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WETLAND CHANGE DETECTION AND INUNDATION NORTH OF LAKE GEORGE, WESTERN UGANDA USING LANDSAT DATA

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ABSTRACT:- *A remote sensing approach has been adopted to detect seasonal change and inundation in the wetlands north of Lake George, western Uganda that is being impacted by anthropogenic factors. Five Landsat (TM and ETM+) satellite imagery of August 1987, January 1995, September 1999, March 2001 and December 2001 were used. During change detection in the wetland region, three broad classes (water bodies, exposed areas and vegetated zones) were generated in a Geographic Information System (GIS) using the Normalised Difference Water Index (NDWI), Normalised Difference Vegetation Index (NDVI), and unsupervised classification supported with ground data. Inundation mapping was carried out using density slicing on image sets with similar precipitation inputs. Change detection shows a slight decrease in vegetated and exposed wetlands areas from August 1987 through March 2001. Inundation mapping presents an increase in waterlogged expanses from January 1995 to December 2001. There is a likelihood of present anthropogenic factors playing a significant role in denuding the wetland land cover. A similar remote sensing approach could be used for monitoring temporal and spatial aspects of other wetlands in the region.*

Keywords*: Wetland, Change detection, Inundation, Lake George, Remote Sensing*

INTRODUCTION

In recent years, there has been increasing awareness of the fact that natural wetlands provide many valuable functions (e.g. flood alleviation, ground water recharge, retention and regulation of pollutants and water plant nutrients); refugia for fish and other fauna; and other attributes (biodiversity, aesthetic beauty for tourists, cultural heritage and archaeology) (Amoros *et al.* 1996, Tockner *et al.* 1999, Robertson *et al.* 1999, Briggs *et al.* 1999, Frazier 1999, Bugenyi 2001). The world's wetlands (including the ecotones) are now recognised as some of the most important and productive ecosystems on earth (Mitsch and Gosselink 1993), and it is recognised that wetland conservation and management are the shared responsibility for all concerned. Prior to conserving wetlands it is crucial to map, establish and quantify the changes that may have taken place over specified time periods.

Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh 1989). Timely and accurate change detection of wetlands provides the foundation for better understanding relationships and interactions with human and natural phenomena to better manage and use its resources. Remote sensing that provides synoptic coverage and repeatability of space information thus provide more cost effective methods for wetland change monitoring. It involves the application of multi-temporal datasets to quantitatively analyse the temporal effects on wetlands.

The choice of Landsat (TM, ETM+) datasets utilised in the present study was based on temporal, spatial, and spectral resolution considerations, as well as size of study area, budgetary constraints and availability of appropriate archived images. Wetland change detection and inundation mapping using Landsat (MSS, TM, ETM+) has been applied extensively worldwide (Munro and Touron 1997, Yang *et al.* 1999, Munyati 2001, Shaikh *et al.* 2001, Dwivedi and Sreenivas 2002, Novo and Mertes 2002, Frazier *et al.* 2003, Rogers and Kearney 2004). For a rapid qualitative change detection analysis, visual interpretation of multi-temporal image colour composite is still a common and valuable method that is aided by GIS techniques (Lu *et al.* 2004). Yang *et al.* (1999) found the combination of TM bands 4, 5 and 1 to be the most effective for the detection and identification of landforms across the boundaries of land and sea.

The wetlands form parts of the Queen Elizabeth National Park that receive contaminants from an old copper mine transported by River Rukoki flowing through it into Lake George (figure 1). This has resulted into large stretches of barren and bare land within the park, which is a protected Ramsar site. The river has also deposited large sediment patches that has de-vegetated significant parts on the northwest of the wetlands. Population and farming activities has increased in the wetland region all of which have impacted on large portions of the protected area. Grasslands are prone to fires and are often burnt out during the dry season that has greatly affected the extent of the wetlands. The objective of this study was therefore to use multi-date Landsat data to detect change in land cover during the dry seasons, and to map the consistence of inundated wetland area during the rainy seasons. Specific reference was to ascertain the extent of bare and exposed wetland areas during the dry seasons.

STUDY AREA

The study area encompasses the wetlands on the lower reaches of the River Rukoki as it joins Lake George, and the northern shores of the lake. They are found within latitudes 0^o and $0^o13'$N and longitudes $30^o05'$E and $30^o12'$E, covering an area of about 300 km^2 (figure 1). It is largely covered by part of the Queen Elizabeth Protected Area (ca. 2000 km^2) with a rich ecosystem that sustains the tourism industry. Sediments in the basin form a plane that is dissected by numerous dry gullies. Rivers flowing through this area have deposited broad gravelly fans. North of Lake George there is a broad, flat and gently undulating plain, developed on Holocene fluvio-lacustrine sediments (silt, clay, sand, locally with travertine-limestone).

Precipitation occurs mainly from March-May, and September-October with an annual mean of 1500 mm. Lake George encompasses an area of about 270 km^2 and has its main catchment area in the Rwenzori range. The largest inflow to the lake is R. Rukoki that has a monthly average of 7 m^3/s (gauged from 1954-83). Discharge from Lake George is only through the Kazinga Channel that flows southwestwards into Lake Edward. Because of high evaporation and very little outflow, water exchange in Lake George is very limited which has led to the alkaline lake (pH 9-10) (BRGM 1994). It is shallow and extremely eutrophic with high biological productivity.

