDVI image and a value of 0.5 on the first, results in a difference of 0.5 on the NDVI change image (i.e. 1 - 0.5 = 0.5), exactly the same as the difference between a 0.75 value on the second and a 0.25 value on the first (0.75- 0.25 = 0.5), which would make the resulting value of 0.5 on the NDVI change image difficult to interpret. For this reason the classification comparison technique was found to be a more useful change detection method, from the image data set used.

To obtain an indication of NDVI trends at specific dense green vegetation sites over the period covered by the images, NDVI values at specific points were examined. Dense green vegetation (because of presence of water) is the main characteristic distinguishing the Kafue Flats as a wetland in the dry season. A site was chosen near Shalwembe Lagoon in the area that showed spatial losses of dense green vegetation between 1984 and 1994 (Figure 6.2). Two sites opposite the Nakambala Sugar Estate in the area showing no losses were chosen for comparison, and, as a control, three dry sites were examined. Because the images were geometrically co-registered (see Section 4.4.3) it was possible to locate the same site on all the images. The sites and their NDVI characteristics are listed in Table 6.10 and the NDVI trends at the sites are as shown in Figure 6.11.

Figure 6.11 shows that for the area that underwent degradation in dense green vegetation around Shalwembe Lagoon (Figure 6.2), represented by site Dense green 3, the vegetation was also undergoing a reduction in vigour because the NDVI was reducing. This means that the vegetation was possibly reflecting less near-infrared radiation, resulting in a smaller difference between the amount of red and near-infrared reflectance and, therefore, reduced NDVI. However, the reducing NDVI could also be because the density of the vegetation had reduced, thereby opening up the canopy and

Table 6.10 NDVI Values at Representative Dense Green Vegetation and Dry Sites

Site	Characteristics (setting)	NDVI Values			
		24 September 1984	3 September 1988	12 September 1991	20 September 1994
Dense green 1	In area not undergoing spatial loss of dense green vegetation	1.000	0.634	0.483	0.773
Dense green 2	In area not undergoing spatial loss of dense green vegetation; opposite irrigation estate	0.846	0.829	0.559	0.624
Dense green 3	In area undergoing spatial loss of dense green vegetation; near Shalwembe Lagoon	0.736	0.443	0.341	0.425
Dry soil 1	Dry bare surface in human settlement area	0.061	0.105	0.031	0.036
Dry soil 2	Dry bare surface in human settlement area	0.080	0.149	0.034	0.096
Dry soil with debris	Dry area in national park	0.094	0.088	0.040	0.011

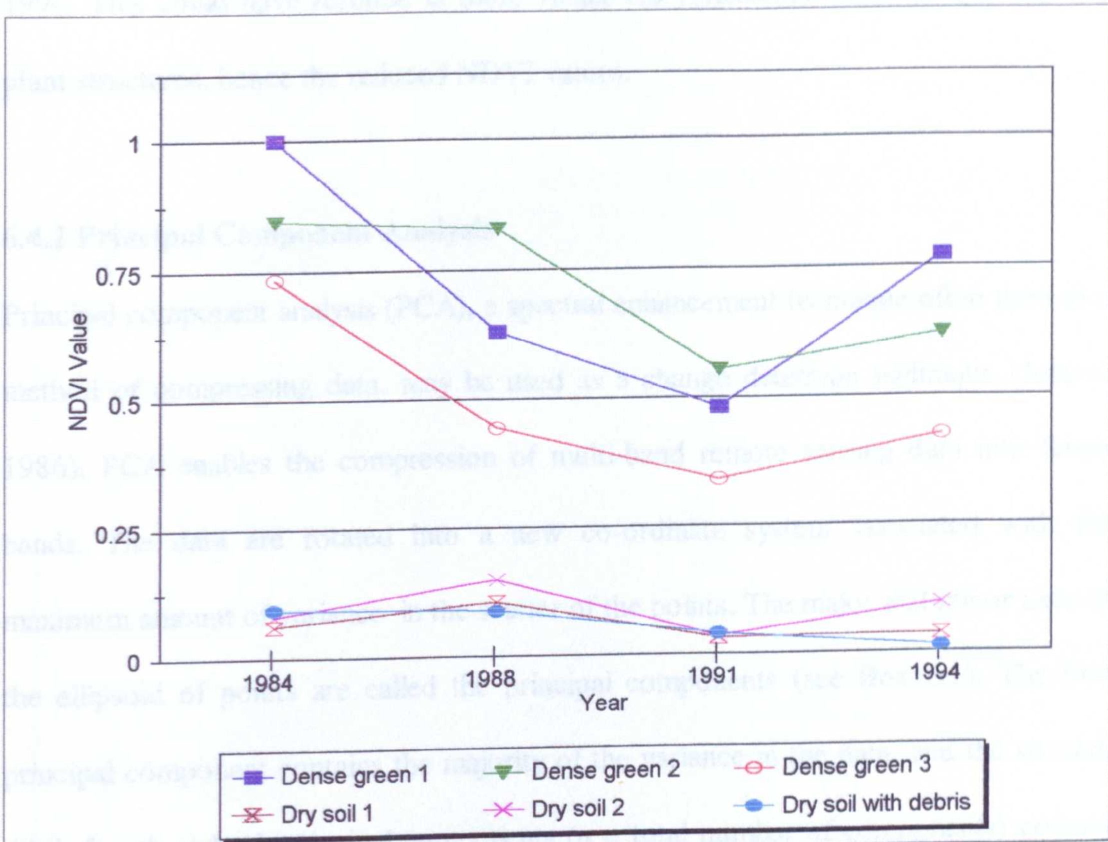


Figure 6.11 Trends in NDVI values at representative dense green vegetation and dry soil sites on the Kafue Flats: 24 September 1984, 3 September 1988, 12 September 1991 and 20 September 1994. There is a general reduction in NDVI values over time, possibly indicating reduced green vegetation vigour, opening up of green vegetation canopy and drying up at the sites.

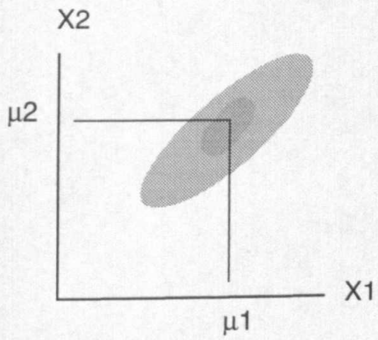
increasing the amount of red reflectance from the soil and dry under storey plant structures. The trend is similar for the other two dense green vegetation sites (Dense green 1 and 2 in Figure 6.11) representing the down stream section of the Kafue Flats which appeared not to have had spatial loss of dense green vegetation between 1984 and 1994 (Figure 6.2). Site Dense green 1 was in a dark/muddy or water land cover type on 24 September 1984 (with zero visible red reflectance), hence the NDVI value of 1.000. The dry (control) sites experienced a small lowering of NDVI values, indicating a possible drying up or increased soil exposure trend between 1984 and

1994. This could have resulted in more visible red reflectance from the soil and dry plant structures, hence the reduced NDVI values.

6.4.2 Principal Component Analysis

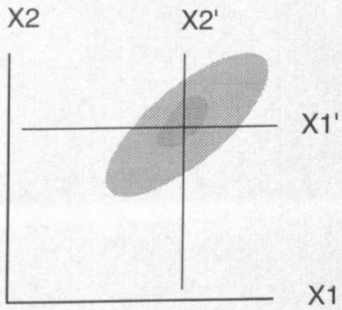
Principal component analysis (PCA), a spectral enhancement technique often used as a method of compressing data, may be used as a change detection technique (Jensen, 1986). PCA enables the compression of multi-band remote sensing data into fewer bands. The data are rotated into a new co-ordinate system associated with the maximum amount of variance in the scatter of the points. The major and minor axes of the ellipsoid of points are called the principal components (see Box 6.1). The first principal component contains the majority of the variance in the data, and the second, third, fourth and *n*th principal components (n = total number of components) contain decreasing amounts of the variance (Figure 6.12). The direction of a principal component is the eigen vector, and its length is the eigen value. An image produced from a principal component is an eigen image (Figure 6.12).

Eigen values and eigen vector characteristics of the raw (un-normalised) image data set used are shown in Table 6.11. The first and second principal components of the 24 September 1984 MSS image contain a total of 98.28% of the variance in the data (Table 6.11a). This is mainly from the contents of the near-infrared bands (bands 3 and 4), because the two bands have the largest vector values, 0.591 and 0.614 respectively, in component 1, and 0.174 and 0.532, respectively, in component 2. Component 3 is made up largely of MSS band 1 reflectance (eigen vector value of 0.786 in Table



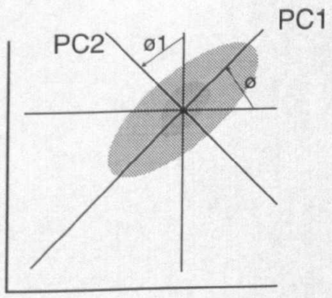
A

A scatterplot of data points collected from two remotely sensed bands labeled X1 and X2 with the means of the distribution labeled μ1 and μ2.



B

A new coordinate system is created by shifting the axes to an X' system. The values for the new data points are found by the relationship X1' = X1 - μ1 and X2' = X2 - μ2.



C

The X' axis system is then rotated about its origin (μ1, μ2) so that PC1 is projected through the semimajor axis of the distribution of points and that the variance of PC2 is a maximum. PC2 must be perpendicular to PC1. The PC axes are the principal components of this two-dimensional data space. Component 1 usually accounts for approximately 90% of the variance, with component 2 accounting for approximately 5%.

Box 6.1 An illustration of principal component analysis: Diagrammatic representation of the spatial relationship between the first two principal components (modified from Jensen, 1986).

(a) An eigen image of Principal Component 1, containing 94.35% of the data variance.

(b) An eigen image of Principal Component 2, containing 4.83% of the data variance and, consequently, less clear than the Principal Component 1 image.

Figure 6.12 An illustration of principal component analysis: Eigen images from a subset of the raw 3 September 1988 MSS data, around Shalwembe Lagoon.

(c) An eigen image of Principal Component 4, containing 0.33% of the data variance, mainly noise. The eigen image from Principal Component 3 (with 0.49% of the data variance) was empty of raster information. Therefore from the original 4 bands, the data over this area could be compressed into these 3 principal components. The eigen vector characteristics for the subset were as follows:

component		1	2	3	4
Band	MSS1	0.168	0.371	-0.348	0.884
	MSS2	0.243	0.871	0.292	-0.311
	MSS3	0.598	-0.067	-0.703	-0.379
	MSS4	0.745	-0.314	0.548	0.216
Eigen value		1019.270	52.223	5.312	3.524

Figure 6.12 (continued) An illustration of principal component analysis: Eigen images from a subset of the raw 3 September 1988 MSS data, around Shalwembe Lagoon.

Table 6.11 Principal Component Analysis Characteristics of Raw Image Data Used

(a) Eigen Vectors and Eigen Values of Principal Components of 24 September 1984 MSS Image

	Component 1	2	3	4
Band 1	0.286	-0.543	0.786	0.073
Band 2	0.439	-0.626	-0.611	0.208
Band 3	0.591	0.174	-0.022	-0.788
Band 4	0.614	0.532	0.092	0.575
Eigen value of component	948.197	71.390	11.646	6.142
Percentage of data variance in component	91.40	6.88	1.12	0.59

(b) Eigen Vectors and Eigen Values of Principal Components of 3 September 1988 MSS Image

	Component 1	2	3	4
Band 1	0.337	-0.560	0.697	0.294
Band 2	0.377	-0.626	-0.682	-0.007
Band 3	0.580	0.164	0.179	-0.777
Band 4	0.638	0.517	-0.127	0.556
Eigen value of component	1 539.627	99.849	13.638	6.348
Percentage of data variance in component	92.78	6.02	0.82	0.38

Table 6.11(continued) Principal Component Analysis Characteristics of Raw Image Data Used

(c) Eigen Vectors and Eigen Values of Principal Components of 12 September 1991 TM Image

	Component						
	1	2	3	4	5	6	7
Band 1	0.393	-0.236	-0.666	-0.480	0.117	-0.646	0.238
Band 2	0.171	-0.029	-0.169	-0.234	0.115	0.035	-0.934
Band 3	0.239	0.087	-0.238	-0.534	0.095	0.720	0.256
Band 4	0.223	0.195	-0.672	0.557	0.382	0.020	0.065
Band 5	0.489	0.682	0.085	0.033	-0.523	-0.114	-0.024
Band 6	0.631	-0.595	0.227	0.343	-0.176	0.218	-0.007
Band 7	0.269	0.279	0.578	-0.002	0.717	-0.036	0.023
Eigen value of component	5 433.109	627.957	152.827	20.293	9.727	6.382	0.721
Percentage of data variance in component	86.92	10.05	2.44	0.32	0.16	0.10	0.01

(d) Eigen Vectors and Eigen Values of Principal Components of 20 September 1994 TM Image

	Component					
	1	2	3	4	5	6
Band 1	0.393	-0.768	0.280	0.207	0.308	0.203
Band 2	0.183	-0.244	0.027	-0.096	-0.196	-0.927
Band 3	0.275	-0.164	0.013	-0.137	-0.888	0.300
Band 4	0.289	-0.163	-0.783	-0.477	0.209	0.082
Band 5	0.696	0.444	-0.159	0.538	0.033	-0.047
Band 6	*	*	*	*	*	*
Band 7	0.410	0.316	0.531	-0.642	0.189	0.040
Eigen value of component	3 097.669	337.747	159.174	18.957	15.645	1.262
Percentage of data variance in component	85.32	9.30	4.38	0.52	0.43	0.03

(*Band 6 unavailable due to technical problem on Landsat)

6.11a), and component 4 is largely made up of MSS band 4 reflectance (eigen vector value of 0.575). Therefore, most of the variance in the 24 September 1984 MSS scene is bands 3 and 4, the near infra red bands (equivalent to TM band 4; see Tables 1.1 and 1.2).

On the 3 September 1988 MSS image principal component 1 also consists mainly of near-infrared reflectance because bands 4 and 3 have the largest eigen vector values of 0.638 and 0.580, respectively (Table 6.11b). Component 2 is largely band 4 (near-infrared) reflectance (eigen vector value 0.517 from the band is the largest in the component) and some reflectance from band 3 (vector value 0.164). Therefore, nearly all of the data variance (98.80%) in the scene is from near-infrared reflectance (bands 3 and 4). Component 3 is largely from green (band 1) reflectance but accounts for only 0.82% of the data variance. Component 4 is largely band 4 reflectance.

The large contribution of infrared bands to the overall image data variance is observed for the TM images as well (Tables 6.11c and 6.11d). On the 12 September 1991 TM image (Table 6.11c), principal component 1 is largely made up of TM6 (thermal infrared), with a vector value of 0.631, TM5 (mid-infrared) with a vector value of 0.489, and, to a lesser extent, TM1 (blue-green) with a vector value of 0.393 (of all TM bands this band has the largest haze interference factor). Component 2 consists largely of TM5 (mid-infrared) reflectance (vector value 0.682). Component 3 is largely TM7 (mid-infrared) reflectance (vector value 0.578). These first three components account for 99.41% of the data variance. Therefore, TM bands 5, 6 and 7 account for most of the variance in the image data. Components 4, 5 and 6 are largely TM4, TM7 and TM3 reflectance, respectively, and together account for only 0.58% of the total variance. Component 7 is difficult to interpret but TM3 has the largest vector value (0.256).

The first principal component on the 20 September 1994 TM image consists largely of TM5 (mid-infrared) reflectance with a vector value of 0.696, TM7 (mid-infrared) with a vector value of 0.410 and TM1 (blue-green with largest haze interference) with a vector value of 0.393 (Table 6.11d). Component 2 is largely TM5 and TM7 reflectance as well (vector values 0.444 and 0.316, respectively) while component 3 is largely TM7 reflectance (vector value 0.531). These first three components account for 99% of the data variance. Components 4, 5 and 6 are largely TM5, TM1 and TM3 reflectance, respectively, with respective vector values of 0.538, 0.308 and 0.300.

Therefore, for the MSS images the near-infrared bands (MSS3 and MSS4, equivalent to TM4) contain most of the data variance, while for the TM images, most of the data variance is in the mid-infrared bands which MSS images do not contain (see Tables 1.1 and 1.2). The reason for the predominance of infrared reflectance is because most of the area in the image scene is dry. Dry soil and dry grass reflect highly in the near-infrared but to a lesser extent than healthy green vegetation (Figure 1.3). The combination of near-infrared reflectance from dry soil, dry grass and healthy green vegetation explains the fact that most of the MSS image variance is in near-infrared bands (see Figure 1.3a). The same explanation accounts for the large variance of the data in mid-infrared TM bands. There was high mid-infrared reflectance from the combination of healthy green vegetation and dry soil and grass, though to varying degrees depending on moisture content. In addition the presence of fire resulted in high mid-infrared (TM5,TM7) and thermal infrared (TM6) reflectance and, therefore, high variance (see Table 4.2).

For change detection purposes using PCA, the lack of directly equivalent near and mid-infrared bands between TM and MSS images, in which most of the data variance was, prevented the direct use of the raw data set. The only equivalent infrared bands between TM and MSS are MSS4 and TM4 (see Tables 1.1 and 1.2). There are two ways in which PCA can be used in change detection (Muchoney and Haack, 1994; Jensen, 1986):-

(1) Independent data transformation analysis - in which multitemporal image data sets area spectrally enhanced separately using PCA. Each image is then separately classified for use in post classification change detection.

(2) Merged data transformations - in which all the bands from the n - dimensional multitemporal image data set are registered and treated as a single N - dimensional data set as input to the PCA (where n is the number of bands per image, $N = n$ x the number of image dates).

Enhancement by PCA prior to post classification change detection was not done in order to avoid the introduction of further classification errors. For example, in an eigen image from the first principal component consisting of near-infrared reflectance it would be even more difficult to separate dry grass from dry soil if they both reflected equal amounts of near-infrared energy, but additional use of visible bands in the original images would probably separate dry grass from dry soil if they have different visible colours. Merged data transformation was done using the normalised, co-registered 3 band images used in the post classification comparison change detection technique. The bands were MSS1, MSS2, MSS4 from the 1984 and 1988 images, TM2, TM3 and TM4 from the 1991 and 1994 images; resulting in a merged 12 band image. The merged 12 band data set was processed into principal components, whose resulting eigen value and eigen vector characteristics are as shown in Table 6.12.

Table 6.12 Eigen Vectors and Eigen Values of Principal Components of Merged Data Set

Band	Component											
	1	2	3	4	5	6	7	8	9	10	11	12
1984 MSS1	0.114	0.077	-0.152	0.163	0.089	0.168	0.129	-0.014	-0.202	0.893	0.173	0.105
1984 MSS2	0.254	0.187	-0.349	0.393	0.273	0.568	0.305	-0.106	-0.003	-0.341	-0.078	0.036
1984 MSS4	0.419	0.150	-0.356	0.464	-0.442	-0.426	-0.264	0.101	0.044	-0.037	0.000	0.006
1988 MSS1	0.121	-0.190	-0.101	-0.060	0.200	-0.321	0.243	0.122	-0.780	-0.227	0.234	-0.058
1988 MSS2	0.222	-0.303	-0.201	-0.060	0.478	-0.447	0.346	0.031	0.491	0.099	-0.122	0.019
1988 MSS4	0.463	-0.711	-0.066	-0.219	-0.198	0.353	-0.238	-0.085	-0.018	0.014	0.002	0.009
1991 TM2	0.120	0.134	-0.031	-0.155	0.104	0.024	-0.106	0.226	-0.111	0.104	-0.118	0.912
1991 TM3	0.266	0.301	-0.078	-0.341	0.272	0.133	-0.321	0.627	0.070	-0.042	0.049	-0.346
1991 TM4	0.421	0.435	-0.006	-0.544	-0.190	-0.084	0.230	-0.488	-0.011	-0.007	0.001	-0.042
1994 TM2	0.104	0.019	0.164	0.092	0.186	-0.076	-0.190	-0.128	-0.292	0.099	-0.860	-0.162
1994 TM3	0.214	0.072	0.334	0.220	0.484	-0.093	-0.487	-0.406	0.023	-0.044	0.371	0.060
1994 TM4	0.386	0.009	0.727	0.236	-0.158	0.037	0.381	0.302	0.062	-0.001	0.022	0.008
Eigen value of component	685.1	274.9	257.3	243.1	115.5	26.8	18.9	14.2	3.9	2.1	1.5	0.8
Percentage of data variance in component	41.67	16.72	15.65	14.79	7.02	1.63	1.15	0.86	0.24	0.13	0.09	0.05

The large contribution of the near-infrared bands (1984 MSS4, 1988 MSS4, 1991 TM4 and 1994 TM4) can be seen from the fact that their vector values in component 1 are the largest (0.419, 0.463, 0.421 and 0.386, respectively; Table 6.12). Visible red (1984 MSS2, 1988 MSS2, 1991 TM3, 1994 TM3) and then green (1984 MSS1, 1988 MSS1, 1991 TM2, 1994 TM2) contribute the next largest and least variance, respectively, in component 1 (Table 6.12). Component 2 is largely made up of 1991 TM4 and 1991 TM3 reflectance (vector values 0.435 and 0.301, respectively).

