Analysis of land use/cover changes and urban expansion of Nairobi city using remote sensing and GIS

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We used three Landsat images together with socio-economic data in a post-classification analysis to map the spatial dynamics of land use/cover changes and identify the urbanization process in Nairobi city. Land use/cover statistics, extracted from Landsat Multi-spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) images for 1976, 1988 and 2000 respectively, revealed that the built-up area has expanded by about $47 \, km^2$. The road network has influenced the spatial patterns and structure of urban development, so that the expansion of the built-up areas has assumed an accretive as well as linear growth along the major roads. The urban expansion has been accompanied by loss of forests and urban sprawl. Integration of demographic and socio-economic data with land use/cover change revealed that economic growth and proximity to transportation routes have been the major factors promoting urban expansion. Topography, geology and soils were also analysed as possible factors influencing expansion. The integration of remote sensing and Geographical Information System (GIS) was found to be effective in monitoring land use/cover changes and providing valuable information necessary for planning and research. A better understanding of the spatial and temporal dynamics of the city's growth, provided by this study, forms a basis for better planning and effective spatial organization of urban activities for future development of Nairobi city.

1. Introduction

Nairobi is Kenya's principal economic and cultural centre and one of the largest and fastest growing cities in Africa (Lamba 1994). For the last 30 years, the city of Nairobi has experienced rapid growth in terms of population and spatial extent compared to other major cities in the region (Stren *et al.* 1994). Despite the lack of basic amenities and infrastructures, Nairobi metropolis still attracts population from rural areas. As a consequence urban population is increasing at a much faster rate, contributing to augmentation of existing problems (Lavalle *et al.* 2001). The population has increased from 500 000 people in 1970 to the current three million. The process of urbanization has been characterized not only by population growth, but also by industrial expansion, increasing economic and social activities and intensified use of land resources (Karuga 1993). The estimated annual rate of growth of urban population in Kenya was 7.1% for the period 1995–2000; the average for African cities was 4.4% and for the world 2.6% (Stren and White 1989). This rate of

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urbanization has overstretched the capacity of infrastructure and services to the extent that large sections of the population live in slums in the peripheral urban areas (Hirst and Lamba 1994). Consequently, the need to have a comprehensive plan to direct Nairobi's growth and development emerged as a result of a number of serious problems affecting the city. These problems included massive influxes of migrants, lagging infrastructure development, environmental degradation, and uncontrolled growth and spreading of the deteriorating slum areas (Mbogua and Nganga 1973, Karuga 1993). Deliberate planning has been lacking and urban growth has led the city to expand outward at the expense of other land uses. Before the Nairobi metropolitan growth strategy report (Nairobi Urban Study Group (NUSG) 1973), the only basic land use planning and development framework was the 1948 master plan. Since then, planning has been done on an ad hoc basis with study groups dealing with specific aspects of city growth (Lamba 1994). The ad hoc land use planning has paid very little consideration to environmental impact or physical constraints, which has given rise to urban sprawl and resulted in physical, socio-economic and environmental problems (Bubba and Lamba 1991).

Planning problems in Nairobi include inappropriate land uses due to ignorance or misconception about physical environment (Lamba 1994), environmental changes due to land use changes and poor availability of spatial information necessary for urban planning. In particular, spatial information on which planning is based, is in the form of unscaled sketches while maps are in different scales making sharing of information among various sectors of the city a problem. The available data and the way they are managed have led to the impossibility of assessing the current situation and have excluded any possibility of effective planning for the future. At the same time, various laws and local government regulations meant to control and regulate urban development have not been adhered to. The consequences are that urban planning for Nairobi city has not worked and is leading to unsuitable land uses, depletion of natural resources, urban sprawl, collapse of public services and other negative environmental and social effects.