Vegetation in the basin is of the savannah-type, a grassland with dispersed trees and bushes. Within the park, five broad categories identified are forests, grasslands, bushed grasslands, acacia woodlands, and lakeshore and swamp vegetation. East of Kasese there is situated a strip of acacia forest, followed by *Chloris-capparis* savannah. Fringes of the lakeshores is dominated by *Cyperus papyrus*, important for local thatching but which also shelters hatching fish (mainly *Tilapia nilotica* and *Haplochromis nigripinnis*) and is home to a large variety of birds. Hippos are common in the west of the lake and the savannah grasslands host several wildlife (Malpas 1978).

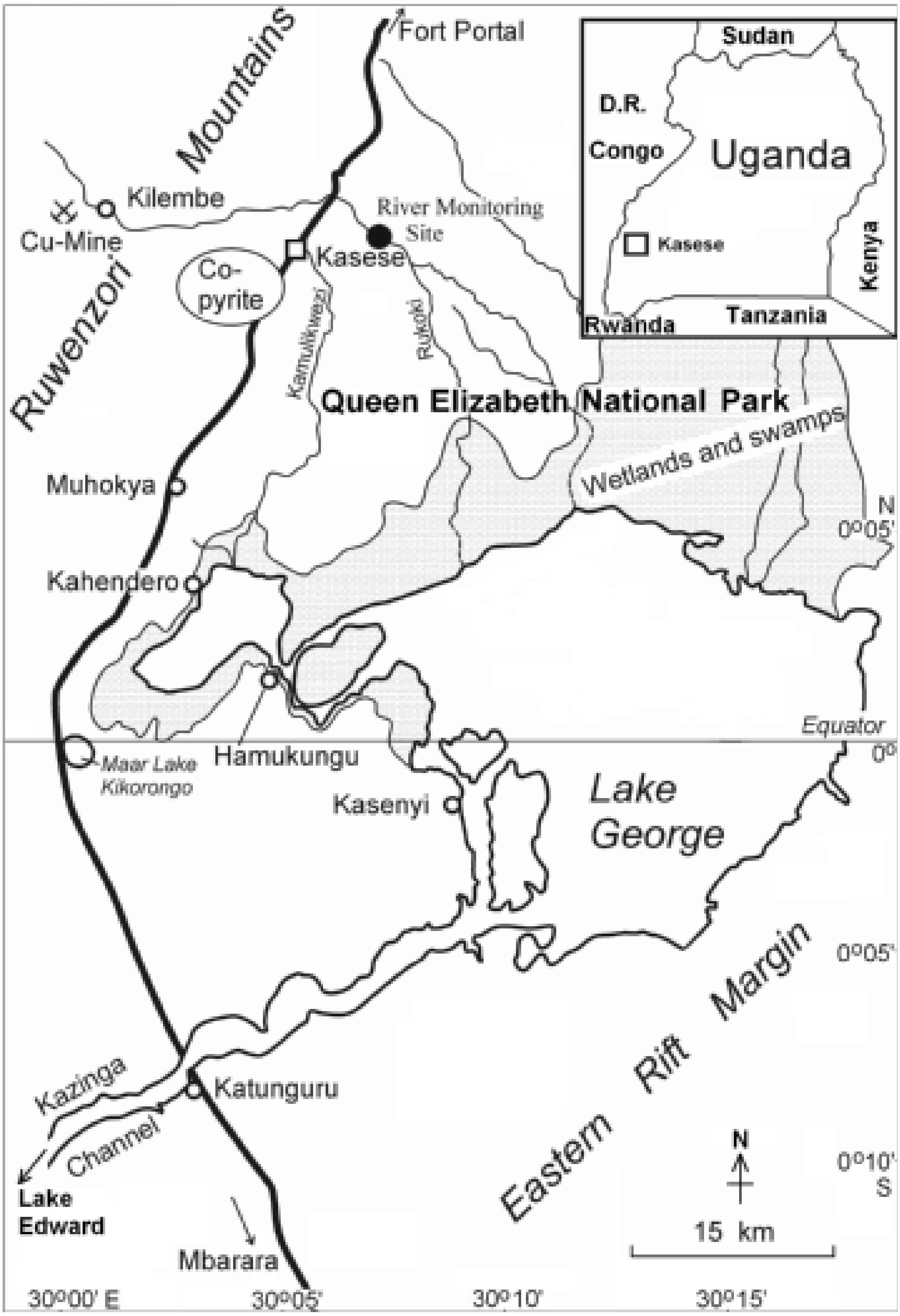

Figure 1: The study area showing the northern basin of Lake George in Kasese, Uganda

METHODS

Image Processing

A systematically corrected Landsat-7 (ETM+) scene (path173, row60) acquired on 11th December 2001 was obtained from the USGS (Table 1). Two pairs of systematically corrected Landsat-5 (TM) (7th August 1987 and 17th January 1995) and Landsat-7 (ETM+) (17th September 1999 and 14th March 2001) were downloaded from the global land cover facility (GLCF) website. These were the only archived images that were available to supplement the one that had been purchased. The images were quite cloud-free especially within the main catchment area of the wetlands region (figure 2). Dark areas are made up of open water bodies. The dark grey regions are mainly mature vegetation both the forest and wetland types as well as swampy, waterlogged areas. Lighter grey areas constitute the grasslands and scattered tree shrubs. Light portions are tilled farmlands, contaminant discharge trails, naturally denudated areas, and downstream river sediment deposits. The course of the River Rukoki was not possible to be mapped on this scale given the dense and overgrowth vegetation along its banks especially within the wetlands region.