Component 3 consists largely of 1994 TM4 and 1994 TM3 reflectance (vector values 0.727 and 0.334, respectively) and component 4 consists of 1984 MSS4, 1984 MSS2, 1994 TM4, 1994 TM3 and 1984 MSS1 reflectance (vector values 0.464, 0.393, 0.236, 0.220 and 0.163, respectively). Eigen images of components 1, 2, 3, 4, 5 and 6, which account for a total of 97.48% of the total variance, were produced. These highlighted the change areas, where as the other components contained non changed areas or redundant information. It was then possible to identify change areas (e.g. see Figure 6.13). However, it was difficult to interpret the change without examining the changed area on each of the original images to see what the change was. Fung and LeDrew (1987) caution that, even though it is a powerful data reducing technique, PCA should be used only with a thorough understanding of the characteristics of the study area to avoid drawing any faulty conclusions. Therefore, although change detection by PCA is possible, interpreting the changes is more complex than in post classification change detection.

6.5 Summary

The following points emerge as the main results of the investigation:-

1. When the area common to all the images used (24 September 1984, 3 September 1988, 12 September 1991, 20 September 1994) was considered, the post classification change detection technique showed that there were inconsistent trends in the change of the area of land cover classes on the Kafue Flats. Substantial losses in, for example, amounts of dense, vigorous green vegetation or water between two images dates were followed by gains, or vice versa. The same is true of dry land categories, sparse green vegetation and burnt land. No significant linear regression equation, therefore, could be fitted to the changes.

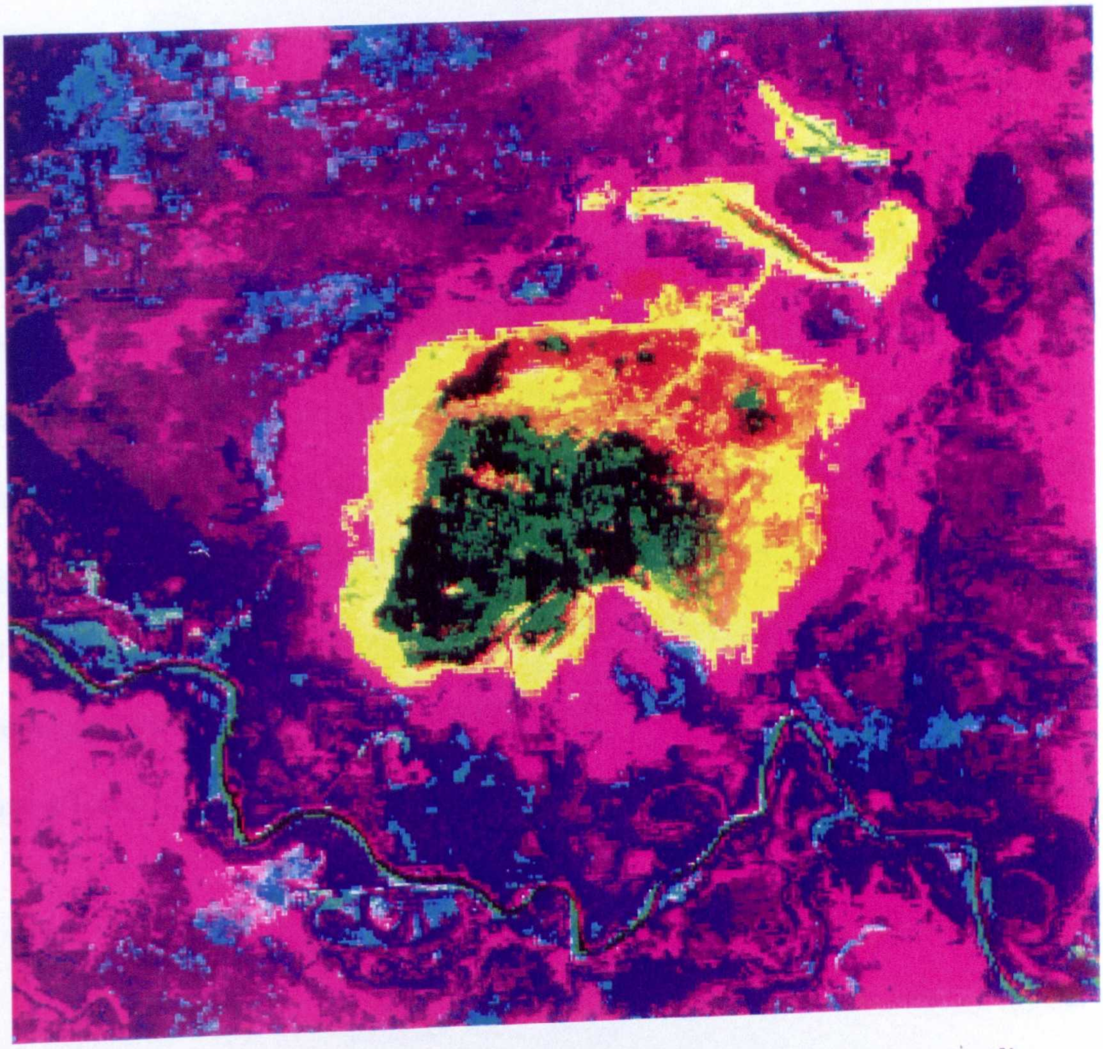


Figure 6.13 A colour composite image of PCA eigen images 3 (red), 2 (green) and 1 (blue) showing the changes in the outline of Shalwembe Lagoon (in middle of picture). The eigen images were produced from the merged data set of all the images used (see Table 6.12). The lagoon has been getting smaller. The 24 September 1984 outline is the outermost red zone, the 3 September 1988 outline is in yellow, the 12 September 1991 outline is the red zone enclosed by the yellow zone, and the 20 September 1994 outline is the central dark zone. Around the lagoon on the floodplain are other (difficult to interpret) changes shown in different colours. See also Table 6.9.

However, separate mapping of dense green and sparse vegetation and overlay analysis in a GIS framework revealed that upstream areas (approximately upstream of Nyimba), in western and north-western parts of the area common to all images, lost dense green vegetation between 24 September 1984 and 20 September 1994. Some areas under dense green vegetation on 24 September 1984 were under sparse green vegetation on 20 September 1994. This dense green vegetation, the main characteristic distinguishing the Kafue Flats as a wetland at the time of the year of the study (September, dry season), was being lost around lagoons, especially Shalwembe lagoon. In spite of the upstream losses, there was more total dense green vegetation on 20 September 1994 than on 24 September 1984, possibly indicating gains in dense green vegetation in downstream areas affected by backing up of water from the lower dam at Kafue Gorge.

2. When subsections of the area common to all images used (24 September 1984, 3 September 1988, 12 September 1991, 20 September 1994) were considered, the post classification change detection technique revealed that there were inconsistent trends in the change of the amount (area) of land cover classes, like in the case of the whole study area. However, the subsections examined - Blue Lagoon West, Lochinvar, Mazabuka West and Blue Lagoon - each showed localised, different fluctuations in the land cover categories, indicating different magnitudes of causes of change for each subsection. The Blue Lagoon West subsection, largely covering the upstream area showing losses in dense green vegetation and gains in sparse green vegetation, revealed that approximately 2 593.5hectares of dense green vegetation were lost between 24 September 1984 and 20 September 1994, with a

gain of approximately 3 879.4 hectares of sparse green vegetation in the same period. Large lagoons fluctuated in water content but no consistent trend emerged.

3. Analysis of NDVI (Normalised Difference Vegetation Index) change for the entire area common to all the images used revealed potential of the technique to indicate how dry (or wet) the area was on the date of image acquisition. NDVI change analysis of the four images revealed that the area was driest on 12 September 1991, coinciding with the date with the lowest amount (area) of dense green vegetation detected by the post classification comparison change detection technique. NDVI change analysis for specific dense green vegetation sites on the four image dates revealed a decline in NDVI in both upstream (near Shalwembe Lagoon) and downstream (near Mazabuka) sites, although NDVI values were generally higher for downstream sites. Dry soil sites revealed a smaller decline. The changes indicate possible reduced dense green vegetation vigour, opening up of the dense green vegetation canopy and general drying up.

4. Principal Component Analysis (PCA) of a merged co-registered image data set consisting of normalised green, visible red and near-infrared bands from each of the four images from the four dates revealed potential use of PCA in indicating where change had occurred. However, interpretation of the change was more difficult than in post classification comparison of the image data without PCA transformations. The technique is generally more complex.

5. Post classification change detection was found to be a very useful change detection technique provided errors in classification are minimised. Principal component

analysis of a merged multi-temporal image data set was found to be an accurate change detection technique but it provided less interpretable information on the nature of the change compared to post classification change detection. As a change detection technique, changes in the normalised difference vegetation index (NDVI) were found not to be a very reliable technique because there was doubt about what ground cover features were causing increases or decreases in red or near-infrared reflectance in the landscape with a mixture of dry land and healthy green vegetation.

Chapter 7

DISCUSSION

7.1 Introduction

This chapter examines the results of the study in terms of ecological significance, possible causes and land management implications. It was established in Chapter 2 that the potential causes of any wetland change on the Kafue Flats are (in order of potential magnitude of impact):

1. Discharges at Itezhi-tezhi dam (magnitude, duration, timing).
2. Local rainfall (magnitude, duration, timing).
3. Abstraction of water for irrigation of sugar cane on the Nakambala Sugar Estate.
4. Burning (human induced).
5. Grazing pressure (from wildlife and cattle).

The results of the study (Chapter 6) indicate that the main wetland change response variable is the spatial extent (and, to an extent, vigour) of green water reeds and water fringe vegetation (referred to as dense green vegetation in Chapter 6). This vegetation category is a mixture of mainly *Cyperus papyrus, Typha domingensis, Polygonum senegalense, Vossia cuspidata, Phragmites mauritianus, Sesbania sesban,* sedges and other grasses (see Section 5.2). Therefore, the land cover categories that potentially could best show the largest change in response to the potential change causative factors are:

1. Dense green vegetation, with the sub - categories of (i) Dense, very vigorous- (ii) Dense, vigorous - (iii) Less dense, stressed - , and (iv) Sparse, stressed water reeds/water fringe vegetation.
2. Amount of dry land.

These land cover categories will be examined for their relationship with potential wetland change causative factors. Potentially, they would all be affected by changes in the wetland's water content and changes in magnitude of the causative factors.

Turner (1982) has observed that there is no simple relation between measured river levels and area of flooding on the Kafue Flats. Because of incomplete data from the Nyimba gauge station (Figure 2.1, Section 2.3.2), which is the only centrally located monitoring station in the area covered by the images, this response variable will not be used analytically as one of the potential change indicative variables. River level data opposite the Nakambala Sugar Estate are complete between 1983 and 1994 (Figure 2.13b) but the river levels in this section of the Kafue Flats are highly influenced by the backing up effect of the lower dam at Kafue Gorge and are, therefore, artificial and unreliable as change response indicative data. Human induced burning is a random event and, therefore, analysis of trends in burning is not very useful as a variable of study on only one day of each of the years under study. Its timing, however, has impact on nearly all the vegetation cover classes.

7.2 Significance and Possible Causes of the Observed Land Cover Changes

The magnitudes of the potential causes and response of wetland change over time are listed in Table 7.1 and their correlations are listed in Table 7.2. The correlation table

(Table 7.2) lists both the correlations of the causative variables among themselves and with the response variables, and the correlations of the response variables among themselves.

Interpretation of the correlation in the context of cause-and-effect should be undertaken with caution because there may be high correlations between variables when they really represent two measurements, each quite closely related to some third variable, and not to one another directly. The low number of observations also limits the confidence with which conclusions can be made. However, the resulting correlations do point to possibilities of cause-and-effect. Correlation coefficients (r) which were greater than those (in statistical tables) at the 5% level of probability were taken to be significant. The null hypothesis was that the correlation coefficient (r) was zero, in order to test whether or not the calculated r (positive or negative) was significantly different from zero.

There is an almost significant positive correlation between total local seasonal rainfall (at Kafue Polder, Figure 2.4) on the Kafue Flats and the peak discharge into the Flats at Itezhi-tezhi dam ($r = 0.463$, $P = 0.071$; Table 7.2). The peak discharge (called `freshet') takes place towards the end of the rain season (around February - April), is a simulation of the previously natural event prior to damming (see Section 2.7.1) and its magnitude, timing and duration are very important to the wetland's ecology (see Section 2.3.1.2) because they determine how wet the wetland stays in the dry season. The almost significant positive correlation between local rainfall and the peak discharge at Itezhi-tezhi dam suggests that peak discharges through the dam, regulated by the

Table 7.1 Magnitudes of Potential Wetland Change Cause and Effect Variables on the Kafue Flats

(a) Potential Wetland Change Causes

Image Date	Rain Season and Hydrological year (preceding image date)	[a] Total local rainfall, at Kafue Polder (mm)	[b] Peak mean monthly discharge at Itezhi-tezhi (m^3s^{-1})	[b] Lowest mean monthly discharge at Itezhi-tezhi (m^3s^{-1})	[c] Total abstraction for sugar cane irrigation (m^3)
	1977/78	1 080.2	----	----	----------
	1978/79	788.1	1 386	204	----------
	1979/80	*693.2	931	126	122 588 615
	1980/81	1 047.4	1 466	145	107 642 892
	1981/82	817.3	481	132	143 879 334
	1982/83	*549.7	296	115	119 248 803
24/9/84	1983/84	*460.1	285	133	141 024 440
	1984/85	*639.7	480	135	135 766 028
	1985/86	*764.7	588	118	155 491 208
	1986/87	*644.4	356	121	146 768 592
03/9/88	1987/88	*586.8	645	97	189 709 161
	1988/89	1 045.3	411	97	188 613 064
	1989/90	904.7	428	108	180 801 422
12/9/91	1990/91	*638.0	304	106	185 291 224
	1991/92	*509.2	203	120	193 780 651
	1992/93	*749.8	755	83	144 735 326
20/9/94	1993/94	*585.4	844	65	150 059 917

* Below average (771 mm) seasonal rainfall
[a] Data: Zambia Meteorology Department, Lusaka.
[b] Data: Zambia Electricity Supply Corporation (ZESCO), Lusaka.
[c] Data: Zambia Sugar Company, Mazabuka. Graphed in Figure 2.28.

(b) Potential Wetland Change Effect Variables

Variable	Area on image date (see Tables 6.1 and 6.2) 24 Sep. 1984	3 Sep. 1988	12 Sep. 1991	20 Sep. 1994
Class 2	4 994.9 ha	11 915.7 ha	4 280.2 ha	4 959.5 ha
Class 3	17 153.7 ha	13 684.1 ha	12 934.5 ha	15 305.3 ha
Class 4	13 690.0 ha	23 741.2 ha	18 150.8 ha	19 564.8 ha
Class 5	20 207.4 ha	27 996.3 ha	17 501.1 ha	30 429.5 ha
Total dense green	35 838.6 ha	49 341.0 ha	35 365.5 ha	39 829.6 ha
Total dry land	126 159.3 ha	128 800.5 ha	124 079.5 ha	138 939.0 ha

Where:

Class 2 = Dense, very vigorous water reeds/water fringe vegetation
Class 3 = Dense, vigorous water reeds/water fringe vegetation
Class 4 = Less dense, stressed water reeds/water fringe vegetation
Class 5 = Sparse, stressed water reeds/water fringe vegetation
Total dense green = total area under Classes 2, 3, and 4
Total dry land = total area under dry land classes (see Table 6.2)

Table 7.2 Correlation of Potential Wetland Change Cause and Response Variables on the Kafue Flats

Variable	1	2	3	4	5	6	7	8	9
2	**r = 0.463 P = 0.071 NS**								
3	r = 0.146 P = 0.590 NS	**r = 0.427 P = 0.099 NS**							
4	r = -0.046 P = 0.870 NS	**r = -0.529 P = 0.042 ***	**r = -0.432 P = 0.107 NS**						
5	r = 0.100 P = 0.900 NS	r = 0.344 P = 0.656 NS	r = -0.082 P = 0.916 NS	r = 0.556 P = 0.444 NS					
6	**r = -0.933 P = 0.067 NS**	r = -0.082 P = 0.918 NS	r = 0.331 P = 0.669 NS	**r = -0.936 P = 0.064***	r = -0.307 P = 0.693 NS				
7	r = 0.650 P = 0.350 NS	r = 0.652 P = 0.348 NS	r = -0.614 P = 0.386 NS	r = 0.720 P = 0.280 NS	r = 0.775 P = 0.225 NS	r = -0.685 P = 0.315 NS			
8	r = 0.101 P = 0.899 NS	**r = 0.969 P = 0.031 ***	r = -0.774 P = 0.226 NS	r = -0.085 P = 0.915 NS	r = 0.479 P = 0.521 NS	r = 0.058 P = 0.942 NS	r = 0.630 P = 0.370 NS		
9	r = 0.202 P = 0.798 NS	r = 0.586 P = 0.416 NS	r = -0.343 P = 0.657 NS	r = 0.499 P = 0.501 NS	**r = 0.962 P = 0.038***	r = -0.320 P = 0.680 NS	**r = 0.872 P = 0.128 NS**	r = 0.685 P = 0.315 NS	
10	r = 0.088 P = 0.912 NS	**r = 0.916 P = 0.084 NS**	**r = -0.850 P = 0.150 NS**	r = -0.388 P = 0.612 NS	r = -0.018 P = 0.982 NS	r = 0.211 P =0.789 NS	r = 0.297 P = 0.703 NS	**r = 0.869 P = 0.131 NS**	r = 0.241 P = 0.759 NS

Where :

r = Pearson's correlation coefficient
P = Probability of correlation coefficient being zero
NS = correlation coefficient not significant at 5%
* = correlation coefficient significant at 5% (significant and almost significant correlation coefficients are highlighted)

Variable 1 - Total local rainfall
Variable 2 - Peak discharge at Itezhi-tezhi dam
Variable 3 - Lowest discharge at Itezhi-tezhi dam
Variable 4 - Abstraction for sugar cane irrigation
Variable 5 - Dense, very vigorous water reeds/water fringe vegetation
Variable 6 - Dense, vigorous water reeds/water fringe vegetation
Variable 7 - Less dense, stressed water reeds/water fringe vegetation
Variable 8 - Sparse, stressed water reeds/water fringe vegetation
Variable 9 - Total water reeds/water fringe vegetation
Variable 10 - Total dry land

Zambia Electricity Supply Corporation (ZESCO), are high when there is a lot of rainfall (and, therefore, high reservoir water levels and excess water in the reservoir). It, therefore, means that in below average rain seasons when there is no excess water in the reservoir, the wetland will receive less water than would be the case naturally because water from upper parts of the basin will be held back by the dam at Itezhi-tezhi - the inlet for upper basin flood water (Sections 2.3.1.1 and 2.3.1.2). The data in Table 7.1 confirm this. Normal (average) rainfall on the Kafue Flats at Mazabuka and Kafue Polder is 771 mm (Zambia Meteorology Department, see Section 2.2), and ZESCO assured a freshet of at least 300 m^3s^{-1} for four weeks, even in dry years (Section 3.4.1.1). A number of the rain seasons listed in Table 7.1 had below average rains (droughts)[1]. In 3 out of 11 of these drought years, ZESCO barely discharged the assured 300 m^3s^{-1} freshet, and this was in seasons with some of the lowest total rainfall, i.e. 1982/83 (549.7 mm total rainfall, 296 m^3s^{-1} peak discharge), 1983/84 (460.1 mm total rainfall, 285 m^3s^{-1} peak discharge), and 1991/92 (509.2 mm total rainfall, 203m^3s^{-1} peak discharge, the lowest ever). In the other drought seasons the peak discharges were higher than the 300 m^3s^{-1} assured freshet, perhaps due to other reasons like surges in demand for electricity generated at Kafue Gorge. The low peak discharges in dry years confirm predictions made in the 1970's and early 1980's (Section 3.4.1.1). The reductions in maximum reservoir water levels in the 1983/84 and 1991/92 hydrological years (Figure 2.12a) coincide with the droughts in these seasons, and minimum reservoir water levels respond to droughts with an approximately 1 - year time lag, during which reservoir water is depleted and recovery is a year later (Figure

[1] These were 1979/80, 1982/83, 1983/84, 1984/85, 1985/86, 1986/87, 1987/88, 1990/91, 1991/92, 1992/93 and 1993/94 rain seasons. The corresponding peak discharges at Itezhi-tezhi during these seasons were 931 m^3s^{-1}, 296 m^3s^{-1}, 285 m^3s^{-1}, 480 m^3s^{-1}, 588 m^3s^{-1}, 356 m^3s^{-1}, 645 m^3s^{-1}, 304 m^3s^{-1}, 203 m^3s^{-1}, 755 m^3s^{-1} and 844 m^3s^{-1}, respectively, which were low compared to 1 466 m^3s^{-1} in the 1980/81 season (Table 7.1).

2.12a). The fluctuations in peak discharge shown in Table 7.1 are approximately synchronous with the fluctuations in mean annual discharges at Itezhi-tezhi shown in Figure 2.12b).

The almost significant negative correlation between total local rainfall and amounts of dense, vigorous water reeds/water fringe vegetation ($r = -0.933$, $P = 0.067$; Table 7.2) might be accidental since only 4 values were used. Alternatively it might be a result of the fact that with high total rainfall and, consequently, high discharge at Itezhi-tezhi, a wider area of the Kafue Flats is flooded. This results in more vegetation under the less dense, stressed category by September (image acquisition time) when it is stressed (stranded) by the retreated flood. There is a high, positive correlation between total local rainfall and less dense, stressed water reeds/water fringe vegetation, which seems to support this suggestion ($r = 0.650$, $P = 0.350$, not significant; Table 7.2).