Regular and up-to-date information on urban change is required for urban planning, land use management and for appropriate allocation of services and infrastructure within the urban areas (Barnsley and Barr 1996). In this context, accurate information on the current extent of urban areas is needed for documenting growth, making policy decisions and improving land use planning (Gross and Schott 1998, Bullard and Johnson 1999, Jacobson 2001), and is a required parameter for predictive urban modelling (Epstein *et al.* 2002). Dynamic spatial models, and in particular cellular automata (CA) modelling, which incorporates data on urban land uses, are becoming useful tools for predictive modelling of urban spatial dynamics (Deadman *et al.* 1993, Batty and Xie 1994, 1997, Clarke *et al.* 1997, White and Engelen 1997, Batty *et al.* 1999). Predictive modelling for Nairobi city would make it possible to assess the future consequences of current urban growth trends. Monitoring urban changes leads to forecast of the amount of changes and the location of future built-up areas, which is extremely valuable to urban planners who can use this information to monitor the impact of urban growth and also to evaluate and modify existing urban policies and develop appropriate responses or strategies. Efforts are being made by Nairobi's city planning department for an integrated urban planning strategy. Such an integrated strategy has to recognize, anticipate, measure and understand urban land use dynamics and their consequences. Such a strategy and the necessary predictive modelling for estimating

future impacts of existing spatial plans and policies requires immediate, accurate and up-to-date information on land uses and an understanding of drivers of the land use/cover changes.

In this context, the aim of this study is to analyse land use/cover changes and the dynamics of urban expansion of Nairobi city. The specific objectives are, using multi-temporal Landsat data together with social economic data: (1) to create a three epoch time series for urban growth for the period 1976–2000; (2) to detect the urban sprawl directions and land use conversions that have occurred within Nairobi; (3) to examine the scope and rate of urban expansion using post-classification methods; and (4) to analyse the driving forces and factors influencing the urban expansion. To achieve these objectives, Landsat Multi-spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) data acquired on February 1976, October 1988 and February 2000, respectively, were used. Post-classification comparison strategy was employed to identify land use/cover changes and areas of the urban encroachment. Topographic, soils, and geologic data at various scales, together with socio-economic data, were used for the qualitative analyses of the factors that are thought to influence the urban expansion.

2. Study area

The study area, Nairobi city, extends between 36° 4′ and 37° 10′ east and approximately between 1° 9′ and 1° 28′ south, covering an area of 689 km^2 (figure 1). The average altitude is approximately 1700 m above sea level with a mean
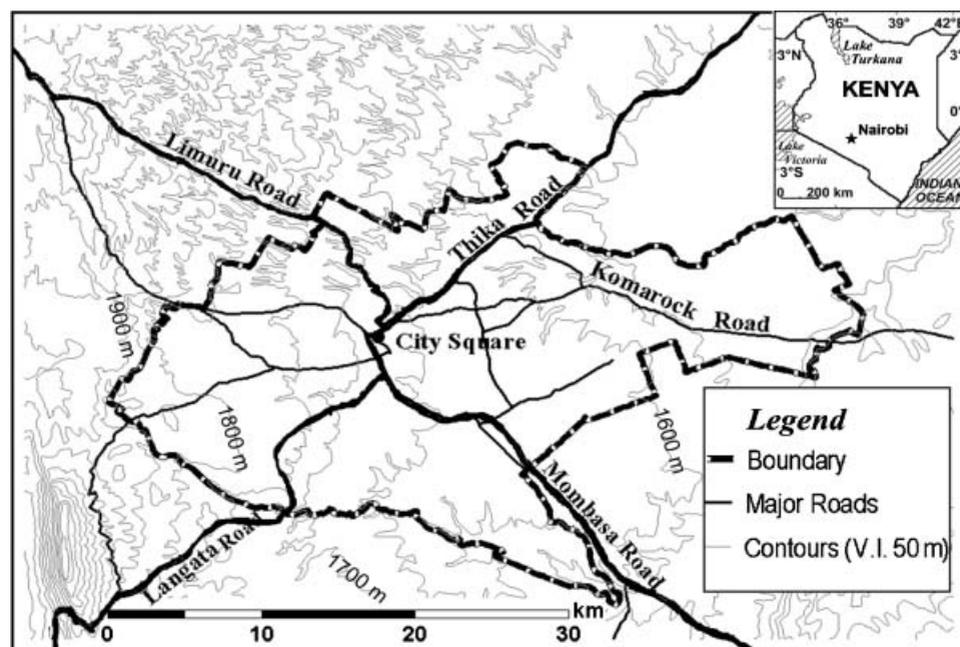