In order to ascertain the weather condition of the area during image acquisition, the maturity of dense vegetation cover with total monthly rainfall measured at the Kasese airstrip for up to six months prior to the acquisition date was compared for the different dates (Table 2). Apparently the period preceding the acquisition of the August 1987, September 1999 and March 2001 images generally have low average rainfall amounts. These can be constituted to be relatively dry period images. The January 1995 and December 2001 images on the other hand have a relatively higher rainfall average and have been taken to be wet periods.

Table 1: Image data used for change detection and inundation mapping in the Lake George basin.

Image date	Landsat sensor	Spatial resolution (m)	Pre-processing level	Parameters
7 Aug 1987	TM	30	L-1G, systematically corrected by GLCF, map oriented	WRS: 173/60 Sun Elevation = ** Sun Azimuth = **
17 Jan 1995	TM	28.5	L-1G, systematically corrected by GLCF, map oriented	WRS: 173/60 Sun Elevation = ** Sun Azimuth = **
17 Sep 199	ETM+	30	L-1G, systematically corrected by GLCF, map oriented	WRS: 173/60 Sun Elevation = 62.6^o Sun Azimuth = 84.8^o
14 Mar 2001	ETM+	28.5	L-1G, systematically corrected by GLCF, orthorectified, map oriented	WRS: 173/60 Sun Elevation =58.2^o Sun Azimuth =94.7^o
11 Dec 2001	ETM+	30	Fast-L7A Format, Systematically corrected by USGS, orthorectified, map oriented	WRS: 173/60 Sun Elevation =54.3^o Sun Azimuth =132^o

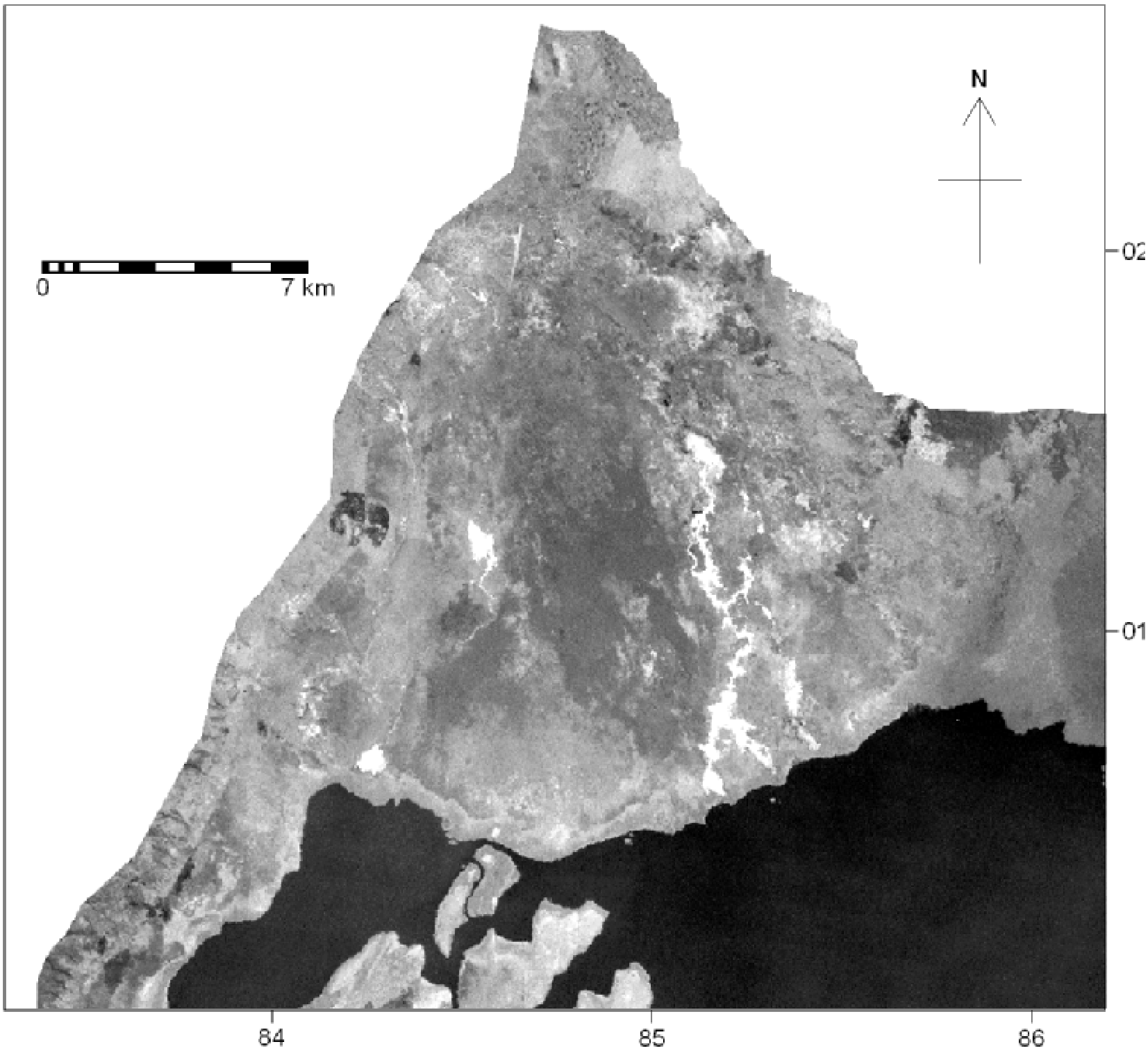

Figure 2: Colour composite (intensity displays) of Landsat bands 4, 5 and 1 for the August 1987 acquisition date in the Lake George basin

Table 2. Total monthly rainfall for six months preceding the Landsat image acquisitions in the Lake George basin