There is an almost significant positive correlation between peak and lowest discharges through Itezhi-tezhi dam ($r = 0.427$, $P = 0.099$; Table 7.2), suggesting that when peak discharges are high (in water surplus rain seasons), ZESCO can afford to allow more water out of the reservoir in the dry season. Peak discharges at Itezhi-tezhi show significant negative correlation with abstractions of water for irrigation of sugar cane by the Zambia Sugar Company (ZSC) ($r = -0.529$, $P = 0.042$; Table 7.2). It is difficult to ascertain the reason for this, especially because ZESCO and ZSC respond to dissimilar levels of demand for the electricity and sugar products, respectively, in their levels of operation. However, the negative correlation might be because when there is normal or surplus seasonal rainfall (and, therefore, high peak discharge at Itezhi-tezhi), there is less need for irrigating the sugar cane in the rain season, resulting in less abstraction of water for irrigation and hence the negative correlation. As pointed out in Section 2.7.2, cane irrigation in the rainy season is used as a supplement to the rainfall, according to the Estate's Irrigation Manager[1]. The total abstractions in the below average rainfall seasons (1979/80, 1982/83, 1983/84, 1984/85, 1985/86, 1986/87, 1987/88, 1990/91, 1991/92, 1992/93 and 1993/94) are, however, difficult to compare with the normal rainfall years in terms of whether or not there was higher total abstraction for irrigation in the corresponding hydrological years because there has been a general increase in annual total abstractions by ZSC since 1979 (Figure 2.28), perhaps due to the expansion of the sugar estate (Section 2.7.2).

Significant positive correlation ($r = 0.969$, $P = 0.031$; Table 7.2) between peak discharge at Itezhi-tezhi and the amount of sparse, stressed water reeds/water fringe vegetation might be because higher peak discharges result in wider flooding (spatially), leaving more sparse, stressed water reeds/water fringe vegetation by September (image acquisition time) when the flood has receded. It is difficult to account for the high (nearly significant) positive correlation ($r = 0.916$, $P = 0.084$; Table 7.2) between peak Itezhi-tezhi discharges and the total amount of dry land but perhaps it is because with high peak discharge, the resulting wider flooding maintains more green vegetation for longer periods, which prevents early burning. By September (image acquisition time), this vegetation is dry in sections of the outer most areas of the floodplain where it may still be unburnt. Lowest discharges through Itezhi-tezhi show nearly significant negative correlation with total amounts of dry land ($r = -0.850$, $P = 0.150$), meaning that there is more dry land with lower minimum discharges through Itezhi-tezhi dam. This is likely to be because lower minimum discharges in the dry season sustain less

[1] Nang'omba, pers. comm. (as Irrigation Manager, 1995).

green vegetation on the floodplain. Lowest discharges through Itezhi-tezhi dam also show nearly significant negative correlation with abstractions of water for irrigation of sugar cane (r = -0.432, P = 0.107; Table 7.2). This is perhaps because when the discharges are lower (in the dry season and after below average rains), there is more need for irrigation and, therefore, abstractions are higher.

The almost significant and high negative correlation between abstractions for sugar cane irrigation and amounts of dense, vigorous water reeds/water fringe vegetation (r = -0.936, P = 0.064; Table 7.2) is difficult to account for but it might mean that with higher amounts of abstraction of water, less water is left upstream to sustain dense, vigorous water reeds/water fringe vegetation on the wetland in the dry season. The amount of vegetation in the dense, very vigorous water reeds/water fringe vegetation and the less dense, stressed water reeds/water fringe vegetation categories shows positive correlation with the total amount of green water reeds/water fringe vegetation. For these respective variables, r = 0.962 (P = 0.038, significant) and r = 0.872 (P = 0.128, not significant; Table 7.2). Perhaps these classes could serve as indicators of the plight of green water reeds/water fringe vegetation. Amounts of sparse, stressed water reeds/water fringe vegetation show almost significant positive correlation (r = 0.869, P = 0.131; Table 7.2) with amount of dry land, perhaps because they occur in close proximity, i.e. as more sparse, stressed water reeds/water fringe vegetation dries out, more dry land results.

7.2.1 Changes in the Whole Study Area

The total rainfall received by the Kafue Flats shows nearly significant positive correlation with discharges into the Kafue Flats from Itezhi-tezhi dam (r = 0.463, P =

0.071). It is the main influence on the discharges into the Kafue Flats from Itezhi-tezhi dam, which in turn are the main influence on the wetness and green vegetation content of the Flats in the dry season (Table 7.2; Section 7.2). The rainfall and hydrological conditions in the periods leading up to the image acquisition dates are as shown in Table 7.3. The conditions could help to account for the changes observed for the study area taken as a whole (Tables 6.1 and 6.2; Figure 6.1). The total seasonal rainfall prior to the image dates decreases in the image date order 12 September 1991, 3 September 1988, 20 September 1994 and 24 September 1984. However, differences in the timing, distribution and amount of the local rainfall in the preceding season probably have little effect on the inter-image changes because the months May, June, July and August are similar prior to all the image acquisition dates because they were dry (Figure 7.1).

Table 7.3 Comparison of the Timing of Rainfall and Hydrological Events on the Kafue Flats Prior to the Image Acquisition Dates

Image date	Preceding rain season and hydrological year *	Kafue Polder total rainfall (mm) **	Date of first rains, and amount of rain **	Date of last rains, and amount of rain **	Length of rain season (no. of months)	Peak mean monthly discharge at Itezhi-tezhi (m^3s^{-1}) ***	Lowest mean monthly discharge at Itezhi-tezhi (m^3s^{-1}) ***	Peak discharge month ***	Lowest discharge month ***
24.9.84	**1983/84**	**460.1**	**15.10.83 (10.8mm)**	**1.4.84 (7.9 mm)**	**7**	**285**	**133**	**Mar. `84**	**Sep. ` 84**
3.9.88	**1987/88**	**586.8**	**2.10.87 (22.4mm)**	**21.4.88 (1.7 mm)**	**7**	**645**	**97**	**Mar. `88**	**Jan. `88**
12.9.91	**1990/91**	**638.0**	**16.11.90 (0.3 mm)**	**7.4.91 (8.5 mm)**	**6**	**304**	**106**	**Apr. `91**	**Feb. `91**
20.9.94	**1993/94**	**585.4**	**5.11.93 (13.0 mm)**	**23.4.94 (9.0 mm)**	**6**	**844**	**65**	**Feb. `94**	**Jul. `94**

* Rain season is from October/November in the previous calendar year to March/April in the calendar year concerned. Hydrological year is from October in the previous calendar year to September in the calendar year concerned.

**Data: Zambia Meteorology Department

***Data: Zambia Electricity Supply Corporation

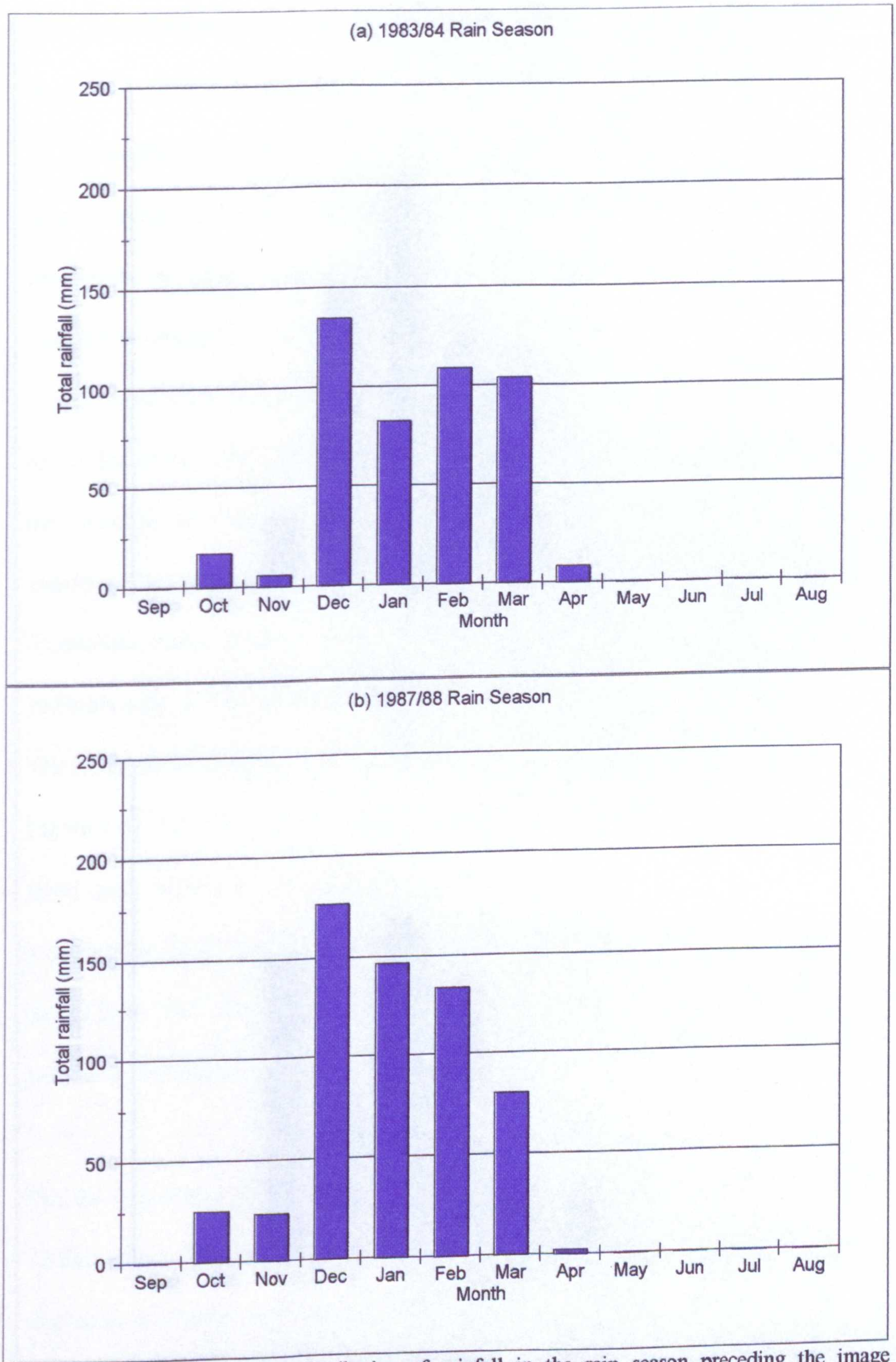


Figure 7.1 Comparison of the distribution of rainfall in the rain season preceding the image acquisition dates: (a) Preceding the 24 September 1984 image (b) Preceding the 3 September 1988 image. The rain season started in October/November in the preceding year, ended in the April before the respective September image acquisition dates. [Data: Zambia Meteorology Department, Lusaka]

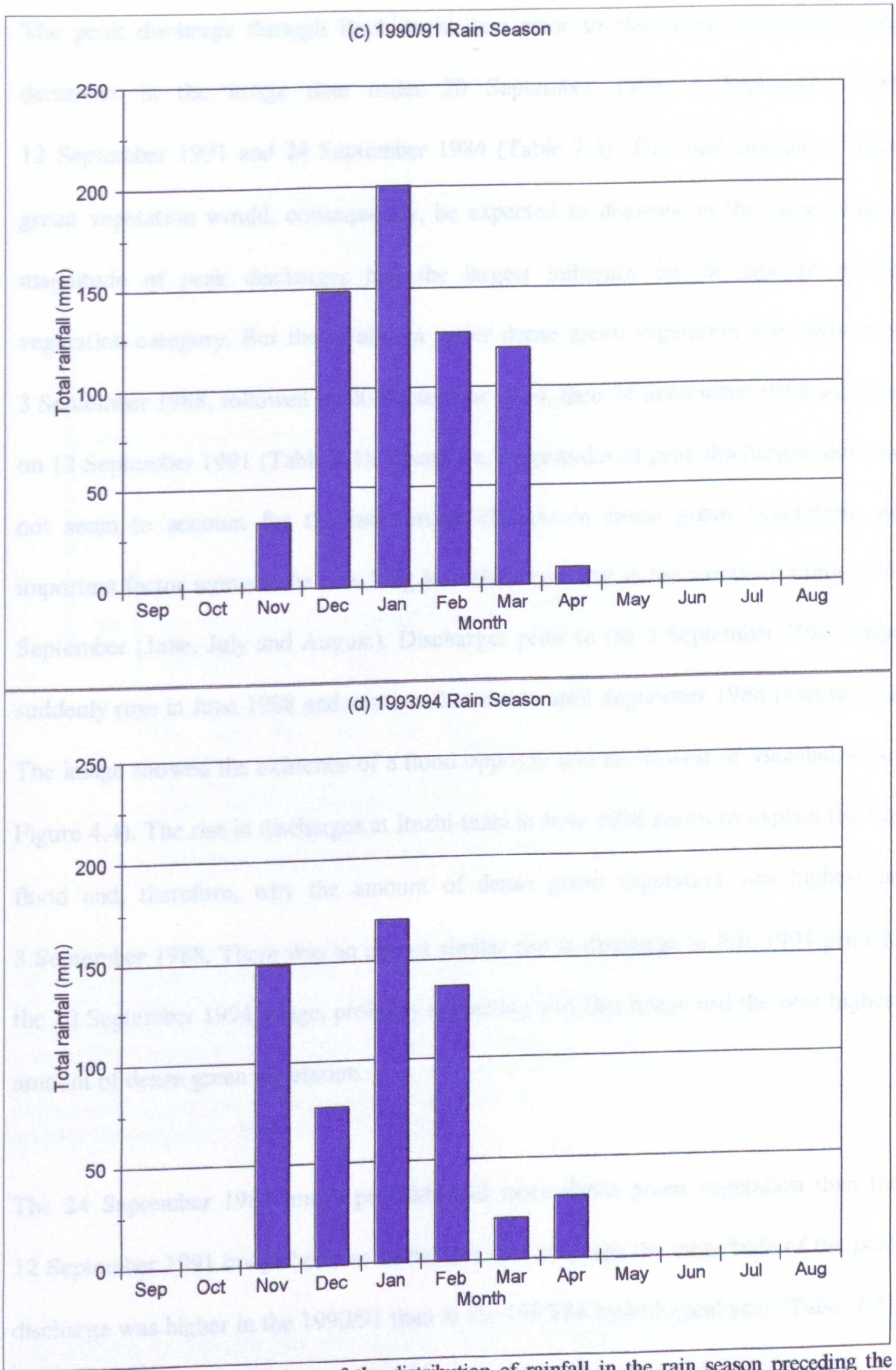


Figure 7.1 (*continued*) Comparison of the distribution of rainfall in the rain season preceding the image acquisition dates: (c) Preceding the 12 September 1991 image (d) Preceding the 20 September 1994 image. The rain season started in October/November in the preceding year, ended in the April before the respective September image acquisition dates. [Data: Zambia Meteorology Department, Lusaka].

The peak discharge through Itezhi-tezhi dam prior to the image acquisition dates decreases in the image date order 20 September 1994, 3 September 1988, 12 September 1991 and 24 September 1984 (Table 7.3). The total amount of dense green vegetation would, consequently, be expected to decrease in the same order if magnitude of peak discharges had the largest influence on the amount of this vegetation category. But the total area under dense green vegetation was highest on 3 September 1988, followed by 20 September 1994, then 24 September 1984 and least on 12 September 1991 (Table 7.1). Therefore, magnitudes of peak discharges alone do not seem to account for the inter-image changes in dense green vegetation. An important factor seems to be how long low discharges last in the months leading up to September (June, July and August). Discharges prior to the 3 September 1988 image suddenly rose in June 1988 and continued to do so until September 1988 (Figure 7.2). The image showed the existence of a flood opposite and north-west of Mazabuka (see Figure 4.4). The rise in discharges at Itezhi-tezhi in June 1988 seems to explain the late flood and, therefore, why the amount of dense green vegetation was highest on 3 September 1988. There was an almost similar rise in discharge in July 1994 prior to the 20 September 1994 image, probably explaining why this image had the next highest amount of dense green vegetation.

The 24 September 1984 image probably had more dense green vegetation than the 12 September 1991 image because of the fact that although the magnitude of the peak discharge was higher in the 1990/91 than in the 1983/84 hydrological year (Table 7.3), a higher discharge was sustained in the months May, June and July 1984 than in the same months in 1991 (Figure 7.2). NDVI change analysis was, therefore, correct in detecting that on the images used, the area was driest on 12 September 1991 and wettest on 3 September 1988 (see Figure 6.10; Section 6.4.1).

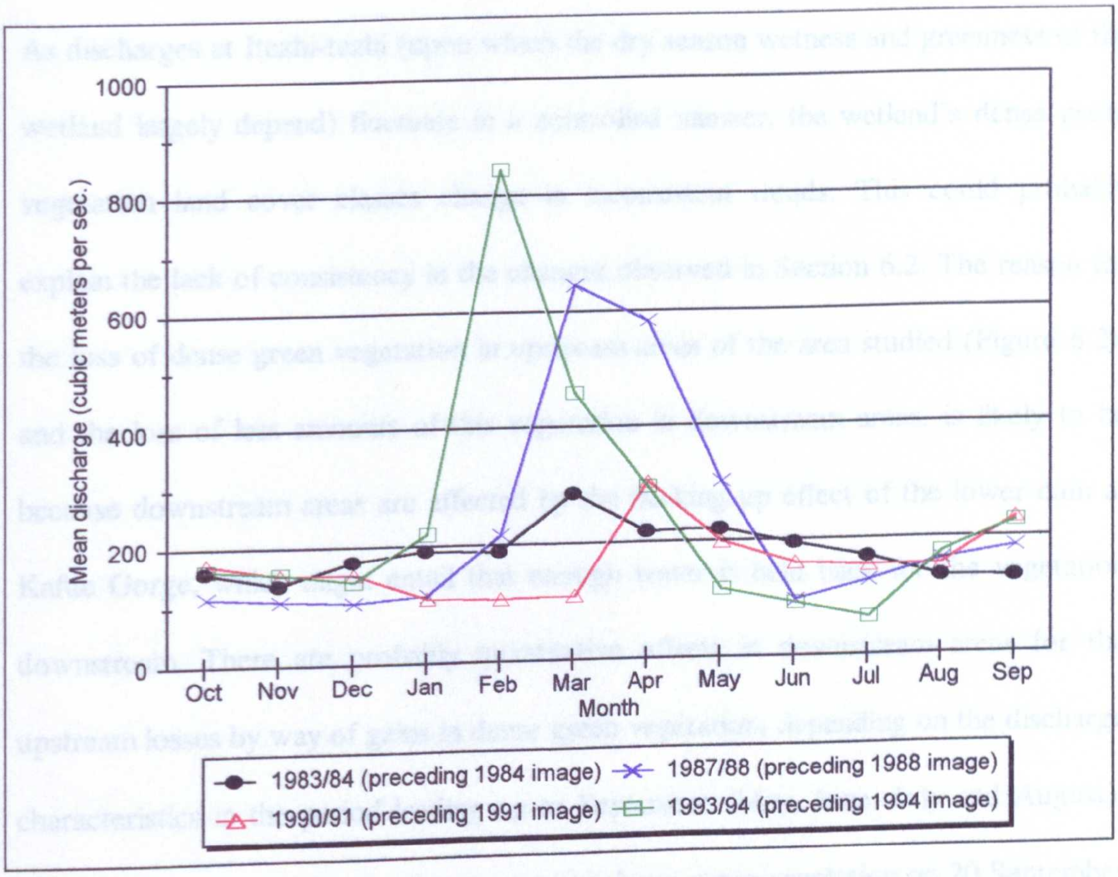


Figure 7.2 Comparison of discharges from Itezhi-tezhi dam into the Kafue Flats in the periods preceding the image acquisition dates. The hydrological year started in October of the preceding year and ended in September, the month of acquisition of the respective images. In the legend, 1983/84 refers to the 1983/84 hydrological year which preceded the 24 September 1984 image, 1987/88 refers to the 1987/88 hydrological year which preceded the 3 September 1988 image, 1990/91 refers to the 1990/91 hydrological year which preceded the 12 September 1991 image, and 1993/94 refers to the 1993/94 hydrological year which preceded the 20 September 1994 image. No actual daily data were available for comparison. [Data: ZESCO, Lusaka]

It is difficult to account for site specific NDVI changes (Figure 6.11) because site specific conditions on the day of image acquisition, such as presence or absence of water, prior burning or grazing, and opening up of the vegetation canopy by cattle, might have been responsible. No ground visits to these sites on the image acquisition dates were made.

As discharges at Itezhi-tezhi (upon which the dry season wetness and greenness of the wetland largely depend) fluctuate in a controlled manner, the wetland's dense green vegetation land cover classes change in inconsistent trends. This could probably explain the lack of consistency in the changes observed in Section 6.2. The reason for the loss of dense green vegetation in upstream areas of the area studied (Figure 6.2), and the loss of less amounts of this vegetation in downstream areas, is likely to be because downstream areas are affected by the backing up effect of the lower dam at Kafue Gorge, which might entail that enough water is held back for the vegetation downstream. There are probably quantitative offsets in downstream areas for the upstream losses by way of gains in dense green vegetation, depending on the discharge characteristics in the period leading up to September (May, June, July and August). This might be the reason why there was more dense green vegetation on 20 September 1994 than on 24 September 1984 (Table 6.2) in spite of the upstream losses.