Figure 1. Map showing the city of Nairobi. The boundary indicates the current extent of the city's administrative area. Contours and the major roads are shown. Inset: location of Nairobi.

annual rainfall of about 900 mm. The vegetation varies from grassland scattered with acacia trees in the east to remnants of hardwood forests in the higher areas to the west. Land use within the study area is divided roughly into urban use, agriculture, rangeland and remnants of evergreen tropical forests. Much of the forests, however, has been removed as a result of both the agricultural and urban expansions. Nairobi city has a population of about three million, with population densities varying widely within the city. High-income locations have average densities as low as 500 people/km^2 while low-income locations such as those in the slums have densities as high as 63 000 people/km^2.

3. Satellite images and reference data

Data used to extract land use/cover information for Nairobi consisted of three available archive remote sensing images. The earliest image was acquired on 11 February 1976 with the 79 m spatial resolution Landsat MSS sensor, while the other two scenes were acquired with the 28.5 m spatial resolution Landsat TM and ETM+ sensors on 17 October 1988 and 21 February 2000, respectively.

Reference data for ground control points and for accuracy assessment included contact prints of aerial photographs acquired in 1980 and in 1997 at a nominal scale of 1 : 25 000, and topographical maps at a scale of 1 : 50 000 produced from aerial photography acquired in 1997. Socio-economic data comprising mainly statistical information regarding the city's population and economy as well as geology and soil maps produced in 1985 at a scale of 1 : 100 000 were also used in this study. The image processing and data manipulation were conducted using algorithms supplied with the ERDAS Imagine image processing software, which also incorporates Geographical Information System (GIS) functions. Arc/Info was used for GIS overlay analyses.

4. Strategies for land use/cover change detection

Change detection and monitoring involve the use of multi-date images to evaluate differences in land use/cover due to environmental conditions and human actions between the acquisition dates of images (Singh 1989). Several authors have attempted to better observe and define change features using remotely sensed data (e.g. Singh 1986, Lambin 1996). Chen (2001) presented the issues in change detection methods, by looking at the numerous algorithms that have been developed: multi-date composite image change detection (Fung and LeDrew 1987, Eastman and Fulk 1993), image change algebra detection (Green *et al.* 1994), image regression (Jensen 1983, Singh 1986), manual on-screen digitization of change (Light 1983, Wang *et al.* 1992) or post-classification comparison detection (Rutchey and Velchneck 1994). As noted by Jensen (1996), the selection of an appropriate change detection algorithm is critical. Different methods introducing fuzzy logic, neural networks (Halls *et al.* 2000) or knowledge-based vision systems (Wang 1993, Gong *et al.* 1996) have also been tested to examine the likelihood of changes detected from remotely sensed data. Metternicht (1999) proposed a standard procedure using fuzzy sets and fuzzy logic, whereby the membership function of the fuzzy model can be adapted to identify the areas that have undergone changes during the period of observation. Lopez *et al.* (2001) based their study on the Markov transition matrices to predict land use/cover change in the city of Morelia, Mexico.