	Months to data acquisition					
Period	6	5	4	3	2	1
Aug 1987	59	48	133	100	68	36
Jan 1995	49	24	104	164	63	21
Sep 1999	58	66	23	5	115	37
Mar 2001	147	149	73	5	22	52
Dec 2001	50	62	94	138	89	54

The images were downloaded into the ILWIS 3.31 GIS and image processing software. Data format for import of the images was band sequential (BSQ) with an eight bit data type. Each band was imported separately using information from the metafile about the appropriate number of pixels per line and lines per band. Using the information about the pixel sizes and corner coordinates the images were geo-referenced. The January 1995 and March 2001 images had distortions in the corner coordinates and had to be geo-referenced using tie points. In the January 1995, 26 active ground points (randomly chosen and covering large parts of region) using the affine transformation gave a root-mean-square error (RMSE) of 0.62. In March 2001 with a similar transformation gave a RMSE of 0.67 for 48 active ground control points.

The relative coordinates in the UTM coordinate system were obtained from the georeferenced December 2001 image as well as the area topographic map (1:50 000). Since January 1995 was a wetter period, it was difficult to obtain as many accurate ground control points as in March 2001. For moderate distortions over relatively small flat ground areas an affine transformation often suffices (Lillesand et al. 2004). A check against an independent set of ground control points still yielded a RMSE of <1 pixel in both cases. Ground control points in both cases were mostly road junctions with streams as well as river bends and junctions. Accurate geometric registration of a multitemporal image set with RMSE of 0.25-0.5 pixel or 1 pixel at the most, is necessary for accurate change detection (Jensen 1986; Milne 1988; Mouat *et al*. 1993).

The August 1987, September 1999 and December 2001 images had a pixel size of 30 m while those of January 1995 and March 2001 sets had a pixel size of 28.5 m. The latter two were resampled to the 30 m pixel size using the nearest neighbour method that ensured that there was minimum alteration to the original spectral characteristics. A subset of the whole image scene was created to cover only the area of interest and to hasten the digital processing time. The Mbarara-Fort Portal road in the west was the boundary, in the north is was the Rukoki sub-county following the course of the Chalanga River, in the east it was the 30°15'E latitude, and in the south it was the equator.

The potential to use remotely sensed data in classifying wetlands is contingent upon there being a relationship between remotely sensed brightness values and actual surface conditions (Jensen *et al.* 1995). However, factors such as sun angle, earth/sun distance, detector calibration differences between the various sensor systems, atmospheric composition and sun/target/sensor (phase angle) geometry will also affect pixel brightness values (Eckhardt *et al.* 1990). The necessary corrections were made during pre-processing. The option to compare image sets during similar climatic conditions attempted to make equivalent spectral bands (from different dates) appear as though imaged through the same sensor, under similar illumination and atmospheric conditions. The relatively flat and even nature of the terrain in the area mapped ensured that shadow effects due to altitude differences like on the foothills of the Rwenzori were negligible.

Change Detection

The dry period image sets (August 1987, September 1999 and March 2001) were used to map changes within the catchment through them. Three broad classes were chosen, namely: water bodies (open water and moist areas), exposed areas (contaminated bare trails and naturally denudated parts, river sediment deposits, open grassland and scattered shrub, settlements and tilled land), and vegetated zones (including tree shrub, forest cover and swampy papyrus mashes). For each of water and vegetated areas on the three dates, two spectral indices from the image bands were created for the Normalised Difference Water Index (NDWI) and Normalised Difference Vegetation Index (NDVI), respectively. The NDWI (McFeeters 1996) and NDVI (Townshend and Justice 1986) were determined by the following band combinations:

$$NDWI = \frac{(band3 - band5)}{(band3 + band5)} \tag{1}$$

$$NDVI = \frac{(band4 - band3)}{(band4 + band3)} \tag{2}$$

McFeeters (1996) used TM bands 3 (0.63-0.69 μm) and 4 (0.76-0.90 μm) to detect open water, while Gao (1996) employed the reflectance at 0.86 and 1.24 μm to estimate leaf moisture. TM bands 3 and 5 (1.55-1.75 μm) were selected for water because only water is more reflective in band 3 than band 5 (Rogers and Kearney 2004). The combination of TM bands 3 and 4 for NDVI is already a well-established standard where vegetated areas have a relatively high reflection in the near-infrared and a low reflection in the visible range of the spectrum (Townshend and Justice 1986). Clouds, water and snow have larger visual than near-infrared visual reflectance. Rocks and bare soils have similar reflectance in both spectral regions.

The exposed areas were determined by initially cluster gathering using the unsupervised classification with a 4, 5, and 1 (0.45-0.52 μm) band image combination of each of the three dates. Originally 25 clusters were created that were later edited and assigned to one of the three classes. Printouts of colour composites (1:60 000 scale) of the acquisition date images were taken to the field to compare land cover classes. Ground field reference data were recorded in March 2001, March 2002, August 2003 and April 2004. In as much as these dates were not able to capture the actual wetland conditions, they were still bound to yield the seasonal trends in cover classes during the acquisition dates. Each homogeneous field site was located using a Garmin-12 Global Positioning System (GPS) (accuracy of about 10 m) where qualitative descriptive information was depicted (i.e. water, vegetated, exposed, etc). These sites later also formed the basis for assessing the reliability of the classification. Use was also made of low altitude aerial photo mosaics taken in the Lake George wetland basin in September 1998. The classification was complemented with those generated from the NDWI and NDVI maps.