It is likely that the dry season losses in dense green vegetation in the upstream areas have had ecological effects. Pin pointing exactly what the effects have been needs detailed field surveys and monitoring of both plant and animal species, which would yield information on what plant or animal species has become more abundant or rare. The lack of unique spectral signatures from each of the many plant species means that the satellite borne remote sensing images used are unable to distinguish the reflectance from the different plant species if they have, for example, the same leaf type, colour, density of stands and stage (vigour) of growth. The green vegetation which has been lost includes reeds (e.g. *Cyperus papyrus, Typha domingensis, Polygonum senegalense, Phragmites mauritianus, Sesbania sesban*) and many grass species (e.g. *Vossia cuspidata,* other grasses) and sedges (see Figures 2.20 and 2.21). As a habitat, field observations indicated that such dense reeds are not favoured by large grazers like zebra (*Equus burchelli*), wildebeest (*Connochaetus taurinus*) and antelopes like lechwe (*Kobus leche kafuensis*). However, Sitatunga (*Tragelaphus spekei*) are directly at threat because, as aquatic ungulates, their habitat is dense reed marshes (Ellenbroek, 1987). Also, cattle graze in such dense reed areas (e.g. see Figures 5.2 and 5.3b). To other grazers such as lechwe and wildebeest, shorter but green vegetation stands (categorised as sparse and very sparse green vegetation in Table 6.2) seem to be more important at the time of the year of the study in September (see Figures 2.22 and 2.29). These do not seem to be reducing, at least in quantity (Figure 6.1), although spatial location and species may or may not still be ideal. For example, the abundance of drought resistant, unpalatable herbs (e.g. see Figure 5.8a) may be on the increase but the herbs are largely ungrazed by large wildlife species and cattle and are, therefore, probably of little benefit to them. Some bird species (e.g. weaver birds) were seen to be utilising the reed vegetation as perches and, possibly, as nesting sites. Invertebrates, amphibians and reptiles are also likely inhabitants of such vegetation. In addition to sitatunga it is, therefore, small birds, reptiles and amphibians which face possible direct adverse effects from losses of dense green vegetation in the dry season. However, the edge of this reed vegetation habitat is of relevance to grazers as well and its retreat in upstream areas could have some effect on them too.

What is probably a consolation, in spite of these dry season ecosystem stresses, is that the wetland does recover to varying degrees each year at the height of the rain season.

This is usually around January - March, during which period the Kafue Flats become a veritable vast shallow lake with emergent vegetation as far up the floodplain as the termitaria zone. A delay in the onset of the rain season after September postpones the beginning of this recovery and, therefore, if the rains start as late as November (as was the case in the 1990/91 and 1993/94 seasons - Table 7.3), the ecosystem stresses are prolonged and worsened. It is comforting to note that the population of the endemic Kafue lechwe (*Kobus leche kafuensis*), which was once said to be endangered, seems to be recovering from its earlier downward trend (see Table 2.5). The recovery has been attributed to the involvement of the local people in conservation and wetland management, which has reduced poaching (Jeffrey and Chooye, 1991). No reliable source of population data for the wattled crane (*Grus carunculatus*), which was also once said to be endangered, was available (see Table 2.4).

7.2.2 Changes in the Blue Lagoon West Area

This subsection included the area west and north-west of Nyimba (Figure 6.4), which revealed the largest losses in dense green vegetation and gains in sparse green vegetation in Figure 6.2. The biggest lagoon in the area (Shalwembe Lagoon) and other smaller outlying lagoons seem to have been shrinking in size (see Figure 6.13), leaving behind some green vegetation and mud. This seems to explain the steady increase in dense green vegetation from 1988 to 1991 and then onto 1994, following a large reduction between 1984 and 1988 (Table 6.4; Figure 6.5) due to losses north-west of the lagoon (Figure 6.2).

The fluctuations in the other land cover classes are perhaps due to year to year differences in discharge characteristics at Itezhi-tezhi in the months prior to the image acquisition dates as explained in Section 7.2.1. Early burning is likely to have randomly affected the vegetation classes too. Very sparse green vegetation shows a consistent declining trend, perhaps due to general drying up because dry land categories largely increased consistently between 1984 and 1991(Figure 6.5). This loss of sparse green vegetation potentially threatens wildlife grazers as the area's floodplain was seen to be grazed by lechwe and zebra (see Figure 2.22).

7.2.3 **Changes at Lochinvar**

The most notable cause of dry season change in the Lochinvar area (besides wetness characteristics in the preceding hydrological year) seems to be burning of the grassland started in the human settlement area at Itebe (Figure 6.4). This is illustrated by the fact that when there was very little burnt land on the 3 September 1988 image, the total amount of dry land was highest (Figure 6.6; Table 6.5). However, this image was unreliable for the Lochinvar area due to the presence of smoke which caused the spectral signatures of features to acquire more dry land characteristics (Figures 4.11 and 4.17). Burning also determines the amount of sparse green vegetation, as fresh grass shoots will have emerged by September after early (May/June/July) burning. Thus, when there was very little land under dry cover classes on the 1994 image (due to evident burning), very sparse green vegetation (including new shoots after burning) was the largest land cover class (Figure 6.6) due to a large amount of land under Class 10 (emergent vegetation in shallow water or after burning in Table 6.5a). The exact implications of the burning (positive or negative) on the availability of grazing areas in the national park need detailed, species specific investigation in the field. The amount of open water and dense green vegetation classes varied probably due to May, June, July and August discharge characteristics at Itezhi-tezhi as explained in Section 7.2.1.

7.2.4 **Changes in the Blue Lagoon Area**

This subsection included sparse woodland areas but the majority of it included the floodplain (see Figure 6.4). Like in the Lochinvar subsection, the larger the size of land which has been burnt, the lower the amount of dry land (under grassland) that remains. Early burning (in May, June, July) also results in sparse green vegetation by September. There is likely to have been early burning in 1984, which resulted in a large amount of land under Class 10 (emergent vegetation in shallow water or after burning, Table 6.6a), hence the large amount of land under the very sparse green vegetation category in Figure 6.7. The amount of water seems to have remained the same in the subsection (Figure 6.7). The changes in dense green vegetation are likely to have been due to the discharge characteristics at Itezhi-tezhi during the months May, June, July and August as explained in Section 7.2.1. For example, the large amount of dense green vegetation on 3 September 1988 was due to the presence of a late flood (see Figure 4.4).

7.2.5 **Changes in Mazabuka West**

The subsection largely consisted of the woodland area west of Mazabuka (see Figure 6.4). The observed changes in the subsection are very likely to be due to timing of burning as well as stages in the woodland spring leafing cycle. September is spring time and the later in September the image date is, the more green vegetation resulting from woodland spring leaf there is. This probably explains why the 3 September 1988 image had the least vegetation under the `very sparse green' category, followed by the 12 September 1991 image, then the 20 September 1994 image and then the 24 September 1984 image which had the most sparse green vegetation (Figure 6.8; Table 6.7). The 1988 image probably had the largest amount of dry land for the same reason (woodland having been largely still leafless, in early stages of spring). The amount of dense green vegetation stayed largely the same on the four dates (except for a small increase in 1988 due to the late flood) because the area is in the zone affected by backing up from the lower dam. The changes in sparse green vegetation were probably due to differences in timing of burning.

7.2.6 **Changes at Large Lagoons**

Of the two large lagoons examined (see Tables 6.8 and 6.9), Shalwembe Lagoon showed the more definite trend of drying up and being replaced by dense green vegetation as the water line retreats (see Figure 6.13). The trends in this lagoon indicate the possibility that the dry season underground water table in the upstream parts of the section of the Kafue Flats studied was falling. Chunga Lagoon is just opposite Nyimba, the approximate upstream limit of the backing up effect of the lower dam at Kafue Gorge. In spite of this, Chunga Lagoon also showed a declining trend in water content (Table 6.8).

7.2.7 **Predictions for the Future Using Observed Trends**

As was established in Section 7.2, the total local rainfall received is the main factor influencing the discharges into the Kafue Flats from Itezhi-tezhi dam. The magnitude and timing of the discharges are in turn the main influencing factor on the dry season wetness and dense green vegetation content of the floodplain wetland.

High peak discharges are ecologically more beneficial to the wetland (Sections 2.3.1.2, 2.5 and 2.6), but statistics show that the Zambia Electricity Supply Corporation (ZESCO), which regulates the discharges, is most likely to allow high peak discharges through the dam if there is normal or above average rainfall (Table 7.2). This conflict between ecology and development is likely to continue, and it is likely that national energy requirements will override ecological considerations. From the wetland conservationist's view, it might be important to predict the peak discharges through Itezhi-tezhi dam given a certain forecast amount of total seasonal rainfall. This would probably enable the conservationist to expect certain effects on the wetland, such as duration and extent of the annual flood, and the maintenance of the greenness of the floodplain. This is not an easy task, given the observed unpredictable nature of the rains recently (Section 2.2.1). Using the observed rainfall and peak discharges between 1978 and 1994 (Table 7.1), the regression relationship between the two variables is:

$$D_{max} = 1.0\ (TR) - 98 \qquad (7.1)$$

$[r^2 = 21.4\%;\ F = 3.81,\ P = 0.071]$

Where: D_{max} = Highest peak mean discharge (m^3s^{-1})
TR = Total local seasonal rainfall at Kafue Polder (mm)
F = the variance ratio statistic
P = Probability of regression not being significant (i.e. probability of slope of regression line being zero).

The regression equation is not significant. The discharge (and rainfall) values from the 1978/79 hydrological year might be unreliable because the dam at Itezhi-tezhi had just been completed and, therefore, discharges had not yet fitted into the long term pattern. If they are eliminated, the equation becomes:

$$D_{max} = 0.879\ (TR) - 58 \qquad (7.2)$$

$[r^2 = 23.1\%;\ F = 3.91,\ P = 0.070]$

(Where D_{max}, TR, F and P as in Equation 7.1).

Equation 7.2 is slightly a better regression fit than Equation 7.1 but it is not significant. As a predictive equation, its accuracy is as shown in Table 7.4, which shows that in its original form, Equation 7.2 is very inaccurate due to large prediction errors. The equation's average error, calculated using the absolute values of the prediction errors (i.e. ignoring positive or negative nature) is 228.6 m^3s^{-1} (Table 7.4). Adding and subtracting the average error to and from the predicted mean peak discharge, respectively, yields a predicted range in which the actual peak discharge is likely to be (column 6 in Table 7.4), given a certain amount of total seasonal rainfall. This operation can be summarised as:

$$D_{max} = [0.879\ (TR) - 58]\ ^{+}/_{-}\ 228.6 \qquad (7.3)$$

(Where D_{max}, and TR as in Equation 7.1).

The resulting predicted ranges encompass the actual peak mean monthly discharges observed at Itezhi-tezhi for all below average rainfall (drought) years. Equation 7.3, therefore, accurately predicts the range of peak discharges to be expected for a given lower than normal rainfall year's forecast sum of seasonal rainfall at Kafue Polder. This is only with the exception of the seasons before and including 1980/81, perhaps because during these seasons the discharge pattern at Itezhi-tezhi dam was not yet settled. Unfortunately this equation cannot accurately be used to predict the peak discharges from a given lower than normal rainfall year's seasonal rainfall forecast from the Zambia Meteorology Department, assuming that ZESCO is unwilling to reveal their discharge plans. The peak discharges significantly correlate statistically with some wetland change cause and response variables such as abstraction of water for irrigation at Nakambala and amount of sparse, stressed water reeds/water fringe

Table 7.4 Performance of a Possible Predictive Equation for Dry Season Discharges into the Kafue Flats from Itezhi-tezhi

Rain Season and Hydro-logical year	Total local rainfall, at Kafue Polder (mm)	Actual peak mean monthly discharge at Itezhi-tezhi (m^3s^{-1})	Equation 7.2's prediction of peak mean monthly discharge at Itezhi-tezhi (m^3s^{-1})	Equation 7.2's Prediction error (m^3s^{-1})	Predicted range of mean monthly discharge at Itezhi-tezhi (m^3s^{-1}) using Equation 7.3
1977/78	1 080.2	----			
1978/79	788.1	1 386			
1979/80	693.2	931	551.3	-379.7	322.7 - 779.9
*1980/81	1 047.4	1 466	862.7	-603.3	634.1 -1091.3
*1981/82	817.3	481	660.4	179.4	431.8 - 889.0
1982/83	549.7	296	425.2	129.2	196.6 - 653.8
1983/84	460.1	285	346.4	61.4	117.8 - 575.0
1984/85	639.7	480	504.3	24.3	275.7 - 732.9
1985/86	764.7	588	614.2	26.2	385.6 - 842.8
1986/87	644.4	356	508.4	152.4	279.8 - 737.0
1987/88	586.8	645	457.8	-187.2	229.2 - 686.4
*1988/89	1 045.3	411	860.8	449.8	632.2 -1089.4
*1989/90	904.7	428	737.2	309.2	508.6 - 965.8
1990/91	638.0	304	502.8	198.8	274.2 - 731.4
1991/92	509.2	203	389.6	186.6	161.0 - 618.2
1992/93	749.8	755	601.1	-153.9	372.5 - 829.7
1993/94	585.4	844	456.6	-387.4	228.0 - 685.2
				Mean = 228.6	

(* Not below average rainfall year)

vegetation. They show nearly significant correlation with the amount of dry land. If an accurate equation was developed, it may then be possible to draw out a range of consequences on the wetland, given an expected range of peak discharge, possibly enabling planning of conservation strategies.

It is impossible to predict future trends accurately, though. The seasonal rainfall at Kafue Polder seems to be going through wet and dry cycles (Figure 2.5b). From Figure 2.5b, the early 1990's seem to be the beginning of a wet phase in recovery from the dry phase which began around 1978. If this is the case, the wetland could become wetter in the dry season than was the case from 1981 to the mid 1990's. The situation is, however, complicated by plans to increase the electricity and sugar cane production activities on the Kafue Flats (see Sections 2.7.1 and 2.7.2).

7.3 Evaluation of Methodological Procedures and the Error Factor

Care was taken to minimise the error factor during each step of the methodological procedures. The inherent, unavoidable errors in the process will in turn be evaluated for their overall bearing on the results.

7.3.1 Design of the Study in Relation to Climatic and Hydrological Cycles

The design of the study is outlined in Section 4.2. The observed changes (Chapter 6) would be most meaningful if the environment, on each of the dates being compared, was similar (i.e. near anniversary dates, see Section 3.2.1.2). On the Kafue Flats, seasonal and river hydrological (flow) characteristics could result in inter-image land cover differences. These differences could in turn make interpretation of long term change difficult.

The images used (from 24 September 1984, 3 September 1988, 12 September 1991, and 20 September 1994) are from the same season and, therefore, vegetation phenology stage differences were minimised. However, the phenology stages were not *exactly* the same. Being September images (Southern Hemisphere spring time), there were differences in the stages of growth of the spring leaf. In the three weeks between the earliest September date (3 September) and the latest (24 September), some plant species could change from a leafless state to full spring leaf, with the result that the late

September image could have more near infrared reflectance from vegetation than the early September one. Very little could be done to minimise such errors because no `same September date' images were available in archive at the earth receiving station in South Africa. These differences were, however, only applicable to deciduous woodland and floodplain herb and shrub plant species which respond to seasonal temperature differences in their leafing cycle. Wetland species such as water meadows (e.g. *Acroceros macrum*), water lilies (e.g. *Nymphaea* spp.), *Aeschynomene fluitans*, *Cyperus papyrus*, *Typha domingensis*, *Polygonum senegalense*, *Vossia cuspidata*, *Phragmites mauritianus* and *Sesbania sesban* depend more on the presence or absence of surface or near subsurface water for their leafing and vigour status, as the most important factor determining the vegetation on the floodplain is the timing and duration of the flooding (Ellenbroek, 1987).

As much of the peripheral woodland zone as possible was excluded from the study (see Section 4.5). However, the floodplain could not be accurately delineated and isolated for study, mainly because, as is the case with wetlands in general (Kent, 1994a), its boundary is not clear (Turner, 1982). Therefore, analyses of dense green vegetation were correct because dense green vegetation is largely absent from the higher ground in the dry season and is mostly found on the wetland. The dense green vegetation multi-temporal mapping in Figure 6.2 is, therefore, reliable. Analyses of sparse green vegetation were, however, more susceptible to errors introduced by differences in September vegetation phenology stages. These errors were worsened by differences in timing of burning. If burning is early (May/June/July), fresh shoots of some grass species will have grown by September.

A possible solution to avoid spring phenology stage errors would be to use late October or November images when the growth of spring leaves is complete. However, by then the first rains will have fallen (Table 7.3). The rains will have triggered grass seed germination, thereby introducing further inter-image sparse vegetation change errors. Also by then, increased cloud cover due to rain clouds will have introduced more interference of the reflectance from the ground cover classes. Therefore, the best time of study of long term change on the Kafue Flats seems to be just after the cold season (August/September). The wetland is weakest then because discharges into it are approaching their dry season lowest stage. Any trends could best show then. Hydrological differences from year to year are smallest in August and September, in terms of discharges into the wetland from Itezhi-tezhi (see Figures 2.10 and 7.2), although differences in discharges from Itezhi-tezhi in the period May/June/July seem to be very influential on the late dry season greenness of the wetland (Section 7.2.1).

The results of the study are, therefore, reliable in indicating the plight of the Kafue Flats wetland under the climatic and human stresses. It could be argued that the best design of such a study would be to use images from the same day of the month for each of the years. The discharge characteristics into the wetland, weather on the dates and in the preceding period, and the timing of any prior burning should, ideally, be the same. It is, however, unlikely that all of these (human and natural) factors can be exactly the same on dates which are years apart.

7.3.2 Appropriateness of Images Used

It was important to use images which were similar in terms of spectral resolution and region of the electromagnetic spectrum covered. On the images used, MSS band 1 (green, 0.5 - 0.6μm) was equivalent to TM band 2 (green, 0.52 - 0.60μm), MSS band 2 (visible red, 0.6 - 0.7μm) was equivalent to TM band 3 (visible red, 0.63 - 0.69μm), and MSS band 4 (near infrared, 0.8 - 1.1μm) was equivalent to TM band 4 (near infrared, 0.76 - 0.90μm). Although equivalent, the bands differed by very fine regions of the electromagnetic spectrum, mostly present on MSS bands (which have lower spectral resolution) but absent from equivalent TM bands (Table 7.5).

Table 7.5 Comparison of Spectral Resolutions of Image Band Data Used

Equivalent bands	Regions of electromagnetic spectrum covered by equivalent bands	Difference between equivalent bands: Region of the electro-magnetic spectrum covered by one band and not the other
MSS1, TM2	MSS1: 0.50 - 0.60μm (green) TM2: 0.52 - 0.60μm (green)	0.50 - 0.52μm, covered by MSS1 but not TM2
MSS2, TM3	MSS2: 0.60 - 0.70μm (red) TM3: 0.63 - 0.69μm (red)	0.60 - 0.63μm, 0.69 - 0.70μm, covered by MSS2 but not TM2
MSS4, TM4	MSS4: 0.80 - 1.10μm (near infrared) TM4: 0.76 - 0.90μm (near infrared)	0.76 - 0.80μm covered by TM4 but not MSS4; 0.90 - 1.10μm covered by MSS4 but not TM4

The fine spectral regions absent from one MSS or TM band but present in the equivalent band may have led to differences in the amount of soil and vegetation reflectance between the bands due to the presence or absence of reflectance from a spectral region in which either vegetation or soil reflects highly (see Figure 1.3).

Field measurements of soil reflectance (bi-directional reflectance factor) from tropical (Brazilian) and US soils showed that soils having high (> 2%) organic matter content and fine texture (like the majority of those on the Kafue Flats - see Appendix 1) generally have a bi-directional reflectance factor of approximately 18-20% in the 0.60 - 0.63μm region of the electromagnetic spectrum, about 21.5 - 22.5% in the 0.69 - 0.70μm region, approximately 26 - 27.5% in the 0.76 - 0.80μm region, and approximately 29 - 35% in the 0.90 - 1.10μm region (Irons *et al*, 1989). In these regions of the electromagnetic spectrum, the images used differ, although the bands used were equivalent (Table 7.5). The authors do not report the soil bi-directional reflectance factor for the 0.50 - 0.52μm region. Because the regions 0.60 - 0.63μm and 0.69 - 0.70μm are covered by MSS2 (red) but not TM2 (red), there could, respectively, have been 18 - 20% and 21.5 - 22.5% more reflectance from soil detected by MSS images than by TM images. The MSS images could also have had 29 - 35% more reflectance from soil because the region 0.90 - 1.10μm is covered by MSS4 but not by TM4. The TM images on the other hand could have had 26 - 27.5% more soil reflectance than the MSS images because the near infrared region 0.76 - 0.80μm is covered by TM4 but not MSS4.

In theory, MSS images could have had more near infrared and visible red reflectance than TM images. This is probably the reason why dry soil sites had higher NDVI values in 1984 (MSS image) and 1988 (MSS image) than in 1991 (TM image) and 1994 (TM image) (see Figure 6.11) It could also be the reason why Class 7 (sparse green grassland/woodland vegetation) had more near infrared reflectance than Class 6 (mixed green grassland/woodland vegetation) on the MSS images but not on the TM images (Figure 5.1). In terms of delineation of dry soil during the classification process (which enabled post classification change detection), the differences are likely to have had little effect because the maximum likelihood classifier which was used (see Section 4.7) is likely to have correctly classified dry soil either in Class 13 (exposed, trampled dry soil) or Class 14 (bare, compacted dry soil), using class signature statistics. This was done by comparing the green, red and near infrared reflectance values from the soil with those in class signatures and then, using class signature mean, minimum, maximum and standard deviation statistics, assigning the soil pixels to the class they were most likely to belong to. The assigned class was unlikely to be vegetated, burnt, water, muddy or dry grass classes because these were largely spectrally different from bare soil signatures (see Appendix 2 and Figure 5.1).