5. Methodology

There are two basic approaches for land use/cover change detection (Singh 1989): (1) post-classification comparisons, and (2) simultaneous analysis of multi-temporal data. Both approaches have their advantages and disadvantages. The first approach has some sources of uncertainty (Aspinall and Hill 1997). These include locational inaccuracy in the different classifications and the problems derived from classification errors. This approach requires very good accuracy in the classification because the accuracy of the change map is the product of the accuracies of the individual classifications (Singh 1989). In the case of the second approach, several procedures have been developed, such as multi-date classification, image differencing, vegetation index differencing, principal component analysis and change vector analysis (Fung and LeDrew 1987). In these procedures, the basic premise is that changes in the land use/ cover must result in changes in reflectance values which must be larger than those caused by other factors such as differences in atmospheric conditions, Sun angle, soil moisture or precise sensor calibration. Selecting image acquisition dates as close as possible for the different years used minimizes problems related to the Sun position and vegetation phenology (Pilon *et al*. 1988). Nevertheless, there are some problems related to this second approach: (1) most of these procedures provide little information about the specific nature of land use/cover changes; (2) threshold technique used to differentiate changes from no change is usually not clear (Smits and Annoni 2000); and (3) the number of bands and their wavelengths (spectral information) is different (Fung 1992), as well as the sensitivity of the sensors. While this is also a problem in the first approach, it is more critical in the second approach.

Upon examination of the different possibilities in the two approaches discussed, the first approach was chosen, i.e. to compare classification *a posteriori*, because the available data for this study were acquired in different seasons by different sensors with different spatial resolutions. In addition, it is a more common procedure for comparing land use/cover dynamics (Congalton and Macleod 1994).

The image processing procedures (figure 2) included image pre-processing, the design of classification scheme, image classification, accuracy assessment, and analysis of the land use/cover changes and dynamics of urban growth.

5.1 *Preprocessing of satellite data*

Since high precision geometric registration of the multi-temporal image data is a basic requirement for change detection (Morisette and Khorram 2000), firstly, the 1988 Landsat TM image was rectified corresponding to the Clarke 1880 spheroid and the UTM projection. Thirty ground control points (GCPs) and 10 check points, well distributed across the entire image, were located in the image and in the 1 : 50 000 topographical map covering the study area. A digitizing tablet was used to register the image to the topographical map. A second order polynomial was used, resulting in an rms error of less than half a pixel. The image was resampled to a pixel size of 30 m × 30 m, using the nearest neighbour method, in order to maintain the radiometric properties of the original data. The other two images, Landsat MSS and ETM+, were geo-referenced to the 1988 image using approximately 50–70 well distributed GCPs. Second order polynomial equations were used and the maximum rms error was that of MSS image at 0.73 pixels. The images were resampled to a pixel size of 30 m × 30 m using the nearest neighbour method.

Without radiometric calibration of multi-temporal images, non-surface factors can make it difficult to quantify and interpret change (Chavez and McKinnon 1994).
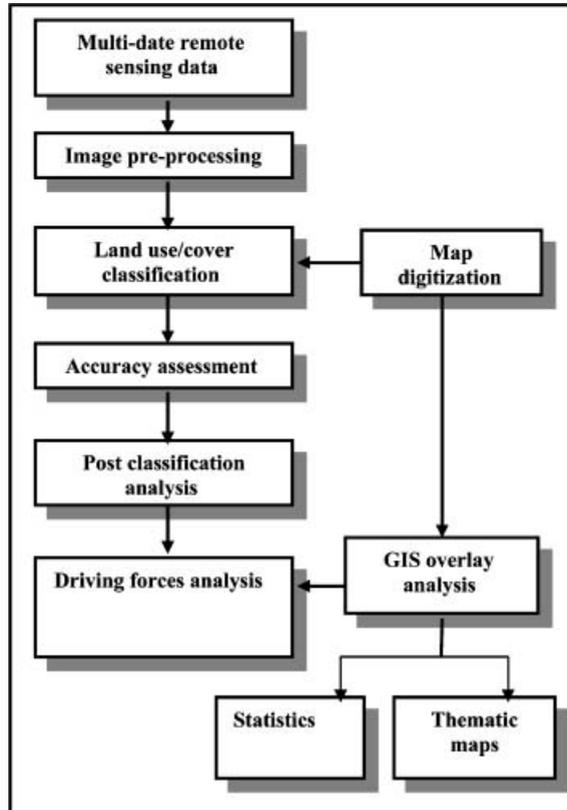
Figure 2.   Flowchart of land use/cover changes and urban expansion.