The spatial and frequency distribution of the NDVI and NDWI values were evaluated to determine the cut-off points for the water bodies, and vegetated regions. Thresholds of the water indices were in most cases easier to be sliced. The thresholds for water were instead obtained from the NDWI indices that showed a clear distinction between open water and other pixels. Thresholds used to delimit the two cover classes for each of the acquisition dates are summarised in table 3. The NDWI, NDVI and the unsupervised classification maps were then combined to form the land cover maps. A 3*3 majority filter was then used to integrate the pixels with a large number of small scattered, individual units to produce the final maps. The three classes were compared visually.

Table 3: Digital number thresholds of the classes for the inundated areas during three acquisition dates in the Lake George basin

DN	Aug 1987	Jan 1995	Dec 2001
Water	25	25	25
Wet areas	70	55	70

Inundation Mapping Analysis

Density slicing is an enhancement technique whereby an image is processed to display a new image in which the pixels have only one of two digital numbers (DN) – either 1 (wet) or 0 (dry). The DN is a measure of the strength of the signal received from the object. Values are assigned based on whether the original pixel had a DN greater or less than the nominated threshold. Density slicing has been found to be very reliable in delineating inundated and non-inundated wetlands (Bennett 1987; Shaikh *et al.* 1989; Johnston *et al.* 1993; Shaikh *et al.* 1998; Shaikh *et al.* 2001). Johnston *et al.* (1993) used a DN of 40 as a threshold to map inundated areas and DN for water of about 25 with TM image band 5 which also depend on the atmospheric conditions.

Band 5 of each image was examined to determine the threshold value between water and non-water pixels. This value was used to convert each image with values below the threshold being assigned to water, and values above the threshold being assigned to no-water. Frazier *et al.* (2000) showed that for this environmental monitoring, density slicing of TM band 5 is sufficient to delineate water bodies accurately.

The three images of August 1987 (dry period), January 1995 (wet period) and December 2001 (wet period) were used from which each frequency distribution of the DNs were derived. There were clear distinctions between the water bodies and wet areas (lower DN) against the dry areas (higher DN). Thresholds were obtained for each of the periods examined (table 4). Except for the January 1995 wet areas threshold, the others were found to be similar in all the images of the three periods.

Table 4. Normalised difference index thresholds of the classes for the three acquisition dates in the Lake George basin

Class	August 1987		September 1999		March 2001	
	NDVI	NDWI	NDVI	NDWI	NDVI	NDWI
Water	0	-0.6	0	-0.4	-0.23	-0.3
Vegetation	0.6	1	0.65	0.7	0.51	0.9

RESULTS

Change Detection Classification

The three major land cover classes for the August 1987, September 1999 and March 2001 periods were generated (figure 3). Land area covered by the open water bodies is fairly even throughout the three periods. There are a few patches of open water spots within wetlands in the September 1999. Vegetation cover is the dominant class in the region for all the periods. Exposed areas generally cover a lower proportion of the region. In September 1999 and March 2001 more exposed areas existed than in August 1987. The downstream River Rukoki sediment deposits were prominent in all the three periods.

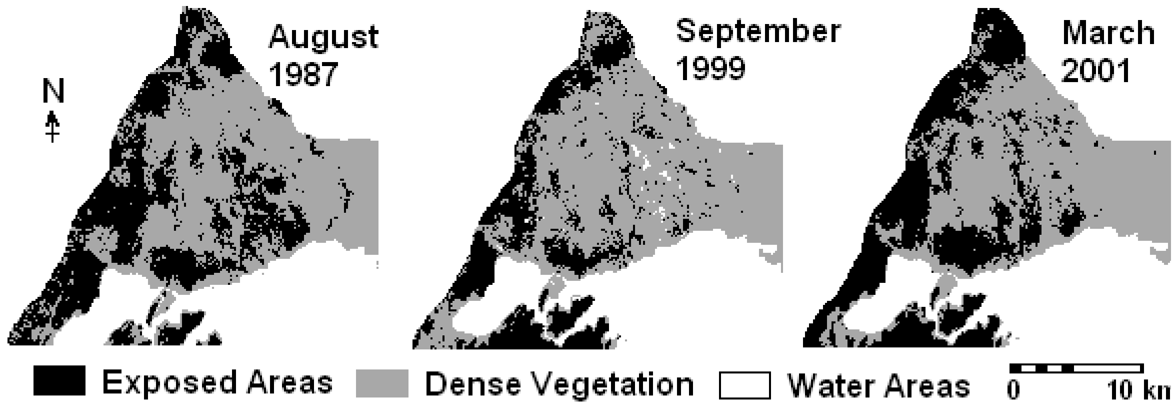

Figure 3: Changes in land cover for the August 1987, September 1999 and March 2001 periods in the Lake George basin

A summary of the statistics of the land cover for the three periods is represented in the figure 4. There is about 44 % of the area covered by dense vegetation, 26 % by water bodies, and 30 % of exposed parts. In August 1987, the water areas show about a 19 % increase in area in September 1999 and 15 % in March 2001 from August 1987. Clearly the latter two periods are slightly wetter and therefore have a few more patches of open water spots. Dense vegetation cover increases by about 10 % in September 1999 and reduces by 6 % in March 2001. Exposed areas decrease by 31 % in September 1999, and 4 % in March 2001.