There may also have been inter-image differences in the detection of vegetation reflectance, possibly arising from the fine spectral region differences between equivalent bands. The vegetation reflectance curve, represented by green grass, has a small peak (11%) between 0.5 - 0.6μm (green) and a very high peak (48%) in the near infrared region of the electromagnetic spectrum between 0.8 - 1.1μm (Figure 1.3). The absence of the 0.50 - 0.52μm region from TM2's coverage, and its presence in MSS1, might have meant that slightly less green reflectance was detected by the TM images. TM4 includes the region 0.76 - 0.80μm, coinciding with the beginning of the near infrared peak reflectance on the green grass reflectance curve. Its equivalent, MSS4, does not include this region. However, MSS4 covers the region 0.90 - 1.10μm, while TM4 does not. In this region, green grass reflectance is almost at peak (47%). Probably the absence, from MSS4, of reflectance in the 0.76 - 0.80μm region was compensated for by the reflectance in the region 0.90 - 1.10μm (in terms of total quantities) but in terms of reflectance from various types of green vegetation, the two bands could have slightly differed in information content. However, the bands overlap in the region 0.80 - 0.90μm, enough to make their reflectance content comparable.

Very little can be done to minimise these system design differences but enough multi-spectral information was available in the three bands that were equivalent on all the images to make the images appropriate for the change detection work. In terms of spatial resolution, the 30m resolution of TM was among the highest available in the multi-spectral mode of satellite images and was, therefore, appropriate. The other images were resampled to this resolution. The effect of the errors in the resampling process is discussed in Section 7.3.4.

7.3.3 **Atmospheric Correction**

The atmospheric correction technique used to correct the reference (1994 TM) image was the dark object subtraction (zero minimum) method (see Sections 4.4.2 and 3.2.1.1.1). The radiometric characteristics of the other images were normalised with the atmospherically corrected reference image. It was necessary to undertake atmospheric correction because the images were evidently hazy (Figures 4.2 - 4.5). The technique used can be criticised because subtracting a constant value from the entire digital image assumes a constant atmospheric additive effect throughout the entire image, which is often not the case (Chavez, 1988).

The technique was used instead of the regression adjustment, radiance to reflectance conversion or atmospheric modelling methods (see Sections 3.2.1.1.2, 3.2.1.1.3 and 3.2.1.1.4) because it was the only one that worked (see Section 4.4.2), and the results of the correction were better than no correction at all (compare Figures 4.7 and 4.2).

Judging the merits and demerits of correcting or not correcting the reference image using the zero minimum method should take into consideration the relative radiometric errors in the image data without and after correction for haze. Atmospheric induced reflectance additive factors cause the apparent detection of more reflectance from a target ground pixel than is really coming from the pixel, especially in short wavelength bands (e.g. MSS1, TM1, TM2). Subtracting this extra atmospheric induced reflectance reduces this effect and, therefore, the radiometric errors. However, assuming that this additive effect is constant throughout the image is, in theory, erroneous because there may be pixels above which the haze effect is very small. For such pixels the subtraction will actually reduce the genuine reflectance from the ground, which is an error. Judging from the histograms of the reference image data before and after the correction, this error was minimal because the shapes of the original histograms were largely maintained (Figure 7.3).

7.3.4 **Image Co-registration and Resampling**

The original MSS images with a spatial resolution of 80m were resampled to the 30m resolution of the TM images. The total root mean square error in the process was between 0.28 and 0.43 of a pixel (Table 4.5). This means that the error in spatial co-registration for a given pixel was a ground distance of 12.9m at the most. The root mean square error was within the advisable range of 0.25 to 0.5 of a pixel (Jensen, 1986), or one pixel at the most (Milne, 1988).

It could be argued that instead of `upgrading' the 80m resolution MSS images to produce the spatial detail of the 30m resolution TM images, the TM images should

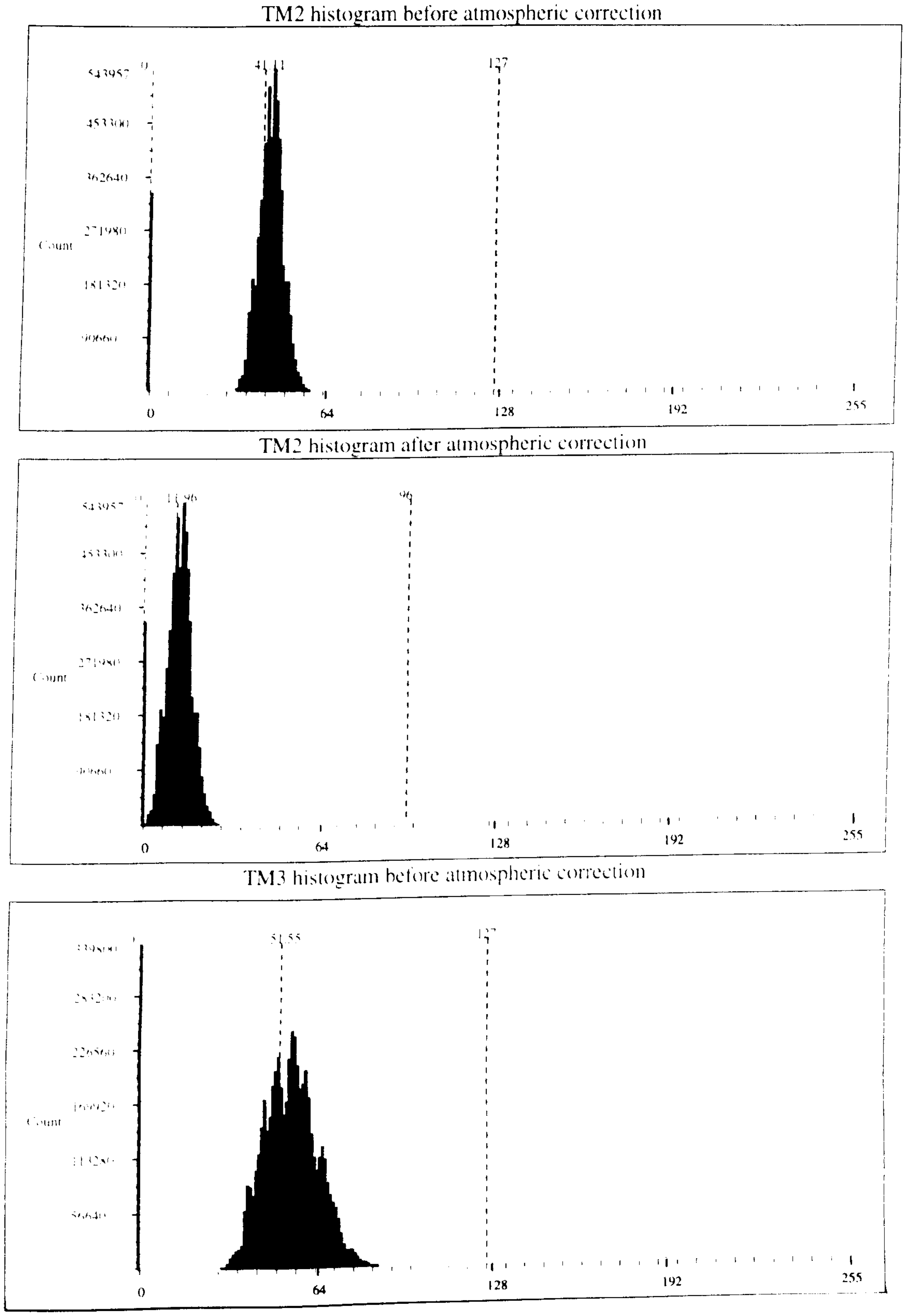
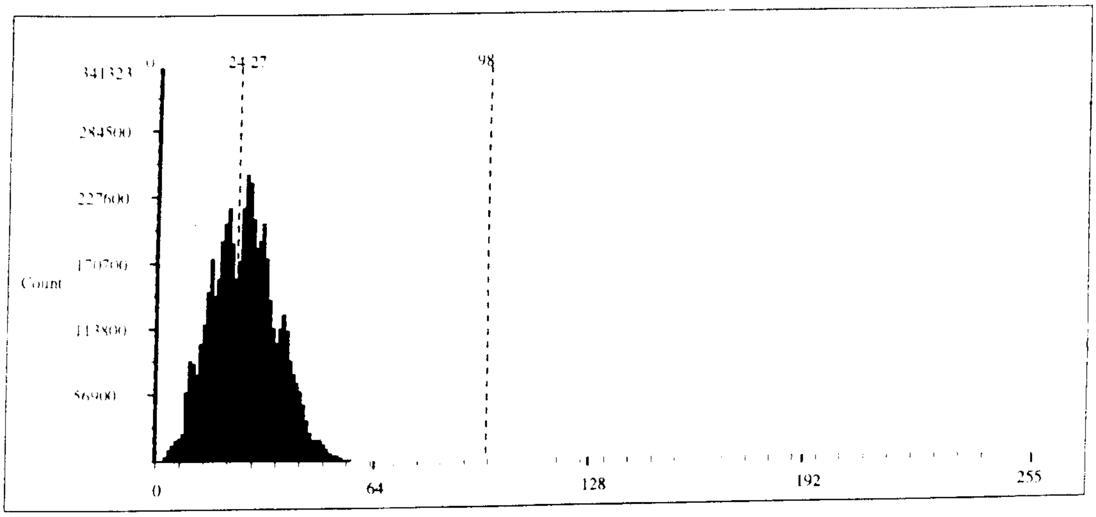


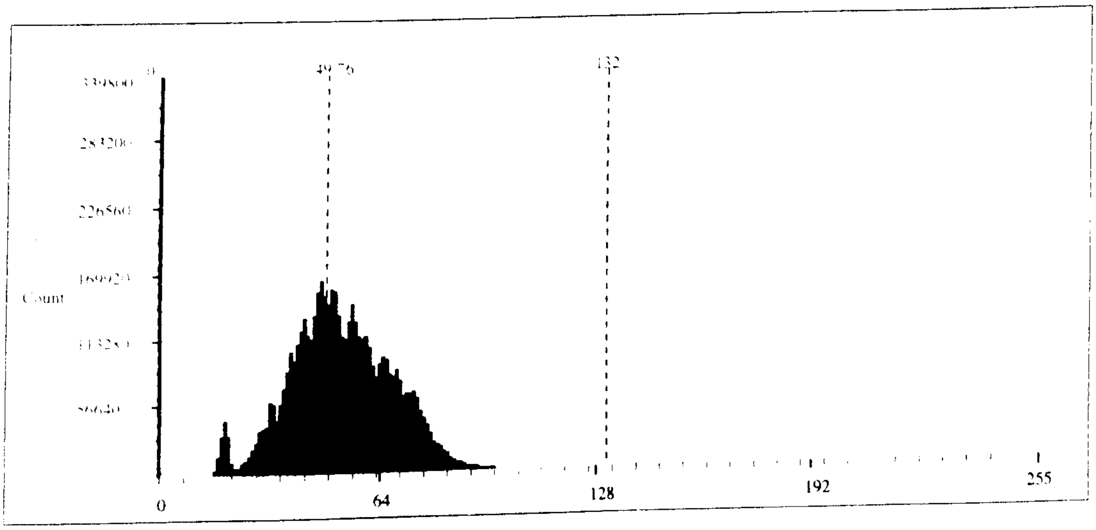
Figure 7.3 Comparison of histograms of band data for the reference (20 September 1994) TM image before and after atmospheric correction using the dark object subtraction (zero minimum) method. Only bands 2, 3 and 4 were used because they had equivalent MSS bands. On the X - axis is reflectance (brightness) digital number values on a scale of 0 - 255. The Y - axis shows how many pixels had a given digital number value. The computation of the mean values shown in the histograms included the zero (background) values surrounding the images. The computation of the means shown in Table 4.2 did not include image background zeros and for this reason the mean values in Table 4.2 are higher than the ones shown in the histograms in this figure.

Figure 7.3 continued

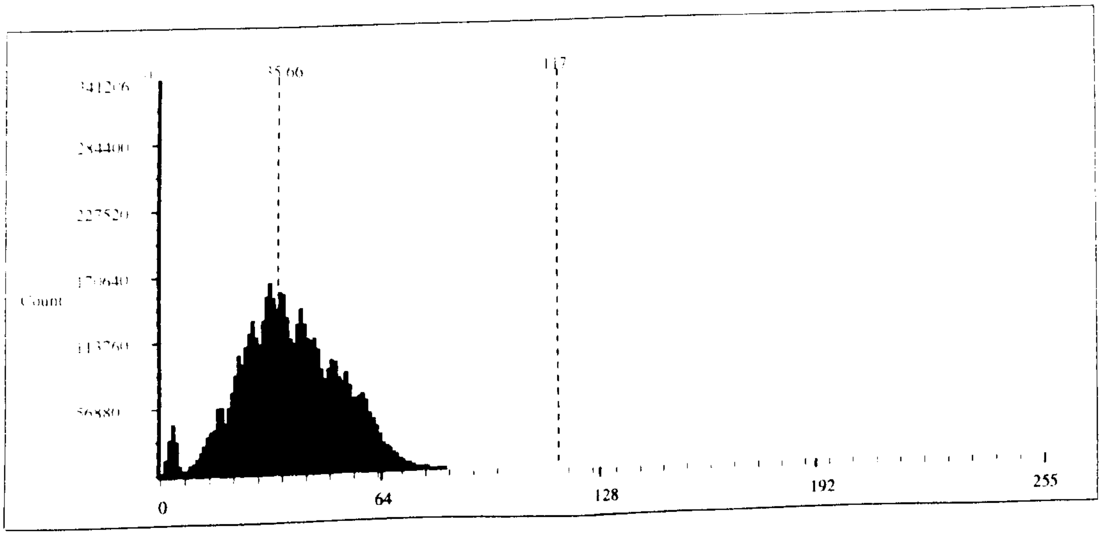
TM3 histogram after atmospheric correction



TM4 histogram before atmospheric correction



TM4 histogram after atmospheric correction



have been degraded to the 80m resolution during resampling. However, the nature of the problem under study (wetland land cover changes) required as much spatial detail as possible. Jakubauskas *et al* (1990) advise that when images with different spatial resolutions are used, post classification change detection (which was used in this study) should be done at a land cover classification level no finer than could be accurately determined by the lowest resolution sensor (MSS in this case). The classes used in this study (see Section 5.2) were broad enough to be determined on the MSS images, especially because they covered large (more than 80m) areas on the ground (except for Open water in sections of the Kafue River where the river was less than 80m wide). Figures 4.11 and 4.12 give an indication of how effective resampling the MSS images to a 30m pixel size was, compared to the original pixel sizes in Figures 4.4 and 4.5, respectively.

The 30m spatial detail was created from the original 80m MSS resolution by using the nearest neighbour interpolation (resampling) algorithm. In the interpolation process, after the creation of a 30m x 30m pixel grid from the original 80 x 80m MSS pixel grid, brightness (reflectance) values for pixel locations in the new grid at which there was no value in the original grid were derived by assigning the values of the nearest neighbouring pixels. Nearest neighbour interpolation is a computationally efficient procedure, favoured by many workers because it does not alter the pixel brightness values during resampling, whereas other interpolation techniques like bilinear interpolation and cubic convolution use averages to compute the new brightness values, often removing valuable spectral information (Jensen, 1986; ERDAS Inc., 1994). Preserving the spectral integrity of the original images is important because it is often the very subtle changes in brightness (reflectance) value that make all the difference when discriminating between one type of vegetation and another.

The processed (classified) images were rectified to the UTM projection by co-registering them with a UTM vector map created as described in Section 4.8. The total root mean square error in this case was much higher (0.38 - 0.95 of a pixel; Table 5.1) but still within the acceptable limit of one pixel at the most (Milne, 1988). It means that the ground error between the classified, rectified images and the UTM map was 11.4 - 28.5m. This error was higher than was the case with image-to-image co-registration (where maximum error was 12.9m) because, firstly, whereas they were sharp on the vector file, the ground control points used (mostly river bends and confluences) were not always clear due to vegetation cover on some images. Secondly, the maps used to create the UTM vector map were drawn using very old aerial photographs (taken in May 1970, according to the Survey Department of the Government of Zambia). The maps were the latest, largest scale (1:50 000) topographic maps available at the Survey Department. Between May 1970 and the latest image date (20 September 1994), these river bend and river confluence ground control points could have changed slightly in location, due to river erosion and deposition activities. It is, therefore, possible that spatial extent changes less than 11.4m were not delineated in the change maps (Figures 6.2 and 6.3).

7.3.5 **Image Normalisation**

Normalisation of the images was necessary in order to minimise non-ground cover differences between images, such as differences in sun angle, atmospheric composition, detector calibration and astronomic differences (see Section 3.2.1.2), which could have caused change detection errors. The acquisition time, sensor, sun angle and radiometric differences among the original images are summarised in Tables 4.1 and 4.2. The normalisation of the images with the atmospherically corrected reference image was performed as described in Section 4.4.4., and the equations used for the linear transformations are listed in Table 4.7. The correlation between equivalent bands was best between the TM images (r^2 was 99.1 - 99.9%), as expected. The correlation between equivalent MSS and TM bands was best between TM4 and MSS4 (near infrared), followed by TM3 versus MSS2 (red), and least between TM2 and MSS1 (green). All correlation coefficients were, however, over 95% (and r^2 greater than 90%), which is quite satisfactory.

The lowest r^2 value was 90.7% (in the green band), meaning that a maximum of 9.3% of non-ground surface (target) differences were maintained. This, however, was in the green band in which there was very little difference among all the spectral signatures (see Figure 5.1). There was more class signature difference in the red and near infrared bands (see Figure 5.1) in which a maximum of only 2.5% of non-ground surface differences were maintained after normalisation (minimum r^2 value was 97.5%, between 1984 MSS2 and reference image's TM3 - see Table 4.7). Therefore, normalisation satisfactorily kept non-target inter image differences as low as possible, meaning that the inter image changes detected were really largely due to land cover changes and not due to other factors like differences in atmospheric composition, sun angle, detector calibration and astronomic differences. The error introduced by phenological differences is discussed in Section 7.3.1. For the bands used, normalisation largely retained the inter-band correlation shown in Table 4.3.

7.3.6 **Field Work**

Although the field work undertaken (Sections 4.5 - 4.6.3) enabled the acquisition of general knowledge of the area covered by the images, the best timing of the field work would have been to coincide it with the time of acquisition of one of the images, especially the reference (20 September 1994 TM) image. The following activities should then have been undertaken at the time of image acquisition:

1. Measurement of on site (*in situ*) reflectance from specific target features which are large enough (e.g. more than 30 x 30m in size), using spectroscopic measurement devices (e.g. spectro-radiometer). Examples of suitable target features are bare soil and dry grassland sites. Knowledge of the reflectance from these sites would have enabled more accurate atmospheric correction of the reference image, using the radiance to reflectance conversion method (Section 3.2.1.1.3).

2. Vegetation surveys to determine the dominant species at selected sites. The qualitative approach employed in this study (see Sections 4.6.1 and 4.6.2) would still have been appropriate, but the surveys should have been done within a few days of the satellite overpass at the latest. In this study the field work was done one year after the acquisition of the reference image, which limited the confidence with which land cover classes could be named. As a result, broad names were used to describe the classes (see Section 5.2) instead of more specific ones.

Coinciding the field work with the time of satellite overpass requires making arrangements with the satellite imaging company, and foresight is needed to determine whether or not on the date arranged the weather will be suitable, and whether or not the area will be cloud free. Lack of such ideal conditions would have meant postponing the field work date until an ideal date was arranged. Its is not possible to be everywhere, simultaneously in the area covered by the image at the time of satellite overpass, which necessitates the use of sample plots. It has been suggested that the ideal amount of ground work is at least 50 pixels per class (Watson, 1995, pers. comm..)[1] .

7.3.7 **Change Detection Techniques**

The main change detection technique employed in the study was post classification comparisons (see Sections 3.2.2.4 and 4.7). The technique was favoured over other digital image change detection techniques like image differencing, image ratioing and image enhancement techniques (see Sections 3.2.2.2, 3.2.2.3 and 3.2.2.5) because it provided more meaningful change analysis in terms of interpretation of change (i.e. from a specified class to another). Differencing and ratioing techniques rely too much on the comparison of brightness (reflectance) numbers, with the implication that if there are radiometric errors, wrong change detection results will be yielded. According to Jensen (1986), image differencing and ratioing of spectral data is practical but may be too simple to identify the variety of change in a complex scene.

Classification comparison methods are only useful if accurate classifications can be obtained (Jensen, 1986). The classification accuracies in this study were in the range 73

[1] Lecturer in Remote Sensing until 1995

- 80% (see Section 5.3.1) and, as discussed in Section 5.3.2, this level of accuracy is comparable with those reported by other workers (e.g. Jensen *et al*, 1995; Sader *et al*, 1991; Treitz *et al*, 1992). Although 100% accuracy is desirable, it is unrealistic (Sader *et al*, 1991) because even the original raw images usually have some degree of radiometric error.

Post classification comparison was important as the main change detection technique because it facilitated interpretation and quantification of the changes in a GIS framework. However, additional change information was obtained when the technique was supplemented by NDVI and PCA change analysis (Sections 6.4.1 and 6.4.2).

7.3.8 The Potential Role of Remote Sensing in Conservation and Planning of Water Use on the Kafue Flats

As was established in Sections 2.7.1 - 2.7.4, the major economic activities which are supported by the water resource on the Kafue Flats are hydroelectric power generation, irrigation, wildlife utilisation (including tourism and hunting), fishing, livestock grazing and municipal water supply. There are, therefore, conflicting demands for the use of the water, between human use and nature conservation. In recognition of the importance of conserving the wetland's natural resources and enhancing their natural productivity, the World Wide Fund for Nature (WWF) included the Kafue Flats in its Wetlands Project in Zambia (Jeffrey and Chooye, 1991). The Wetlands Project also aims at improving the standards of living of the wetland's local communities through the sustainable utilisation of natural resources.