An absolute correction algorithm can be applied to correct images to absolute surface reflectance only if atmospheric depth and sensor calibration data are available for all dates of imagery. No such data were available for the three images used in this study. Of the three methods developed by Schott *et al.* (1988), Hall *et al.* (1992) and Olsson (1993), the method of Hall *et al.* (1992), which uses dark objects (e.g. burned area, water) and bright objects (e.g. bare, sandbars, rock outcrops) for radiometric adjustments was used in this study, because bright and dark targets could easily be found in the images. This method corrects images of a common scene relative to a reference image using dark and bright pixel control sets. Ground targets common to the images, which were considered constant reflectors over time, were selected. For these targets any changes in their brightness values on the multi-temporal image set were attributed to detector calibration, astronomic, atmospheric and phase angle differences. A total of 10 reservoirs and 5 bare sites were used to normalize the 1976 and 1988 images to the 2000 data. The resulting regression models are shown in table 1. The additive component corrects for the difference in atmospheric path radiance between dates, and the multiplicative term corrects for the difference in detector calibration, Sun angle, Earth/Sun distance, atmospheric attenuation and phase angle between dates (Jensen 1996). After the removal of these variations, changes in brightness value could be related to changes in surface conditions (Schott *et al.* 1988)

Table 1. Image normalization regression models developed for the Nairobi city image data.

Image normalized with the 21 February 2000 ETM+ reference image	Regression models	r^2	Number of normalization targets used
17 October 1988 TM	2000 TM2 = −28.4 + 1.00(1988 TM2)	0.991	9 wet, 5 dry
	2000 TM3 = −28.7 + 1.01(1988TM3)	0.997	10 wet, 4 dry
	2000 TM4 = −21.3 + 1.08 (1988 TM4)	0.996	9 wet, 5 dry
11 February 1976 MSS	TM2 = −37.4 + 0.772 MSS1	0.926	9 wet, 5 dry
	TM3 = −39.3 + 0.938 MSS2	0.938	11 wet, 3 dry
	TM4 = −13.7 + 0.757 MSS4	0.982	11 wet, 3 dry

5.2 Classification system design

A modified version of the Anderson classification system (Anderson *et al*. 1976) was adopted for this study. In total, eight land use/cover classes were established (table 2). Some of the factors considered during the design of classification scheme included: the major land use/cover categories within the study area, differences in spatial resolutions of the three sensors which varied from 30 to 79 m, and the need to consistently discriminate land use/cover classes irrespective of the seasonal differences.

5.3 Image classification

An unsupervised classification approach was adopted because it allowed spectral clusters to be identified with a high degree of objectivity (Yang and Lo 2002). This method involved unsupervised clustering and cluster labelling. The ISODATA (Iterative Self-Organizing DATa Analysis) algorithms in ERDAS Imagine were used to identify spectral clusters. ISODATA method uses a minimum spectral distance to assign a pixel to a cluster. The performance of this algorithm is sensitive to the sampling nature and clustering parameters (Vanderee and Ehrlich 1995). To avoid the impacts of sampling characteristics, the ISODATA algorithm was run without assigning predefined signature sets as starting clusters. The algorithm then treated the entire dataset as one cluster and a number of natural spectral clusters

Table 2. Land use/cover classes for satellite derived land use/cover maps.