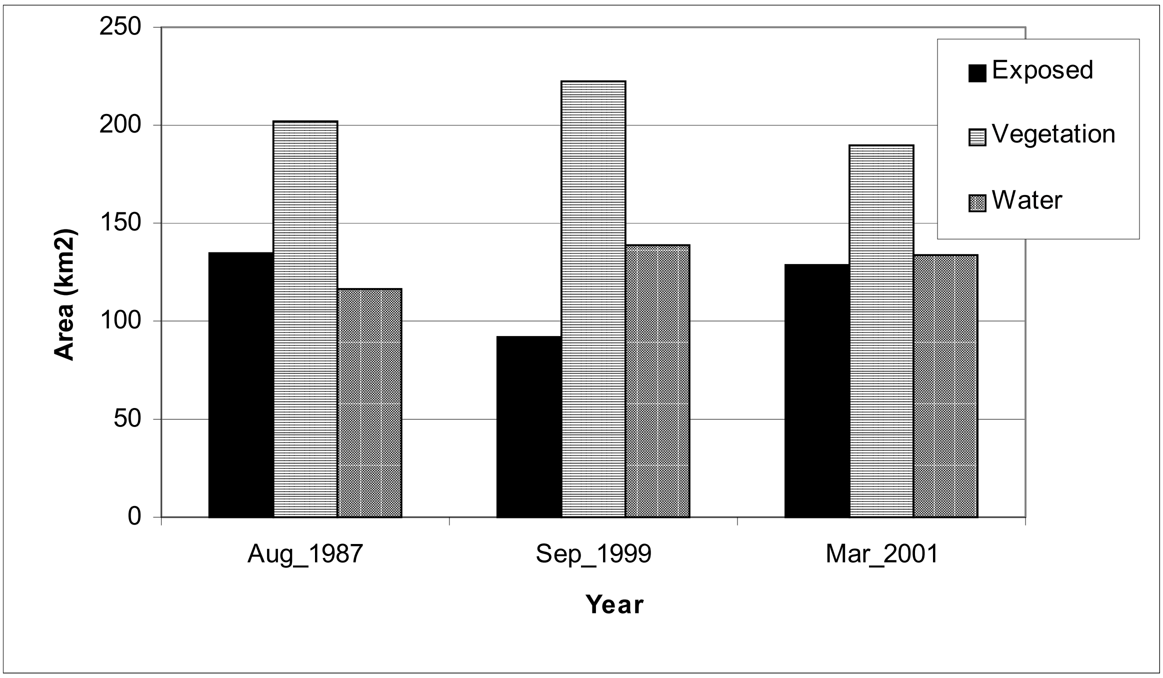

Figure 4: Trends in area of recoded land cover classes for the three acquisition periods in the Lake George basin

Change Detection Reliability

To assess the accuracy of the image classifications a confusion matrix (error matrix or a contingency table) was created and compared with additional ground truth information (Lillesand *et al.* 2004). The strength of a confusion matrix is that it identifies the nature of classification errors as well as their quantities. A new raster map (ground truth map) with the same georeference and resolution as the classified image was created including some test pixels while using an existing map as a reference (ground truth data, colour composite of bands 4, 5 and 1 together with the 1998 aerial photos of the area). The output data was overlaid with a grid. Test cells within the grid were selected randomly and groups of pixels within the test cells were evaluated. The cover types present were determined through collected ground verification data and compared to the classification data. The ground truth map and the classified map were crossed to obtain a cross table from which a confusion matrix was obtained. Statistics of the reliability of the classification techniques for the three periods were calculated (table 5).

The classification of equalised random samples for the individual cover classes during all the periods exceeded 96 % with an overall accuracy of >98 %. The KHAT, $\hat{k}$ statistic (Lillesand *et al.* 2004) for the three periods were over 97 % indicating that the classifications were significantly better than those based on chance. Suffice to say that the very broad classes used enabled the extraction of large homogeneous training areas that has resulted in the very high classification accuracy.

Table 5: Error Matrix resulting from classifying randomly sampled test pixels in the Lake George basin.

	Aug 1987 Reference Data				Sep 1999 Reference Data				Mar 2001 Reference Data			
Classification data*	E	V	W	Row Total	E	V	W	Row Total	E	V	W	Row Total
E	2953	59	0	3012	4333	119	0	4452	6892	220	0	7112
V	39	5368	127	5534	12	11388	0	11400	15	14364	0	14379
W	0	0	8336	8336	0	1	8996	8997	0	0	11982	11982
Column Total	2992	5427	8463	16882	4345	11508	8996	24849	6907	14584	11982	33473
Accuracy (%)	Producer's	User's			Producer's	User's			Producer's	User's		
E	98.7	98			99.7	97.3			99.8	96.9		
V	98.9	97			99	99.9			98.5	99.9		
W	98.5	100			100	100			100	100		
Overall accuracy (%)	98.7				99.5				99.3			
KHAT, $\hat{k}$ (%)	97.8				99.2				98.9			

* E, exposed areas; V, vegetated areas; W, water areas.

Inundation Mapping Areas

The areas unundated are depicted in figure 5. Regions above the fringes of the lake are dry in August 1987, with several pockets of low-lying areas being wet in the upper parts of the catchment. In January 1995 that was a wet period, a consistently wet pattern is seen on the eastern reaches. The central lower-lying areas are also wetter than in August 1987. In the wettest period of December 2001 there were wider waterlogged zones than either in January 1995 or in August 1987. There is a general similarity and agreement in the inundation area for all the periods especially on the eastern part of the wetlands that is continuously waterlogged. Temporal and spatial extents seem to concur quite well.

It was not possible to check the accuracy of the spatial nature of the waterlogged areas in the field during the periods aforementioned. However, the comparisons of the wet and dry period images helped to reduce the errors of commission that might occur if only the wet period images were analysed. The results of the extent of spatial and temporal variations in open water and waterlogged vegetated areas are summarised in figure 6.