This study has shown possibilities for using remote sensing in conservation of nature and planning of water use on the Kafue Flats, in conjunction with ancillary environment and land use data. It was shown in Section 7.2 that land cover data from remote sensing can be used in a statistical analysis with ancillary data to determine the relationships between level of use of the water resource, climate and impact on the wetland's quality. Thus abstraction of water for irrigation of sugar cane was shown to have a negative impact on quantities (and possibly quality) of dense green vegetation. The regulation of discharges of water into the wetland was shown to be very influential on the dry season greenness of the wetland, as well as being related to abstractions of water for irrigation.

There is, therefore, potential for using multi-temporal, multi-spectral remote sensing as a synoptic source of data on trends in the quality and quantity of the wetland's land cover classes resulting from the use of the water resource. To enable planning of future use of the water using observed trends, ancillary data would be needed. The ancillary data needed would be discharge data into the wetland (from the Zambia Electricity Supply Corporation), abstractions for irrigation (from the Zambia Sugar Company), abstractions for municipal water supply (from the relevant municipal authorities, at Kafue, Mazabuka and Lusaka), climate data (from the Zambian government's Meteorology Department), Kafue River hydrological data (from the Zambian government's Water Affairs Department), and ecological data (possibly from the Zambian government's Department of National Parks and Wildlife Services or from WWF - Zambia). The concerned parties would need to state the critical water requirements needed for the sustainability of their operations on the Kafue Flats, and long term remote sensing data would help indicate the wetland land cover consequences of the various demands, in a statistical or mapping framework.

Remote sensing has already been used by WWF to monitor the extent of the annual flood on the Kafue Flats (WWF - Zambia, 1995, pers. comm.). This has been done using Channel 2 AVHRR images, which were available free of charge at the Zambia Meteorology Department. AVHRR images, however, have the disadvantage of having low spatial resolution. Selected AVHRR data are recorded at the full AVHRR resolution of 1.1 km, referred to as local area coverage (LAC), and all of the data are sampled down to a nominal resolution of 4 km, referred to as global area coverage (GAC) (Lillesand and Kiefer, 1994). Such resolutions are too coarse to generate the kind of land cover detail that resulted from this study because small features like the river and other small features less than 1.1km in size would not be distinct. More spatial and spectral detail can be obtained from digital Landsat TM and SPOT images (also Landsat MSS) but these are very expensive (see Section 4.2) and probably too expensive for regular use. Though inferior in terms of spatial resolution, AVHRR images are of higher temporal resolution than Landsat or SPOT images because they can be acquired every 12 hours compared to 16 - 26 days in the case of Landsat and SPOT images (although off-nadir SPOT images can be acquired).

Therefore, the role of remote sensing on the Kafue Flats will depend on the particular detail of the information that is required. The amount of detail will indicate the spatial resolution of imagery needed, the frequency of acquisition of the imagery and the spectral resolution necessary (i.e. whether only one band or several bands are needed). Large scale mapping, for example, only needs aerial photographs, perhaps every five years. Animal counting has also been done from the air (e.g. Howard and Aspinwall, 1984). Satellite imaging provides synoptic, multi-spectral and repetitive coverage of large areas. The most serious hindrance to its use are the image costs and the costs of the necessary image processing hardware and software.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This chapter presents the conclusions arising from the study and some recommendations for future work. The first part of the chapter states the conclusions emerging from the study. The discussion in Chapter 7 highlighted some unforeseen shortcomings in methodological procedures which pointed to the fact that the study was not exhaustive. In the second part of the chapter, recommendations for future work are stated and justified.

8.2 Conclusions

The study set out to investigate the applicability of remote sensing to wetland change assessment on the Kafue Flats. The hypothesis of the work was that, as a wetland habitat, the Kafue Flats were undergoing a trend of land cover degradation as a result of reduced amounts of water received, and that multi-temporal, multi-spectral remote sensing could help in the identification, characterisation and quantification of the change. Three objectives were used in testing this hypothesis. The conclusions of the study will be stated in turn against each of the objectives.

1. The first objective of the study was to assess the Kafue Flats vegetation regime for change in terms of vigour and spatial extent of cover, using multi-temporal remote sensing data.

Taking dense green vegetation as the main characteristic of the wetland in the dry season, it can be concluded that in the dry season there were losses of dense green vegetation (amounting to about 2 593.5 hectares) between September 1984 and September 1994. Spatial mapping revealed that the losses were in upstream areas of the Kafue Flats, which are not affected by the backing-up effect of the lower dam at Kafue Gorge. Though not significantly linear from the four images used, these losses indicate a gradual lowering of the late dry season water level and reduction in soil moisture in the upstream areas of the wetland.

Some lagoons in upstream areas were contracting in size and with this contraction the dense green vegetation around the lagoons was contracting in terms of spatial extent of cover. In some locations in the upstream zone, less vigorous, sparse vegetation was replacing the dense green vegetation. Downstream areas appeared not to be losing any dense green vegetation but the situation was complicated by the timing of dry season high discharges into the wetland, which are regulated. There were inconsistent trends in dry season vegetation cover as a result. Due to time lags in the withdrawal of the regulated high discharge events, downstream areas tended to be wetter and upstream areas drier in the late dry season (September) when the wetland was studied. However, the wetland recovers in the rain season each year, to varying degrees. It is likely that there were changes in the dry season relative abundance of vegetation species over the time period but the lack of known, unique (species specific) spectral signatures for the many wetland plant species meant that remote sensing was unable to determine the changes in the species regime over time.

2. The second objective of the study was to assess the Kafue Flats for other land cover changes, especially areal extent of water bodies and dry land, using multi-temporal remote sensing data.

Apart from green vegetation cover, the other land cover changes that could be assessed by multi-temporal, multi-spectral remote sensing were changes in area of open water, dry land and burnt land. From an assessment on only one day in September of the years 1984, 1988, 1991 and 1994, there were inconsistent year to year trends in the amount of open water, dry land and burnt land. The nature of the fluctuations points to the large human influence on the wetland by way of year to year differences in the timing of the regulated river discharges and burning, which have influence on the amount of dry land left. Many water courses (especially the Kafue River) stayed largely unchanged. Some upstream lagoons, notably Shalwembe Lagoon, were evidently reducing in size gradually.

3. The third objective of the study was to assess the wildlife habitat implications and usefulness of the land cover changes detected, and methodology developed, for nature conservation and planning future use of the water resources on the Kafue Flats, in conjunction with ancillary land use and environmental data.

Without knowledge of the specific plant species that changed in spatial and relative abundance, and without knowledge of which wildlife species are consequently at risk, only general rather than specific statements can be made about the effects of the observed land cover changes on wildlife habitats. Spatial reductions in dry season dense green vegetation in upstream areas of the Kafue Flats pose a threat to avian species which use the dense reed vegetation for nesting and as perches. They also threaten sitatunga (*Tragelaphus spekei*), an aquatic ungulate whose habitat are the dense reed marshes. There is possibly a threat to amphibian and reptile species as well. Grazing species like lechwe (*Kobus leche kafuensis*) and zebra (*Equus burchelli*) may not immediately be threatened because, with the exception of the shy sitatunga (*Tragelaphus spekei*), they prefer the more open, short green vegetation areas for grazing. The year to year fluctuations in dry season amounts of water, dense green vegetation, sparse green vegetation, dry and burnt land might mean that non-migratory wildlife species are subjected to an unstable habitat by man's manipulation of their wetland habitat in the dry season. This is likely to cause them ecological stresses through overcrowding in dwindling suitable habitats and relocation to escape non ideal habitat, perhaps in the same dry season.

The study has demonstrated that multi-temporal remote sensing data are a useful synoptic record of the historic land cover characteristics of the Kafue Flats. Long term ancillary environment and land use data can be used in a statistical framework with the remote sensing data to assess cause and effect characteristics on the wetland habitat. Such assessments can then be used to plan conservation and water use strategies. However, this can only be possible if adequate and reliable ancillary data are available, appropriate and affordable imagery and image processing software and hardware are available, errors in remote sensing image processing and interpretation are minimised, and adequate and reliable information about the ground cover characteristics is available for use in remote sensing image processing and interpretation procedures. Remote sensing, therefore, can only be a source of supplementary and synoptic data but not solely a substitute for ground surveys in assessing change on the Kafue Flats. As demonstrated by this study, appropriate change detection algorithms and geographic information systems can help in the identification, characterisation and quantification of community level changes on the Kafue Flats wetland, in a quicker and planimetrically more accurate manner than can ground surveying. However, changes at the micro-habitat level are more difficult to detect by remote sensing without detailed, targeted surveys on the ground.

With any change detection algorithm, a lot of attention has to be paid to possible sources of change detection error and how to minimise them. Familiarity with the ground cover characteristics being remotely sensed is vital in the process. In view of this, post classification change detection was found to be a very useful change detection technique provided errors in classification are minimised. Principal component analysis of a merged multi-temporal image data set was found to be an accurate change detection technique but it provided less interpretable information on the nature of the change compared to post classification change detection. As a change detection technique, changes in the normalised difference vegetation index (NDVI) were found not to be a very reliable technique because there was doubt about what ground cover features were causing increases or decreases in red or near infrared reflectance in the landscape with a mixture of dry land and healthy green vegetation.

8.2 **Recommendations**

The study only provided preliminary insight into the problem of wetland change assessment by remote sensing on the Kafue Flats. There is scope for adopting a different design by using different imagery or purposely acquired aerial photographs, and using a different time frame in assessing change on the wetland in future. Specific suggestions for future work are as follows:

1. More images need to be used. This study used only four images from September 1984, 1988, 1991 and 1994. More statistically reliable trends would probably emerge if an annual, anniversary or near anniversary image set was used. Ground survey work should be done concurrently with the acquisition of at least one of the images.
2. Ground monitoring ecological work to determine trends in wetland species composition (plant or animal species) needs to be initiated at the micro-habitat level in the context of cause and effect of change. This work should determine possible wetland change indicator (plant) species for long term monitoring. The most suitable location for such work is in upstream parts of the wetland.
3. There is scope for use of purposely acquired anniversary or near anniversary airborne imagery with high spatial and spectral resolution, such as airborne thematic mapper (ATM) imagery. This, however, would involve chartering a company to fly aerial photographic missions and may be too expensive. Airborne Thematic Mapper images have higher spatial and spectral resolution than the Landsat TM and MSS images used in this study. Their spatial resolution is 1 - 10 meters compared to 30 and 120 meters for Landsat TM images, and 80 meters for Landsat MSS images. They have 11 spectral bands in the 0.42 - 12.5 μm region of the electromagnetic spectrum compared to the 7 bands of Landsat TM or the 4 bands of Landsat MSS in the region 0.45 - 12.5 μm. Therefore, more spatial and spectral wetland change detail could be obtained with ATM imagery.

APPENDICES

APPENDIX 1

SUMMARY OF SOIL SAMPLING RESULTS FROM THE KAFUE FLATS

(a) **Lochinvar Area**

Sample	Field land cover type	Soil colour	Soil texture (%Sand, %Clay, %Silt)	% organic matter
LV1	*Acacia* thicket (on edge of Chunga lagoon)	very dark greyish brown (10YR 3/2)	sandy clay loam (56.74, 23.08, 15.52)	4.66
LV2	isolated termitaria with bare soil (game trampled)	dark greyish brown (2.5Y 4/2)	clay (29.28, 53.24, 15.15)	2.33
LV5	edge of periodically watered course, with tall *Sesbania* reeds	black (2.5Y 2.5/1)	clay (11.52, 54.90, 28.29)	5.28
LV11	bare soil with isolated termitaria in floodplain (game trampled)	dark grey (10YR 4/1)	clay (25.75, 51.64, 19.42)	3.18
LV12/13	sparse, green ungrazed herbs in floodplain zone (game trampled)	very dark grey (10YR 3/1)	loam (33.96, 23.67, 35.30)	7.07
LV15	*Hyparrhenia rufa* grassland with patches of bare soil, in floodplain (cattle grazed)	black (10YR 2/1)	loam (40.18, 17.25, 35.35)	7.22
LV20	edge of Chunga lagoon, periodically under water (intense game browsing on *Polygonum* herbs, game droppings abundant)	very dark greyish brown (10YR 3/2)	loam (36.05, 17.22, 39.62)	7.11

Appendix 1 continued - Summary of Soil Sampling Results from the Kafue Flats

(b) **Mazabuka West**

Sample	Field land cover type	Soil colour	Soil texture (%Sand, %Clay, %Silt)	% organic matter
MZW1	annually cultivated land (bare soil)	light olive brown (2.5Y 5/6)	sandy clay loam (57.00, 24.38, 17.07)	1.55
MZW9	regenerating *Acacia* mixed woodland (former settlement area)	dark greyish brown (2.5Y 4/2)	clay (28.08, 49.50, 19.39)	3.03
MZW12	*Acacia gerrardii* mixed woodland with *Setaria* sp. grasses	dark greyish brown (10YR 4/2)	clay (26.16, 53.58, 17.31)	2.95
MZW13	seasonally watered depression in woodland zone	very dark grey (10YR 3/1)	clay loam (38.23, 31.39, 25.95)	4.43
MZW17	termitaria grassland (*Vitiveria* sp.) in floodplain zone	brown (10YR 4/3)	sandy loam (69.34, 12.17, 17.04)	1.44
MZW18	termitaria grassland in floodplain zone	very dark grey (10YR 3/1)	clay (22.65, 53.39, 21.36)	2.60
MZW22	termitaria grassland (*Setaria* sp.) pocket in termitaria-woodland transition zone	dark greyish brown (10YR 4/2)	clay (5.36, 73.00, 17.52)	4.12
MZW23	termitaria zone with short grass, transition to floodplain proper (cattle trampled)	dark grey (10YR 4/1)	clay (12.74, 64.45, 15.90)	6.91
MZW25	sparse green floodplain zone herbs (emerging after burning, ungrazed, *Vernonia* sp.)	black (10YR 2/1)	loam (33.71, 25.87, 33.20)	7.22

Appendix 1 continued - Summary of Soil Sampling Results from the Kafue Flats

(c) **Blue Lagoon Area**

Sample	Field land cover type	Soil colour	Soil texture (%Sand, %Clay, %Silt)	% organic matter
BLW2	depression area with *Setaria* sp. grass, near thick *Acacia albida* woodland	black (10YR 2/1)	clay (12.23, 47.40, 33.19)	7.18
BLW3	regenerating mixed woodland (former settlement area)	greyish brown (10YR 5/2)	silty clay (51.46, 18.48, 27.50)	2.56
BLW5	termitaria grassland (*Setaria* sp.) with isolated trees	dark grey (10YR 4/1)	loam (43.51, 20.77, 31.99)	3.73
BLW6	termitaria grassland with isolated trees	black (10YR 2/1)	clay (16.13, 59.67, 21.40)	2.80
BLW7	ungrazed, tall floodplain grassland (*Hyparrhenia rufa, Eragrostis* sp.)	black (10YR 2/1)	silty clay/silty clay loam (56.80, 20.97, 17.61)	4.62
BLW10	edge of Shalwembe lagoon, seasonally under water, tall water fringe reeds	black (N2.5)	sandy loam (47.17, 17.18, 28.78)	6.87
BLW18	termitaria grassland (*Brachiaria* sp.)	black (10YR 2/1)	clay (23.11, 54.56, 17.63)	4.70
BLW19	*Sorghum versicolor* reeds in floodplain zone	very dark grey (10YR 3/1)	loam (37.74, 27.29, 30.23)	4.74
BLW21	sparse green floodplain grass (*Vossia cuspidata*), emerging after heavy grazing	very dark grey (N3)	loam (42.94, 10.73, 39.50)	6.83
BLW22	grassland in woodland-floodplain transition zone	light greyish brown (10YR 6/2)	sandy loam (79.90, 8.09, 10.92)	1.09
BLW25	sparse, green floodplain grass (*Vossia cuspidata*), grazed	black (10YR 2/1)	sandy clay loam (40.54, 32.25, 20.22)	6.99
BLW33	dry floodplain grassland, short grass affected by burning	black (10YR 2/1)	clay (7.92, 64.65, 20.25)	7.18
BLW34	sparse, green emerging floodplain grass after burning (*Vossia cuspidata*)	black (10YR 2/1)	clay (10.21, 49.52, 33.16)	7.11

APPENDIX 2
CLASS SPECTRAL SIGNATURE STATISTICS

min = minimum digital band reading for class signature in band
max = maximum digital band reading for class signature in band
mean = mean digital band reading for class signature in band
st. dev = standard deviation of digital band readings for class signature in band

Image	Band	Statistic	Class 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1994 TM	green (2)	min.	0	5	4	2	8	5	2	5	10	1	6	8	12	13	1
		max.	4	24	22	19	25	22	17	21	35	16	24	28	40	96	7
		mean	**2.1**	**14**	**13**	**10**	**15**	**13**	**9.4**	**11**	**17**	**8.2**	**13**	**15**	**19**	**22**	**3.1**
		st.dev	0.7	3.1	2.2	2.0	1.6	1.4	1.7	1.4	2.0	1.6	1.5	1.7	2.2	4.2	1.2
	red (3)	min.	0	5	5	4	22	18	1	16	28	3	20	25	31	31	1
		max.	6	42	34	25	37	32	24	29	49	22	32	40	55	98	10
		mean	**3.7**	**21**	**21**	**18**	**30**	**26**	**18**	**22**	**36**	**16**	**26**	**31**	**40**	**45**	**5.2**
		st.dev	1.0	5.7	4.9	3.5	2.9	2.6	3.1	2.0	2.8	2.5	1.8	1.9	3.6	6.3	1.8
	near infra-red (4)	min.	0	71	54	42	46	37	29	13	33	14	22	23	41	48	3
		max.	12	117	71	61	63	48	41	31	49	31	36	41	63	112	20
		mean	**3.2**	**80**	**62**	**49**	**52**	**42**	**34**	**26**	**43**	**23**	**32**	**36**	**54**	**64**	**11**
		st.dev	1.2	8.3	4.0	3.9	3.5	2.7	3.1	2.9	2.5	2.7	2.2	2.2	3.9	5.1	3.3
1991 TM	green (2)	min.	1	4	4	3	8	7	4	5	10	2	7	9	12	14	2
		max.	5	22	19	15	20	21	15	15	23	14	20	21	27	47	8
		mean	**3.0**	**14**	**11**	**10**	**14**	**12**	**10**	**10**	**16**	**8.1**	**12**	**14**	**19**	**23**	**5.0**
		st.dev	0.8	2.7	2.0	1.6	1.4	1.2	1.0	0.9	1.4	1.1	1.0	1.1	1.9	3.0	0.9
	red (3)	min.	3.0	5.0	5.0	5.0	22	19	9	11	29	5	22	24	32	36	6
		max.	9	40	33	26	37	33	26	26	44	23	33	37	53	91	17
		mean	**5.6**	**22**	**21**	**19**	**29**	**26**	**22**	**20**	**36**	**17**	**26**	**30**	**42**	**52**	**10**
		st.dev	0.8	5.1	4.1	3.4	2.9	2.1	1.8	1.3	2.3	1.8	1.3	1.9	3.3	6.5	2.1
	near infra-red (4)	min.	0	66	47	31	42	28	21	13	34	11	19	30	42	51	4
		max.	11	112	67	49	61	37	32	28	48	30	28	40	67	106	16
		mean	**2.2**	**76**	**55**	**41**	**48**	**32**	**25**	**21**	**43**	**19**	**27**	**36**	**52**	**66**	**8.6**
		st.dev	1.1	7.7	4.7	4.3	3.9	1.5	1.9	1.3	2.6	1.9	1.3	2.2	4.1	7.6	1.7

Appendix 2 continued - Class Signature Statistics

Image	Band	Statistic	Class 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1988 MSS	green (1)	min.	0	0	0	0	0	3	5	9	2	0	4	6	10	13	0
		max.	2	22	14	12	17	20	23	27	26	26	26	28	36	48	6
		mean	**0.1**	**12**	**5.4**	**3.0**	**6.8**	**10**	**13**	**18**	**9.3**	**8.4**	**11**	**14**	**19**	**24**	**1.3**
		st. dev.	0.3	3.1	2.6	2.0	2.1	2.1	2.3	2.5	2.1	3.5	2.1	2.4	3.2	3.7	1.3
	red (2)	min.	0	0	0	0	2	13	14	24	12	9	18	23	27	33	0
		max.	4	33	19	16	22	29	34	44	33	32	36	41	53	72	15
		mean	**0.5**	**19**	**11**	**8.0**	**15**	**21**	**25**	**34**	**21**	**18**	**26**	**31**	**37**	**44**	**7.3**
		st. dev.	0.9	5.0	4.1	3.4	3.3	3.0	3.5	3.1	2.8	2.8	2.5	2.7	3.9	4.6	2.6
	near infra-red (4)	min.	0	67	48	26	37	46	54	61	24	11	27	34	42	56	3
		max.	13	107	75	47	51	60	70	83	40	33	48	57	64	108	34
		mean	**1.6**	**77**	**58**	**35**	**44**	**53**	**61**	**68**	**34**	**26**	**41**	**49**	**57**	**73**	**14**
		st.dev.	3.4	6.4	5.3	4.7	3.2	2.9	3.4	3.9	2.5	3.6	2.7	3.1	3.4	5.8	4.0
1984 MSS	green (1)	min.	0	0	0	4	3	0	0	0	7	0	6	4	9	12	0
		max.	4	19	13	19	16	13	14	16	24	16	20	18	32	43	3
		mean	**1.4**	**7.9**	**6.5**	**12**	**10**	**5.7**	**8.2**	**8.5**	**15**	**5.9**	**13**	**10**	**18**	**21**	**0.2**
		st. dev.	1.2	2.6	2.4	2.4	1.8	1.9	1.5	1.5	2.0	1.5	1.7	1.6	2.4	3.0	0.5
	red (2)	min.	0	0	0	14	14	0	10	15	26	6	24	20	31	33	0
		max.	3	33	19	37	28	19	25	28	45	24	39	34	56	83	5
		mean	**0.6**	**11**	**10**	**24**	**22**	**13**	**19**	**19**	**34**	**14**	**29**	**24**	**41**	**50**	**0.5**
		st. dev.	0.9	5.2	4.3	5.4	3.2	4.2	1.8	1.8	2.7	2.1	2.3	1.9	3.8	5.9	1.1
	near infra-red (4)	min.	0	66	42	54	41	28	32	16	39	12	31	27	46	52	5
		max.	9	105	66	84	54	42	43	32	57	28	47	41	70	103	13
		mean	**2.1**	**78**	**54**	**63**	**46**	**32**	**35**	**29**	**48**	**24**	**42**	**36**	**56**	**68**	**8.4**
		st. dev.	1.3	8.3	5.9	5.1	3.3	3.0	2.4	2.0	2.9	2.0	2.4	2.5	3.7	6.8	1.8