Classes	Description
Urban/built-up areas	Residential, commercial and services, industrial, transportation, communication and utilities
Agricultural areas	Cropland, coffee plantations, horticultural farms, greenhouses, other agricultural crops
Bush land	Dense shrubs, perennial grass understorey, trees rarely above 5 m, impoverished woodlands near the forests
Deciduous forests	Evergreen forests, mixed forests with higher density of trees, little or no understorey vegetation
Mixed rangeland	Sparsely distributed scrub species. Ground layer covered by grass. Species include acacia *mellifers*, *lawsonia inermis*
Shrub/brush range	Very sparsely distributed, low-lying scrub species. Usually less than 1 m, typical species include *A. reficiens*, *salvadora dendroides*, ground usually bare or covered by annual grasses
Open/transitional areas	Bare, exposed areas, quarries and transitional areas
Water	Rivers, reservoirs

could eventually be identified after a number of iterations. The most important clustering parameter is the number of classes. This number affects the performance of an ISODATA classifier in capturing most of the land surface variability for the image data being analysed (Yang and Lo 2002). If too small, relatively broad clusters may be generated which may not produce true results. If the number is too big, very pure clusters may be yielded with highly demanding computational resources and substantial increase in time required for cluster labelling. To find the optimum number, different numbers of classes were empirically tried and 40 was found to be optimum for TM, ETM+ and MSS data for the study area.

All the four bands of radiometrically normalized MSS data and the six bands (thermal band excluded) of the TM and ETM+ were used in ISODATA clustering. Other parameters that were specified for ISODATA clustering included convergence value specified at 0.990, the maximum number of iterations at 80 to allow clustering to stop naturally upon reaching the convergence threshold, and true colour scheme so that the output could be compared with the original images.

The resulting clusters were assigned to one of the eight classes (see table 2) with the help of the geo-referenced aerial photographs and the use of local knowledge. The labelling, which was quite similar to manual image interpretation, allowed the identification of the corresponding land use/cover class for each spectral cluster with the reference information. Spectral clusters that were labelled into more than one land use/cover class because of the similarity of spectral content were split into smaller clusters and labelled using spatial reclassification procedures. These procedures reduced boundary errors and lessened spectral confusion. However, boundary errors occurred at the class boundaries due to spectral mixing within pixels in the form of *salt and pepper* which were removed and replaced with values based on their surroundings using a 3×3 modal filter.

Spectral confusion, which occurs because several land use/cover classes have similar spectral response, is the major cause of inaccuracy in classifications based on spectral response. Yang and Lo (2002) noted that as image spatial resolution decreases, the number of mixed pixels increases and spectral confusion tends to be more serious. In this study, spectral confusion was more discernible in the MSS image than in TM and ETM+ and also more noticeable in urban/built-up and transitional areas than in other land use/cover classes. Spatial and contextural properties of the images were used in resolving spectral confusion. Visual interpretation, which allowed use of spectral as well as spatial content and local knowledge, was employed. This way, spectrally confused clusters were split and recoded into their correct land use/cover classes using GIS tools such as AOI (area of interest), overlaying and recoding.