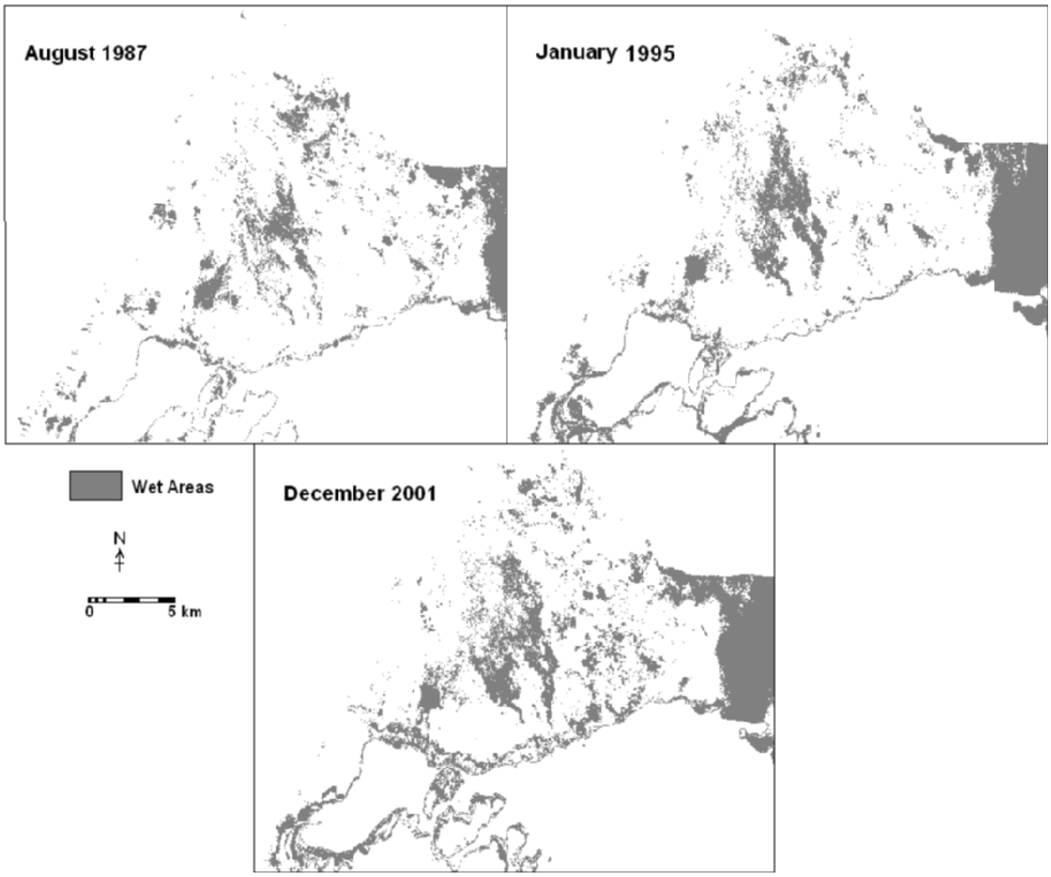

Figure 5: Wet inundation areas for the August 1987, January 1995 and December 2001 periods in the Lake George basin

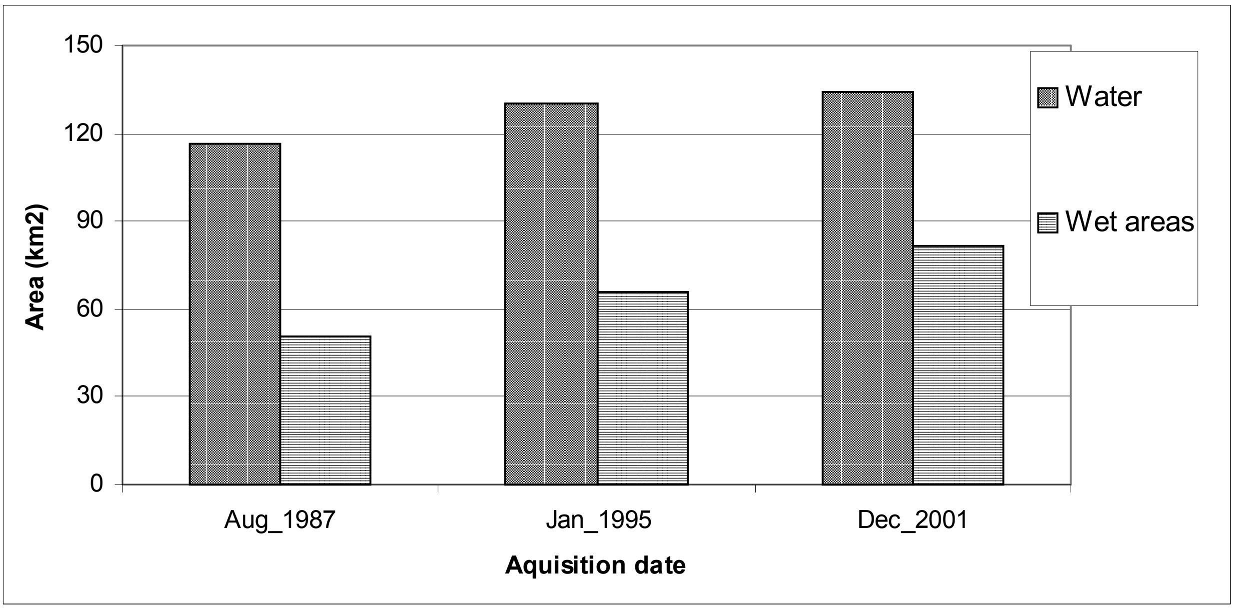

Figure 6: Change in inundation areas over the August 1987, January 1995 and December 2001 periods in the Lake George basin

The waterlogged areas in the dry period of August 1987 covered about 30 % of the region with the water bodies occupying up to 70 %. There is an increase in water bodies during the wet periods of January 1995 and December 2001 by 12 % and 15 %, respectively. Waterlogged expanses on the other hand increase by 31 % in January 1995, and 62 % during the slightly wetter December 2001. This reflects a spread of about 23 % in waterlogged areas between the wet periods of January 1995 and December 2001. There is generally a significant difference in the spatial extent of waterlogged areas during the wet and the dry periods.