APPENDIX 3
COMPARISON OF IMAGE AND GROUND COVER CLASSES

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV1 UTM grid 35 **525**699E, 8**250**254N	On 18 September 1995: Leafless *Acacia* thicket (≈50%) with bare, trampled, very dark greyish brown sandy clay loam soil (4.66% organic matter). *Acacia* trees 3-5m tall, with 4.5-6m canopies. Ground largely bare, intense grazing by lechwe, soil trampled and compacted. Few *Odontotermis* and *Cubitermis* termite mounds among trees. (see Figure 5.7a)	13 - Exposed, trampled dry soil with surface debris	Acceptable classification since trees leafless. Presence of classes 9 (Very sparse green vegetation/termitaria with isolated green trees) and 14 (Bare, compacted dry soil) around correctly depicts the variation on the ground.
LV2 UTM grid 35 **526**544E, 8**250**392N	On 18 September 1995: Bare, dark greyish brown clay soil (2.33% organic matter) with isolated termite mounds. No trees. Heavy grazing and trampling, grass cropped to the ground except for herbs unpalatable to game, many animal droppings. (see Figure 5.7b)	13 - Exposed, trampled dry soil with surface debris	Correct classification.
LV3 UTM grid 35 **530**124E, 8**249**422N	On 18 September 1995: Open dry floodplain grassland without termite mounds. Grass ≈20cm tall, complete ground cover, no trees or shrubs. Little grazing but animal tracks present.	9 - Very sparse green vegetation/termitaria with isolated trees	Acceptable class because area is in floodplain zone and, therefore, grass may have been sparsely green in 1994 because flood timing varies from year to year.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV4 UTM grid 35 **532**652E, 82**47**464N	On 18 September 1995: Open dry floodplain grassland without trees. Grass about 1m tall, mainly *Hyparrhenia rufa*, ungrazed but animal tracks present	Outside image area	Site fell just outside image cover area by about 500m. It was difficult to determine this in the field before image rectification.
LV5 UTM grid 35 **537**574E, 82**49**606N	On 18 September 1995: Tall water fringe reeds/shrubs, mainly *Sesbania sesban*. Reeds/shrubs about 5m tall, in leaf, canopies small but almost closed, stems with climbers, making area almost impenetrable, although vegetation opened up by cattle/animal tracks. Fire damage evident. Sparse green grass around, water at centre. Black clay soil (5.28% organic matter)	5 - Sparse, stressed water reeds/water fringe vegetation	Correct classification since classified image has gradation inwards from Class 5 (Sparse, stressed-) to 4 (Less dense, stressed-) to 3 (Dense, vigorous-) to 2 (Dense, very vigorous water reeds/water fringe vegetation).
LV6 UTM grid 35 **528**390E, 82**49**128N	On 18 September 1995: Termitaria zone, isolated *Acacia* trees/bushes, dry grass and ungrazed green *Compositae* herb (*Vernonia* species; an annual grass dicotelydon (Rees, 1978a - see Figure 5.8a). *Acacia* bushes about 2m tall, canopies 2m wide, emerging leaves (spring). High grazing pressure, ground cropped bare except for *Compositae* herbs, dark greyish brown clay soil exposed between bushes and herbs.	9 - Very sparse green vegetation/termitaria with isolated trees & (nearby) 13 - Exposed, trampled dry soil with surface debris	Correct classification, ground cover variation reproduced.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV7 UTM grid 35 532717E, 8255682N	On 7 September 1995: Shallow, periodically watered depression in floodplain zone, with water at the centre and isolated thickets of *Sesbania sesban* stranded by retreating water line. Where dry, depression bed has cracked clay, covered by green herbaceous plants. (see Figure 2.21e)	10 - Emergent vegetation in shallow water or after burning	Acceptable classification because of possibility of existence of damp, dark clay + green herbs mixture at time of image acquisition. Water in depression's centre and surrounding reeds/thicket clearly demarcated as Class 1 (Open water) and Class 5 (Sparse, stressed water reeds/water fringe vegetation), respectively.
LV8 UTM grid 35 533201E, 8260455N	On 7 September 1995: Scattered depressions with water and reeds and grass on peripheries; surrounded by dry grass areas which are trampled by cattle. Depressions typically ≈30m x 80m, probably former river channels, then ox-bow lakes, now diminished in size. (see Figure 2.30)	6 - Mixed green grassland/woodland vegetation	Because of dry grass patches around, grazing and small sizes of the depressions, water fringe vegetation not prominent. Class 7 (Sparse, green grassland/woodland vegetation) farther east and the water (Class 1) delineated, correctly reproducing ground cover variation.
LV9 UTM grid 35 533451E, 8260878N	On 7 September 1995: Kafue River channel. River ≈20-25m wide, with water fringe grass/reeds (mainly *Vossia cuspidata, Polygonum senegalense*) on banks. Near south bank is village (Banachibwembwe) (see Figures 2.21a and 2.21b).	10 - Emergent vegetation in shallow water or after burning	Wrong class. Narrow nature of river open water width probably made it difficult to separate it as open water (Class 1) without the inaccuracy of old burning areas with new shoots of vegetation (Class 10) being classified as burnt (Class 15) and freshly burnt areas in woodland and floodplain zones being classified as Open water (Class 1).

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV10 UTM grid 35 532500E, 8259412N	On 7 September 1995: Kafue River channel. River ≈ 20-25m wide, grass (mainly *Vossia cuspidata*) and floating water hyacinth (*Salvinia molesta*) on bank. Farther from bank (east) are open, dry spaces used as cattle kraals and milking areas. Site close to village (Kabwe). (see Figure 2.21c)	10 - Emergent vegetation in shallow water or after burning	Wrong class. Narrow nature of river open water width probably made it difficult to separate it as open water (Class 1) without the inaccuracy of old burning areas with new shoots of vegetation (Class 10) being classified as burnt (Class 15) and freshly burnt areas in woodland and floodplain zones being classified as Open water (Class 1). Sparse water fringe vegetation on banks of river farther south detected as Class 5 (Sparse, stressed-). Farther east, the cattle patches correctly classified as Class 13 (Exposed, trampled dry soil with surface debris).
LV11 UTM grid 35 526782E, 8251770N	On 19 September 1995: Bare, dark grey clay soil (3.18% organic matter), very isolated *Acacia* bushes (≈1.5m tall) in partial spring leaf, isolated *Odontotermis* termite mounds. Area intensely grazed and trampled by game animals. End of termitaria-floodplain ecotone.	13 - Exposed, trampled dry soil with surface debris	Correct classification. Class 9 (Very sparse green vegetation/ termitaria with isolated trees) present around, correctly reproducing ground cover variation.
LV12 UTM grid 35 528905E, 8254724N	Isolated *Acacia polycacantha* tree stand (≈20x30m) in floodplain zone. Trees about 7m tall, in leaf, with *Sesbania* bushes (in leaf) between trees. Cover around tree pocket as at LV13.	6 - Mixed green, grassland/woodland vegetation	Correct classification. Pocket of trees too small to be separated from LV13 cover. Site visited on same day as LV13.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV13 UTM grid 35 529013E, 8254752N	On 19 September 1995: Bare, very dark grey, loam soil (7.07% organic matter) with ungrazed, apparently unpalatable green *Compositae* herbs (*Grangea maderaspatana*) (20-30cm tall). Herbs about 40% of cover, the rest bare dark soil.	6 - Mixed, green grassland/woodland vegetation	Correct classification.
LV14 UTM grid 35 532111E, 8254724N	On 19 September 1995: Shallow, small stream draining large lagoon (Chunga). Stream about 2m wide but with belt of sparse, green *Compositae* herbs (*Grangea maderaspatana*) around it. Beyond this belt are dry, game trampled grass stems with sparse *Grangea maderaspatana* herbs.	9 - Very sparse green vegetation/termitaria with isolated trees	Correct identification of sparse greenness. Stream too small to be delineated (less than pixel (30m) in size).
LV15 UTM grid 35 534729E, 8256600N	On 19 September 1995: Dry, open floodplain grassland (mainly *Hyparrhenia rufa*), grass ≈1m tall, almost complete ground cover but intermittent, ≈15-20cm wide patches of exposed black, loam soil (7.22% organic matter). Moderate grazing by cattle, mainly as transit zone.	8 - Very sparse green grassland/woodland vegetation)	Acceptable class. Area may have had sparse greenness in 1994, depending on timing and duration of flood recession, as clearly shown by vegetation reflectance characteristics on image.

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV16 UTM grid 35 536530E, 8256867N	On 19 September 1995: Dry, open floodplain grassland, little soil exposure, grass about 40cm tall, very little grazing, mainly cattle zone, outside national park. Dry brown grass. (see Figure 2.19a)	7 - Sparse green grassland/woodland vegetation	Acceptable class. Area may have had sparse greenness in 1994, depending on timing and duration of flood recession, as clearly shown by vegetation reflectance characteristics (more intense than at LV15) on image.
LV17 UTM grid 35 538542E, 8257918N	On 19 September 1995: Short, reddish, semi-dry floodplain grassland. Grass ≈20cm tall. Almost complete cover, but about 30% soil exposure. Very little grazing, mainly cattle zone, outside national park. (see Figure 5.6a)	7 - Sparse green grassland/woodland vegetation	Acceptable class. Area may have had sparse greenness in 1994, depending on timing and duration of flood recession, as clearly shown by vegetation reflectance characteristics (more intense than at LV15) on image.
LV18 UTM grid 35 538523E, 8259102N	On 19 September 1995: Open water body (small lagoon) with green grass and water reeds on fringes. Near village, grass grazed by cattle. (see Figure 5.3b)	1 - Open water & 10 - Emergent vegetation in shallow water or after burning, (with 15 (Burnt area or muddy, dark surface) around)	Classification reproduced the variation in land cover characteristics around the lagoon. Class 15 (burnt area or muddy, dark surface) referred to dark, wet clay around lagoon in this case.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
LV19 UTM grid 35 532464E, 8254385N	On 19 September 1995: Pocket of green herbaceous shrubs (*Gomphocarpus rostratus*), ≈30x60m. Shrubs 1.5-1.6m tall, with 1-1.5m canopies, constituting about 50% of site cover, the rest is dry grass mat at ground level (≈45%) and small number (≈7) of young *Acacia polyacantha* trees (5%) in leaf. Grass 10-15cm tall, *Acacia* trees 2-3m tall. Pocket surrounded by dry, heavily grazed floodplain grassland.	6 - Mixed green grassland/woodland vegetation	Acceptable classification.
LV20 UTM grid 35 517815E, 8250318N	On 20 September 1995: Lagoon fringe (Chunga Lagoon). Open water on one side, periodically inundated heavily grazed ground around. Heavily grazed, periodically inundated ground has *Polygonum* species cropped to the ground. Beyond are ungrazed green *Grangea maderaspatana* herbs among dry, trampled very dark greyish brown loam soil (7.11% organic matter)	Outside image area	Site fell just outside image cover area by about 600m. It was difficult to determine this in the field before image rectification. Open water in lagoon to the north, however, correctly classified (Class 1).
LV21 UTM grid 35 531704E, 8251811N	On 7 September 1995: Dry floodplain twigs (≈40%) among dark clay soil patches. Twigs yellowish, ≈80cm tall. No grazing, but transit area for animals. Site just outside national park.	12 - Dry land with leafless plant structures (woodland/grassland)	Class should probably have been 11 (Dry grassland and termitaria zone without trees) but tall nature of twigs among dark clay soil patches probably makes Class 12 acceptable.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW1 UTM grid 35 **565**782E, 82**44**851N	On 8 September 1995: Crop fields in dry season fallow after harvesting and clearing of debris. Isolated green shrubs in some. Dry, bare soil with scanty dry grass cover, light olive brown sandy clay loam soil (1.55% organic matter). Isolated trees between fields.	13 - Exposed, trampled dry soil with surface debris.	Acceptable classification. Class 14 (Bare, compacted dry soil) and sparse green vegetation classes also distinguished, correctly reproducing the variation on the ground.
MZW2 reference 15°50'35"S, 27°35'43"E.	On 8 September 1995: Mixed broad leaved bushes + bare ground	9 - Very sparse green vegetation/termitaria with isolated trees.	Error: coordinates not recorded as UTM. Class acceptable.
MZW3 UTM grid 35 **563**446E, 82**56**978N	On 8 September 1995: Depression in termitaria zone with tall grass (0.5-1m) in non-contiguous tuft stands, mainly *Vitiveria nigritana*. Large (*Macrotermis*) termite mounds (≈1.5m tall). Ecotone: transition zone between tree termitaria zone and floodplain grassland. (see Figure 2.18a)	12 - Dry land with leafless plant structures (woodland/grassland)	Acceptable class given non-contiguous nature of tall grass cover and the large termite mounds among the grass tufts.
MZW4 UTM grid 35 **564**184E, 82**50**996N	On 8 September 1995: Drying grassland (about 30% moist, mainly in lower stem and leaf portions), with frequent termite mounds (*Microtermis* and flattened *Odontotermis* mounds) and isolated *Acacia* bushes. Grass 20-50cm tall, yellowish brown in colour. (see Figure 2.18b)	11 - Dry grassland and termitaria zone without trees	Acceptable class.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW5 UTM grid 35 **567**256E, 82**642**01N	On 8 September 1995: Kafue River channel. River about 40-50m wide but open water section only about 30m wide due to water fringe vegetation (*Vossia cuspidata, Cyperus papyrus*). Farther from bank (south) are open, dry spaces used as cattle kraals and milking areas, with drying grass (40-50cm tall) farther south. Site is close to village (Shakapinka). (see Figure 2.21d)	1 - Open water & 3 - Dense, vigorous water reeds/water fringe vegetation (farther south of river bank; 11 - Dry grassland and termitaria zone without trees)	Correct reproduction of the varied nature of the land cover characteristics
MZW6 UTM grid 35 **564**380E, 82**615**01N	On 8 September 1995: *Acacia* trees (3-5m tall, 3.5-5m canopies) in spring leaf, among short, dry grass and *Odontotermis* termite mounds.	9 - Very sparse green vegetation/termitaria with isolated trees.	Correct class.
MZW7 UTM grid 35 **571**744E, 82**545**36N	On 9 September 1995: Wetland, apparently perennial marsh, with extensive and dense *Typha domingensis* reed cover. Reed density increasing inwards, peripheral areas disturbed by burning and cattle grazing. Village area (Kabanje) just south, dry grass to the west with frequently occurring *Acacia* bushes and isolated termite mounds. (see Figure 5.2)	4 - Less dense, stressed water reeds/water fringe vegetation & 3 - Dense, vigorous water reeds/water fringe vegetation	Water reed vigour/density classes increase inwards from periphery of marsh. Class 2 - Dense, very vigorous- delineated inwards. Correct classification.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW8 UTM grid 35 564085E, 8247671N	On 21 September 1995: Bare ground with light olive brown soil (75%) and mixed species, scattered green shrubs. Ground compacted and dry, scattered dry grass patches at ground level. Shrubs 1-3m tall, with 1-4m canopies, some in leaf. Near villages, cattle trampling evident. Shrub species include *Albizia*, *Combretum* and *Acacia*.	13 - Exposed, trampled dry soil with surface debris.	Correct class.
MZW9 UTM grid 35 563561E, 8248780N	On 21 September 1995: Mixed woodland, tree species include *Combretum*, *Albizia*, *Acacia*. Largely leafless, some trees in early spring (especially *Combretum* and *A. polyacantha*). Site ≈48% covered by leafless trees, 37% by short grass, 6% bare dark greyish brown clay soil (3.03% organic matter), 9% dead leaf debris on ground. Tree height 1.5-8m, canopies up to 10 wide, closed in some places. Woodland recovering from degraded state, area evidently former human settlement.	12 - Dry land with leafless plant structures (woodland/grassland)	Correct class since woodland not in leaf.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW10 UTM grid 35 562984, 8249535N	On 21 September 1995: Mixed woodland, not in leaf, mainly *Acacia polyacantha* trees especially in area just south between site and MZW9. Area coppiced in places due to previous human settlement. Tall (≈40-90cm) grass between trees. Cattle grazing evident but not intense.	12 - Dry land with leafless plant structures (woodland/grassland)	Correct classification. Classes 11 (Dry grassland and termitaria zone without trees), 9 (Very sparse, green vegetation/termitaria with isolated trees), and 6 (Mixed green grassland/woodland vegetation) delineated around site, correctly reproducing ground cover variation.
MZW11 UTM grid 35 562635E, 8250496N	On 21 September 1995: Woodland largely not in leaf, mainly *Acacia gerrardii* with dry grass (mainly *Setaria sphacelata*) between trees. About 40% tree cover, 32% dry grass cover, and 4% bare, dark clay soil. In addition to *A. gerrardii*, are *Combretum* and *Albizia* trees. Tree height 8-15m, canopies 5-6m, some in early spring leaf.	12 - Dry land with leafless plant structures (woodland/grassland)	Correct classification. Classes 9 (Very sparse, green vegetation/ termitaria with isolated trees), and 6 (Mixed green grassland/ woodland vegetation) delineated around site, correctly reproducing ground cover variation, as some trees had leaves.
MZW12 UTM grid 35 562776E, 8252100W	On 21 September 1995: Mixed woodland in early spring, with *Acacia gerrardii, Colophospermum mopane, Albizia harveyi* and mixed composition thickets on *Odontotermis* mounds, including *Euphorbia* species. Dry grass and dark greyish brown soil (2.95% organic matter) between trees. Trees up to 20m tall.	9 - Very sparse green vegetation/termitaria with isolated trees	Correct detection of sparse greenness. More green than MZW11. Classes 12 (Dry land with leafless plant structures) and 11 (Dry grassland and termitaria zone without trees) also distinguished around site, correctly reproducing ground cover variation.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW13 UTM grid 35 563463E, 8255286N	On 21 September 1995: Depression in woodland zone, with bare, loose, very dark grey, clay loam soil (4.43% organic matter), intermittent tussocks of dry, brown grass (*Setaria* sp.), *Acacia* thickets in leaf on *Macrotermis* termite mounds (5 mounds in 30x30m area). Depression roughly 500m north-south, and 200m east-west. *Acacia gerrardii, Albizia harveyi* and *Acacia polyacantha* trees/bushes in spring around depression. To the south between MZW12 and MZW13 is predominantly *A. harveyi*, leafless woodland with trees up to 20m tall.	9 - Very sparse green vegetation/termitaria with isolated trees	Correct depiction of sparse ground cover greenness. Classes 12 (Dry land with leafless plant structures) and 11 (Dry grassland and termitaria zone without trees) also distinguished around site, correctly reproducing ground cover variation.
MZW14 UTM grid 35 563440E, 8256887N	On 21 September 1995: Woodland-termitaria transition (with grassland), about 88% dry grass (mainly *Vitiveria nigritana*), 12% isolated trees on *Macrotermis* termite mounds, some trees in leaf. Mixed woodland around.	12 - Dry land with leafless plant structures (woodland/grassland)	With Class 9 (Very sparse green vegetation/termitaria with isolated trees), ground variation reproduced by classification.
MZW15 UTM grid 35 563446E, 8256978N	On 21 September 1995: Termitaria zone with isolated *Acacia* trees/bushes, with tall dry grass (mainly *Vitiveria nigritana*, ≈60cm-1m). Trees/bushes 3-6m tall.	12 - Dry land with leafless plant structures (woodland/grassland)	Correct class. Site actually very nearly MZW3, the two visited on separate dates.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW16 UTM grid 35 564373E, 8260470N	On 21 September 1995: Termitaria zone with *Acacia* trees in leaf between termite mounds, and dry, brown *Hyparrhenia rufa* and *Setaria eylesii* grass. Tree height 2.5-10m.	9 - Very sparse green vegetation/termitaria with isolated trees	Correct class. Classes 12 (Dry land with leafless plant structures) and 11 (Dry grassland and termitaria zone without trees) also distinguished around site, correctly reproducing ground cover variation.
MZW17 UTM grid 35 563997E, 8261968N	On 21 September 1995: Dry floodplain grassland, mainly *Hyparrhenia rufa, Vitiveria nigritana* brown in colour. Very isolated *Acacia* bushes in leaf. Intermittent exposure of brown sandy loam soil (1.44% organic matter). Grass 40-60cm tall. Few *Cubitermis* termite mounds.	9 - Very sparse green vegetation/termitaria with isolated trees & 12 - Dry land with leafless plant structures	Correct reproduction of ground cover variation. Moisture (and greenness) status could have been different in 1994 because of variation in flood timing from year to year.
MZW18 UTM grid 35 562693E, 8264349N	On 21 September 1995: Open dry floodplain grassland, mainly *Hyparrhenia rufa,* almost no trees except for very isolated -1.5m tall bushes. Grass 1-1.6m tall, almost completely covering the very dark grey clay soil (2.60% organic matter). Little grazing but cattle tracks present.	11 - Dry grassland and termitaria zone without trees	Correct classification.