5.4 *Classification accuracy analysis*

Accuracy assessment was performed for the 1976, 1988 and 2000 land use/cover maps (figure 3) using aerial photographs, topographical maps and local knowledge. Stratified random sampling design, where the points were stratified according to the distribution of land use/cover classes, was adopted. By allowing the reference pixels to be selected at random, the possibility of bias is lessened (Congalton 1991). For the 1976 land use/cover map, a total of 482 pixels were selected, which were then checked with reference to the aerial photographs acquired in 1980. The results show an overall accuracy of 90% and a Kappa index of agreement of 0.86 (table 3(*a*)). In
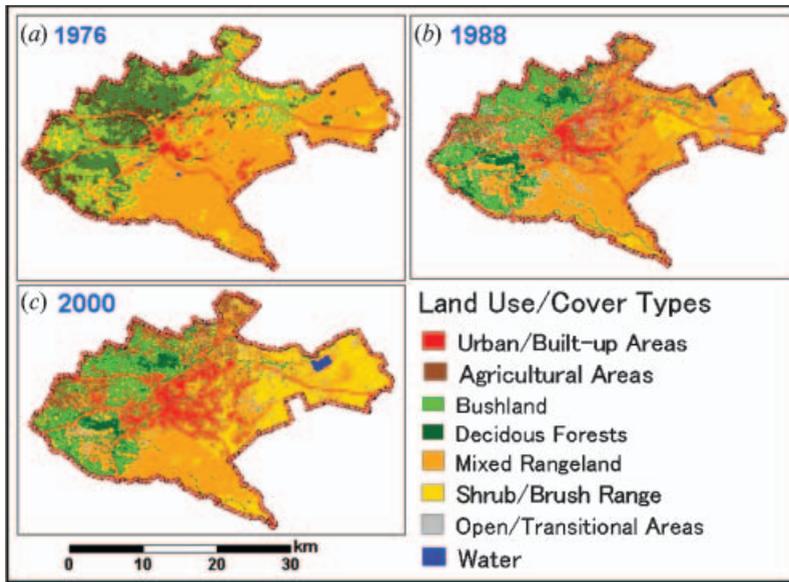
Figure 3.   Classified land use/cover maps of Nairobi in 1976, 1988 and 2000.

terms of producer's accuracy, all classes except shrub/brush were over 85% while in terms of user's accuracy, all classes were over 78%, except for the forest class.

For the 1988 land use/cover map, a total of 489 pixels were selected. These were again checked using the aerial photographs and local knowledge. The result indicated an overall classification accuracy of 91% and a Kappa index of agreement of 0.85 (table 3(*b*)). On examining the producer's accuracy, the open/transitional and bush land areas had the lowest accuracies of 71% and 70%, respectively. Other classes had producer accuracies of above 80%. In terms of user's accuracy, each class exhibited accuracies of over 70%. The overall accuracy of the 21 February 2000 classification assessment was 87% with a Kappa coefficient of 0.81 (table 3(*c*)).

Overall, the maps met the minimum accuracy stipulated by the Anderson classification scheme (Anderson *et al*. 1976). The image processing approach was judged to have been effective in producing compatible land use/cover data over time, irrespective of the differences in spatial, spectral and radiometric resolution of the satellite data.

5.5   *Data processing in GIS*

Digitization was done for sets of layers for which digital data were not available. Major roads, contours, and administrative boundaries were digitized into layers from the published topographical maps. Geology and soil maps, published by the Survey of Kenya at a scale of 1 : 100 000, were also digitized. Analysis of terrain surfaces was done using the Arc-GIS 3D Analyst. In addition to allowing a perspective view of surfaces and symbolization, the 3D Analyst provided tools for getting more information about specific points on surfaces and allowed derivation of information such as slope, aspect and a digital terrain model (DTM). The classified images together with the digitized layers were manipulated in Arc/Info. The GIS capabilities allowed the post-classification comparisons, and facilitated qualitative assessment of the factors influencing urban expansion.

Table 3. Error matrix of land use/cover maps derived from Landsat data.

(*a*) 1976 (MSS)

Data	1	2	3	4	5	6	7	8	Total	Producer's accuracy (%)	User's accuracy (%)
1	14	0	0	3	0	1	0	0	16	93	87
2	0	23	1	3	0	0	0	0	27	95	86
3	0	1	52	2	7	1	0	0	62	91	83
4	0	0	3	66	0	1	0	0	70	92	78
5	0	0	4	0	230	10	0	0	244	93	94
6	1	0	0	0	5	30	0	2	38	71	78
7	0	0	0	0	2	0	10	0	12	90	83
8	0	0	0	0	0	0	1	12	38	85	92
Total	15	24	57	71	245	42	11	14	482		

Overall accuracy 90%, Kappa statistic 0.86

(*b*) 1988 (TM)