DISCUSSIONS

The spatial resolution of the Landsat (visible and infrared bands, 30 m) images used was not exact enough to map the course of the Rukoki River as well as its old meander channels. Acquisition months that fell during the dry season in the wetland basin were in certain cases found to actually have significant local rainfall (like January 1995). The August 1987 dry period had low rainfall that shot up four months prior to and kept dropping consistently to the acquisition date. On the other hand the dry period September 1999 had consistently low rainfall prior to that shot up a month to acquisition. For the third dry period of March 2001, the rainfall started dropping five months to but slightly rose up two months to acquisition. The wet periods of January 1995 and December 2001 were quite similar in that they both had rainfall rising five months to image date that peaked three months to, though the latter had more rain rainfall two months to acquisition. Thus the vegetated and waterlogged areas were higher in the December 2001 than the January 1995.

In August 1987, it was a dry period when exposed areas clearly depicted open grasslands and scattered shrubs, a few tilled farmlands, contaminant discharge and wildlife trails, naturally denudated areas, and downstream river sediment deposits. A section of the exposed areas got vegetated in September 1999 when it was wetter. Segments of open water are discernable within the wetlands during September 1999. This reduced the proportion of exposed patches during this period. In March 2001 when it was also slightly wetter than in August 1987, human encroachments and farming increased in the northwestern part of the wetlands. This resulted in a reduction in the densely vegetated land cover within the wetlands. It is also important to note that the exposed area in a wetter March 2001 is similar to what it was during the dry August 1987 period. There is the likelihood of present anthropogenic factors playing a significant role in modifying the wetland land cover.

The wet areas mapped showed small patches that were quite inconsistent between the different acquisition dates. These were attributed to the differences in the duration of inundation. Some parts of the wet areas received additional water due to rainfall prior to the image date. The December 2001 map indicates that the wetlands still sustain a large part of the basin during the wet periods.

Owing to the irregularly acquired images it was therefore difficult to compare actual wet or bare areas based on similar rainfall inputs or as expected a drier weather pattern. Although there were classification errors arising from lack of unique spectral signatures between exposed areas and dense vegetation, the change detection results give a reliable indication of the change that the wetland area has undergone. This is because the final change classification classes used were broad which minimised the errors. The lack of consistency in the changes of the land-cover classes could be explained by the seasonal weather influence (river sediment deposits, open bare areas, grassland growth), wildlife patterns (trails,) and other anthropogenic factors (farming, human settlements, contaminant flow trails) on the wetland. Annual variations in seasonal rainfall have no clear direct influence on the changes detected but have the indirect influence of dictating the human and ecological use of the water resources.

CONCLUSIONS

The global coverage, synoptic view and repeatability of remotely sensed information provide more cost effective methods for environmental monitoring of the impacts of these phenomena that shows temporal and spatial variations. Use of the NDWI to compliment the NDVI coupled with unsupervised classification (with ground data) helped delineate open water features and vegetated areas, while simultaneously exposed and bare features were depicted.

Change detection of water areas show about a 19 % increase in area in September 1999 and 15 % in March 2001 from August 1987. In August 1987, about 44 % of the area is covered by dense vegetation cover that increases by about 10 % in September 1999, and reduces by 6 % in March 2001. Exposed areas decrease by 31 % in September 1999, and 4 % in March 2001.

Inundation mapping shows that there is an increase in water bodies during the wet periods of January 1995 and December 2001 by 12 % and 15 %, respectively.

Waterlogged expanses increase by 31 % in January 1995, and 62 % during December 2001. This reflects a spread of about 23 % in waterlogged areas between the wet periods of January 1995 and December 2001.

There is a likelihood of present anthropogenic factors playing a significant role in denuding the wetland land cover. Changes of the land-cover classes could also be explained by the seasonal weather influence and wildlife patterns. Annual variations in seasonal rainfall have no clear direct influence on the changes detected but have the indirect influence of dictating the human and ecological use of the wetlands.

An objective assessment of the temporal and spatial behaviour of vegetation cover and waterlogged areas forms a crucial element in the regional wetlands management programme (Dwivedi and Sreenivas 2002). The ecological implications of the changes detected by this remote sensing approach need a ground monitoring survey. This is because many ecosystem activities (e.g. wildlife behaviour and abundance) do not manifest themselves easily in a spatial manner that can readily be detected (Munyati 2000). The next level of complexity in interpreting satellite data is to map the extent of inundation within each wetland, not just to determine the presence or absence of water anywhere within each wetland. Given the importance of flood duration and wetland/river connectivity, to fish, wildlife and general wetland ecology, it is recommended that future studies investigate the duration of wetland inundation, connectivity and the frequency of flood sequences that reconnect wetlands prior to drying out (Shaikh *et al.* 2001). A similar remote sensing approach can also be used for monitoring temporal and spatial aspects of the other wetlands in the region.

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