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW19 UTM grid 35 560932E, 8266338N	On 21 September 1995: Open dry floodplain grassland, predominantly *Setaria eylesii* grass, stems still green, 40-50cm tall, high cattle grazing pressure. Near fishing village (Nachaba).	8 - Very sparse green grassland/woodland vegetation & 13 - Exposed, trampled dry soil with surface debris	Correct classes. Sparse greenness from the grass stems, trampled soil due to cattle activity. Close by is Class 11 (Dry grassland and termitaria zone without trees). Correct reproduction of variation in ground cover types.
MZW20 UTM grid 35 561419E, 8247299N	On 22 September 1995: Dense *Acacia albida* woodland. Tall trees (15-20m height) with thickets and dry grass and leaf debris at tree bases. very little soil exposure. Trees in full leaf. In southeast land opens up into human settlement and crop fields in dry season fallow below large *A. albida* trees.	6 - Mixed green grassland/woodland vegetation	Correct class. Different grades of woodland greenness at site distinguished, including Less dense, stressed - (Class 4) where trees densest. Therefore correct reflection of ground cover variation.
MZW21 UTM grid 35 559858E, 8248677N	On 22 September 1995: *Acacia* mixed woodland with dry grass (mainly *Hyparrhenia rufa* and *Setaria* sp.) between trees. *Odontotermis* termite mounds among trees. Trees in leaf, 2-15m tall. Very little bare soil exposure, grass between trees; ≈60% grass, 40% trees. Most common trees: *Acacia polyacantha* in leaf. Open, dry grass spaces nearby. Former settlement and cultivation areas.	6 - Mixed green grassland/woodland vegetation	Correct class. Different grades of woodland greenness at site distinguished, including Less dense, stressed -(Class 4) where trees densest.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW22 UTM grid 35 557263E, 8249720N	On 22 September 1995: Grassland depression with *Odontotermis* termite mounds, surrounded by scanty green tree cover and human settlement. Grass mainly dry, yellowish grey *Setaria sphacelata*, ≈1m tall, no grazing pressure. Setting is transition zone between woodland and termitaria zones. Very little exposure of dark greyish brown clay soil (4.12% organic matter).	12 - Dry land with leafless plant structures (woodland/grassland)	Should probably have been more correctly classified as Class 11 (Dry grassland and termitaria zone without trees).
MZW23 UTM grid 35 550978E, 8255209N	On 22 September 1995: Termitaria (*Odontotermis* sp.) with dry, short grass, trampled dark grey clay soil (6.91% organic matter). No trees or shrubs. Intense cattle grazing, area just inside floodplain zone but close to human settlements. Burning evidently used to promote fresh flush of grass.	11 - Dry grassland and termitaria zone without trees.	Classification probably correct state of floodplain grass at time of image acquisition
MZW24 UTM grid 35 547768E, 8257833N	On 22 September 1995: Burnt floodplain grassland with emerging flush of grass.	10 - Emergent vegetation in shallow water or after burning	Correct class. Early burning to promote fresh flush for cattle grazing likely to be annually practiced, hence the similarity between 1994 and 1995.

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
MZW25 UTM grid 35 **550**381E, 8**260**542N	On 22 September 1995: Burnt floodplain grassland with emerging flush of grass and ungrazed *Compositae* shrub (*Vernonia cinerea*). cattle grazing intense. Considerable exposure of black loam soil (7.22% organic matter), with cover of soot from burnt grass.	8 - Very sparse green grassland/woodland vegetation	Probably correct categorization of 1994 stage in flush of grass.
BLW1 UTM grid 35 **549**043E, 8**291**808N	On 24 September 1995: Dry short grass on disused air strip with emerging broad leaf shrubs. Around is *Combretum* woodland in full leaf, some trees coppiced. Trees in woodland 2-5m tall, 3-6m canopies (see Figure 5.4a).	9 - Very sparse green vegetation/termitaria with isolated trees	Correct detection of sparse greenness on disused air strip. Mixed woodland around classified as Class 6 (Mixed green grassland/woodland vegetation)
BLW2 UTM grid 35 **529**706E, 8**292**732N	On 25 September 1995: Dense woodland, mainly *Acacia polyacantha*. Trees 12-20m tall, in leaf. Canopies 7-12m wide, closed in some places, dry grass (mainly *Setaria sphacelata*) between trees. Very little exposure of black clay soil with 7.18% organic matter. (see Figure 2.16)	6 -Mixed green grassland/woodland vegetation & 7 - Sparse, green grassland/woodland vegetation & 4 - Less dense, stressed water reeds/water fringe vegetation	Classification was able to distinguish different grades of woodland density/vigour. Some trees had reflectance characteristics of stressed water reeds/water fringe vegetation, hence the classification of woodland into this class (Class 4).

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW3 UTM grid 35 527592E, 8289917N	On 25 September 1995: Mixed, degraded woodland (30%) in late spring stage of leaf re-growth (almost full leaf), with bare soil (70%). Former human settlement area, woodland regenerating. Trees/bushes 1.5-4m tall, species include *Albizia harveyi, Piliostigma thonningei, Combretum ghasalense* and *Acacia* species. Exposed soil is brown, silty clay. Isolated *Odontotermis* termite mounds. (see Figure 2.17)	9 - Very sparse green vegetation/termitaria with isolated trees.	Probably correct category for site's greenness. Other classes around are 6 (Mixed green grassland/woodland vegetation), 11 (Dry grassland and termitaria zone without trees) and 12 (Dry land with leafless plant structures (woodland/grassland)). Classification correctly reproduced ground cover variation.
BLW4 UTM grid 35 527159E, 8289156N	On 25 September 1995: Tree and bush grassland. Dry grass, mainly *Hyparrhenia rufa*, scattered *Acacia* trees in leaf. Area former human settlement, trees regenerating, transition zone from woodland in north to termitaria zone south.	9 - Very sparse green vegetation/termitaria with isolated trees.	Correct class.
BLW5 UTM grid 35 525883E, 8285780N	On 25 September 1995: Grassland termitaria with isolated bushes (*Albizia, Piliostigma, Combretum* and *Acacia* sp.). Bushes 2-4m tall, with 1-1.5m canopies, in leaf. Grass dry, mainly *Setaria sphacelata*). No grazing. Occasional exposure of dark grey loam soil (3.73% organic matter)	9 - Very sparse green vegetation/termitaria with isolated trees.	Acceptable category for site's greenness.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW6 UTM grid 35 524962E, 8284342N	On 25 September 1995: Termitaria grassland with very isolated trees/shrubs in leaf. *Odontotermis* termite mounds. Grass dry, yellowish brown/grey in colour, mainly *Setaria sphacelata*, 60cm-1m tall, not grazed. Transition zone to floodplain grassland. Black clay soil (with 2.80% organic matter). (see Figure 5.6b)	12 - Dry land with leafless plant structures (woodland/grassland)	Correct class should probably have been Class 11 (Dry grassland and termitaria zone without trees). Perhaps because grass was tall and cast shadows just like leafless woodland, the site was classified the same as leafless woodland.
BLW7 UTM grid 35 523802E, 8282487N	On 25 September 1995: Open, dry grassland with very isolated *Cubitermis* termite mounds. Predominant grass species *Hyparrhenia rufa, Eragrostis lappula, Seteria* sp. Grass yellowish brown, 50cm-2m tall, not grazed, almost completely covering black sandy loam/sandy clay loam soil. (see Figure 2.19b)	11 - Dry grassland and termitaria zone without trees	Correct class.
BLW8 UTM grid 35 523417E, 8282027N	On 25 September 1995: Open, dry floodplain grassland, ungrazed, grass 20-30cm tall, occasional green *Compositae* herbs among dry grass. (see Figure 5.8a)	8 - Very sparse green grassland/woodland vegetation	Correct classification because of green herbs. Around site are classes 11(Dry grassland and termitaria zone without trees) and 12 (Dry land with leafless plant structures (woodland/grassland))

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW9 UTM grid 35 521087E, 8280058N	On 25 September 1995: Open, heavily grazed floodplain grassland. Grass cropped to the ground, new shoots emerging, debris of old grass stems trampled and broken. Intense grazing by lechwe and zebra. Evidence of early burning. (see Figure 2.15)	15 - Burnt area or muddy, dark surface	Was burnt in 1994. Correct class (but unlikely to have been muddy)
BLW10 UTM grid 35 517618E, 8279633N	On 25 September 1995: Dense water fringe vegetation (species including *Cyperus papyrus, Typha domingensis, Polygonum senegalense, Phragmites mauritianus*), 2-4m tall, density increasing inwards towards large lagoon. Cattle grazing evident. Soil black (gley) sandy loam. (see Figure 2.20)	3 - Dense, vigorous water reeds/water fringe vegetation	Correct classification. Inwards from site are Classes 2 (Dense, very vigorous-) and 4 (Less dense, stressed water reeds/water fringe vegetation), a correct reproduction of the ground cover variation.
BLW11 UTM grid 35 541141E, 8294348N	On 26 September 1995: Mixed woodland with concentration of plant with reddish dry pods (especially *Acacia* and *Albizia* species). Some trees in leaf, others in early spring. Open spaces with bare soil between trees. Trees 3-20m tall, with 4-8m canopies. No grazing but in National park (see Figure 5.4b).	8 - Very sparse green grassland/woodland vegetation	Around site are classes 11(Dry grassland and termitaria zone without trees) and 12 (Dry land with leafless plant structures (woodland/grassland)), a correct reproduction of ground cover variation.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW12 UTM grid 35 529062E, 8290856N	On 26 September 1995: Degraded mixed woodland (mainly *Acacia* and *Combretum* species) in former human settlement area, denser woodland immediately east across stream. Trees 2.5-6m tall (≈10m in nearby woodland), in spring leaf, canopies 2-10m wide. About 60% of cover dry grass).	9 - Very sparse green vegetation/termitaria with isolated trees.	Correct category of site's greenness
BLW13 UTM grid 35 530165E, 8289256N	On 26 September 1995: Mixed woodland. Tall trees (10-15m height), canopies (8-10m wide) not touching. Many trees in leaf. Large (*Macrotermis*) termite mounds among trees. Short (≈20cm), dry grass where open spaces occur.	6 -Mixed green grassland/woodland vegetation	Correct classification. Other classes of woodland around are Class 4 (Less dense, stressed-), Class 5 (Sparse, stressed water reeds/water fringe vegetation), a correct reproduction of woodland variation on the ground. Some trees had reflectance characteristics of stressed water reeds/water fringe vegetation, hence the classification of woodland into these classes.
BLW14 UTM grid 35 530769E, 8288355N	On 26 September 1995: Degraded mixed woodland in human settlement area. Trees in leaf (*Acacia, Piliostigma* sp.), 2-2.5m tall, canopies 1-1.5m wide. Short dry grass between trees, also crop fields in dry season fallow (with dry grass and old crop debris).	12 - Dry land with leafless plant structures (woodland/grassland))	Correct depiction of dry state.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW15 UTM grid 35 530521E, 8287738N	On 26 September 1995: Dry grassland (mainly *Hyparrhenia rufa*) among thickets on *Macrotermis* termite mounds. Grass about 60% of cover. Trees 6-12m tall, with 6m wide canopies, in spring leaf. Grass 1-2m tall.	Pockets of : Class 6 - Mixed green grassland/woodland vegetation Class 11- Dry grassland and termitaria zone without trees	Correct reproduction of ground cover variation. Other classes around site are Class 13 (Exposed, trampled dry soil with surface debris) and Class 7 (Sparse, green grassland/woodland vegetation)
BLW16 UTM grid 35 531091E, 8283005N	On 26 September 1995: Termitaria grassland, dry brown grass, isolated trees. Transition zone between woodland and floodplain-grassland zone. *Odontotermis* termite mounds. No grazing.	11 - Dry grassland and termitaria zone without trees	Should probably have been more accurately classified in a sparse green vegetation class. However, Class 8 (Very sparse green grassland/woodland vegetation) present around.
BLW 17 UTM grid 35 531519E, 8280240N	On 26 September 1995: Open, dry floodplain grassland. Grass 20cm-1m tall. Mixed, with various coarse twigs. Area is in delta of seasonally flowing tributary of the Kafue, which disappears in floodplain. No grazing.	11 - Dry grassland and termitaria zone without trees	Acceptable class. Ground cover variation reproduced by classification. Class 12 (Dry land with leafless plant structures (woodland/grassland)) also delineated near site.
BLW18 UTM grid 35 531774E, 8279696N	On 26 September 1995: Open floodplain grassland, very few small (*Cubitermis*) termite mounds. Grass drying, faintly green in lower portions. Main grass species *Brachiaria brizantha*, not grazed. Area is in delta of seasonally flowing tributary of the Kafue, which disappears in floodplain.	10 - Emergent vegetation in shallow water or after burning	Must have had early burning in 1994, resulting in new shoots of grass.

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW19 UTM grid 35 532215E, 8277893N	On 26 September 1995: Tall, dry, brown *Sorghum versicolor* reeds in floodplain zone. Stand over 70x70m in size. Reeds over 2m tall. Shorter grass species between reeds. Very little exposure of loam, very dark grey soil (4.74% organic matter). Reeds form isolated pocket stands to the east of site, the rest being shorter grass.	11 - Dry grassland and termitaria zone without trees	Acceptable class.
BLW20 UTM grid 35 532219E, 8274018N	On 26 September 1995: Open floodplain grassland. Heavily grazed by lechwe and zebra, grass cropped to ground level. Debris of old grass stems trampled and broken. New shoots of grass emerging.	5 - Sparse, stressed water reeds/water fringe vegetation	Acceptable class. Grass may have been in this state at time of image acquisition.
BLW21 UTM grid 35 532914E, 8271978N	On 26 September 1995: Open floodplain grassland. Intensely grazed by lechwe and zebra, grass cropped to ground level. Debris of old grass stems trampled and broken. Evidence of early burning. New shoots of grass emerging. Exposed loam, very dark grey soil (6.83% organic matter) in places, with covering of soot from burning.	13 - Exposed, trampled dry soil with surface debris	Maybe correct class assuming that there was more trampling and blowing of debris by wind in 1994, leaving exposed soil.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW22 UTM grid 35 558798E, 8294972N	On 27 September 1995: Dry grassland with isolated shrubs, bushes and trees, few termite mounds (*Ondontotermis* sp.). Site close to human settlement. Trees, bushes and shrubs 1-15m tall, canopies 1.5-10m wide, many in leaf. Grass dry, brownish, ungrazed, 40cm-1m tall. Little exposure of light greyish brown sandy loam soil (1.09% organic matter)	9 - Very sparse green vegetation/termitaria with isolated trees	With Class 13 (Exposed, trampled dry soil with surface debris) near site, acceptable categorization of state of greenness.
BLW23 UTM grid 35 558829E, 8294452N	On 27 September 1995: Open floodplain grassland. Grass dry in upper portions, fresh shoots in lower portions. Low grazing pressure. Fire damage evident.	11 - Dry grassland and termitaria zone without trees	Acceptable, possible cover class in 1994.
BLW24 UTM grid 35 558579E, 8293469N	On 27 September 1995: Open floodplain grassland. Grass dry in upper portions, fresh shoots in lower portions, about 15cm tall. Higher grazing pressure than BLW23, mainly cattle grazing.	10 - Emergent vegetation in shallow water or after burning	Acceptable class. Could have been burnt in 1994.
BLW25 UTM grid 35 558524E, 8291892N	On 27 September 1995: Open floodplain grassland largely dry but with emerging green shoots. More trampled by cattle than BLW24, more exposure of black sandy clay loam soil.	5 - Sparse, stressed water reeds/water fringe vegetation	May be correct category for state of floodplain at site in 1994.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW26 UTM grid 35 559107E, 8291325N	On 27 September 1995: Depression in floodplain zone, periodically watered, with water reeds (mainly *Typha domingensis*). Small streams leading into depression. Not under water at time but very moist. Cattle grazing evident.	4 - Less dense, stressed water reeds/water fringe vegetation.	Correct class.
BLW27 UTM grid 35 560401E, 8290070N	On 27 September 1995: Open lagoon water (Luwato Lagoon). Lagoon 60-80m wide. Same lagoon as BLW36. Water reeds and water fringe vegetation on lagoon banks (*Typha domingensis* on north bank, *T. domingensis* and *Polygonum senegalense* on south bank). (see Figures 2.23, 4.8, 5.3a and 5.5)	1 - Open water & 4 - Less dense, stressed water reeds/water fringe vegetation	Correct classification
BLW28 UTM grid 35 549838E 8291164N	On 28 September 1995: Termitaria grassland bordering floodplain grassland. Very isolated, mainly *Acacia* shrubs 1-4m tall. *Odontotermis* termite mounds common. Dry, yellowish brown grass (mainly *Graminae* species), up to 1m tall, ungrazed.	9 - Very sparse green vegetation/termitaria with isolated trees	With Class 12 (Dry land with leafless plant structures (woodland/grassland) near site, ground cover variation reproduced by classification.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW29 UTM grid 35 551310E, 8289929N	On 28 September 1995: Open, dry grassland on edge of floodplain. very isolated *Odontotermis* termite mounds. Fewer shrubs than at BLW28. No grazing. Grass as at BLW28.	11 - Dry grassland and termitaria zone without trees	With Classes 12 (Dry land with leafless plant structures (woodland/ grassland) and 9 (Very sparse green vegetation/termitaria with isolated trees) near site, ground cover variation reproduced by classification
BLW30 UTM grid 35 551957E, 8287834N	On 28 September 1995: Dry, open floodplain grassland, mainly ungrazed dark brown twigs (mainly *Vernonia* sp.). Some twigs in leaf but ungrazed. Height of twigs 30-50cm, almost complete ground cover but interrupted by game tracks.	9 - Very sparse green vegetation/termitaria with isolated trees	With Classes 12 (Dry land with leafless plant structures (woodland/ grassland), 6 (mixed green grassland/ woodland vegetation), and 5 (Sparse, stressed water reeds/water fringe vegetation), ground cover variation reproduced by classification
BLW31 UTM grid 35 553490E, 8290044N	On 28 September 1995: *Typha domingensis* water reeds, next to open, heavily grazed floodplain grassland (grazing by lechwe/zebra). Fire disturbance of reeds evident at time of visit. (see Figure 5.8b)	4 - Less dense, stressed water reeds/water fringe vegetation & 5 - Sparse, stressed water reeds/water fringe vegetation	At time of image acquisition in 1994, reeds very likely to have been unburnt. Classification reproduced variation in reed density/vigour.
BLW32 UTM grid 35 556865E, 8291003N	On 28 September 1995: Water reed zone, mainly *Typha domingensis* in shallow seasonally inundated depression. Fire disturbance evident. Low grazing pressure.	4 - Less dense, stressed water reeds/water fringe vegetation	Correct classification.

Appendix 3 continued - Comparison of Image and Ground Cover Classes

SITE	SEPTEMBER 1995 GROUND COVER CHARACTERISTICS	20 SEPTEMBER 1994 IMAGE CLASS	COMMENTS
BLW33 UTM grid 35 561654E, 8290153N	On 28 September 1995: Open floodplain grassland, near shallow stream with water. Grass partially green, short (≈15cm tall), mixed. Cattle grazing evident but grass not cropped to the ground. Black, moist clay soil (7.18% organic matter) exposed in few spaces between under grass.	5 - Sparse, stressed water reeds/water fringe vegetation	Correct classification. Grass had reflectance characteristics of sparse, stressed water reeds/water fringe vegetation.
BLW34 UTM grid 35 560780E, 8287696N	On 28 September 1995: Burnt open floodplain grassland near (Luwato) lagoon channel. Emerging new shoots of grass grazed by cattle. Site near human settlement camp (cattle herders). Over 80% of ground is exposed black clay soil (7.11% organic matter)	10 - Emergent vegetation in shallow water or after burning	Being near human settlement, site likely to have been the same in 1994 as in 1995 (burnt for fresh growth of grass). Therefore classification correct.
BLW35 UTM grid 35 560998E, 8286181N	On 28 September 1995: Burnt open floodplain grassland near (Luwato) lagoon channel. Tufts of emerging shoots of grass after burning. Over 90% of ground cover is exposed black clay soil similar to that at BLW34. Less cattle grazing pressure than at BLW34.	15 - Burnt area or muddy, dark surface.	Correct classification, was burnt at time of image acquisition too.
BLW36 UTM grid 35 534005E, 8271017N	On 26 September 1995: Dry lagoon channel (about 8m wide) with stranded *Sesbania sesban* shrubs of 2-3m height. Open, heavily grazed, trampled floodplain around.	5 - Sparse, stressed water reeds/water fringe vegetation	With classes 8 (very sparse green grassland/woodland vegetation) and 13 (Exposed, trampled dry soil with surface debris) nearby, ground cover variation reproduced.

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