Data	1	2	3	4	5	6	7	8	Total	Producer's accuracy (%)	User's accuracy (%)
1	12	0	2	1	1	0	0	0	16	85	75
2	1	15	1	0	0	0	0	0	17	94	88
3	0	0	22	1	7	0	0	1	31	71	70
4	1	0	1	15	0	0	0	0	17	83	88
5	0	0	3	0	207	12	2	0	224	70	71
6	1	1	0	1	4	162	0	0	170	93	95
7	0	0	0	0	2	0	5	0	7	70	71
8	0	0	2	0	0	0	0	5	7	93	95
Total	14	16	31	18	221	174	7	6	489		

Overall accuracy 90%, Kappa statistic 0.85

(*c*) 2000 (ETM+)

Data	1	2	3	4	5	6	7	8	Total	Producer's accuracy (%)	User's accuracy (%)
1	7	0	0	0	0	1	0	0	8	77	88
2	0	45	0	0	0	0	2	3	50	90	90
3	0	0	12	2	1	0	0	0	15	86	80
4	0	4	1	56	0	0	0	0	61	90	78
5	0	0	0	0	173	32	0	0	205	95	84
6	0	0	1	2	13	129	0	0	145	79	89
7	0	0	0	0	0	0	5	1	6	62	83
8	2	1	0	0	0	0	1	1115	74	73	
Total	60	15	187	14	8	9	50	162	505		

Overall accuracy 87%, Kappa statistic 0.81

1, Urban/built-up areas; 2, Agricultural areas; 3, Bush land; 4, Deciduous forests; 5, Mixed rangeland; 6, Shrub/brush; 7, Open/transitional areas; 8, Water

6. Land use changes and dynamics of urban growth

The post-classification comparison approach was employed for detection of land use/ cover changes, by comparing independently produced classified land use/cover maps. The main advantage of this method is its capability to provide descriptive information on the nature of changes that occurs. The classified land use/cover maps for Nairobi in 1976, 1988 and 2000 are shown in figure 3. The spatial distributions of each of the classes were extracted from each of the land use/cover maps by means of GIS functions. The trends in all the land use/cover changes are summarized in table 4.

The urban/built-up areas covered 15 km^2 in 1976 and increased to 41 km^2 in 1988. These areas increased further to 62 km^2 by the year 2000. Forests on the other hand have decreased substantially from 100 km^2 in 1976 to a mere 23 km^2 in year 2000, a record loss of 77 km^2 in the 24 years of the study period. The agricultural fields occupied 49 km^2 in 1976, increased to 57 km^2 in 1988, and further increased to

Table 4. Land use/cover changes for Nairobi city as extracted from Landsat images, 1976–2000.

Classification	Map	Urban areas	Agriculture	Forests	Bush lands	Mixed range	Shrub/brush	Open/transitional	Water	Total
11 February 1976	km^2	13.99	49.83	100.15	154.48	357.32	25.22	6.92	0.50	713.41
	%	1.9	6.98	14.04	22.35	50.08	3.53	0.96	0.07	100
17 October 1988	km^2	41.18	57.82	29.09	101.49	340.62	64.19	77.96	1.09	713.44
	%	5.77	8.10	4.08	14.22	47.74	8.99	10.92	0.15	100
21 February 2000	km^2	61.23	87.78	23.56	95.98	237.63	170.78	32.72	3.77	713.45
	%	8.58	12.30	3.30	13.45	33.31	23.94	4.58	0.53	100

88 km² in 2000. Rangelands, consisting of mixed rangeland and shrub/brush rangeland have decreased from 357 km² in 1976 to 237 km² in 2000. The rangelands have given way mainly to the expanding agriculture and urban sprawl. The trends in land use/cover changes for the three most important classes—urban, agricultural fields, and forested areas—are shown in figure 4.

The comparison of figures 3(a), 3(b) and 3(c) indicates that the urban/built-up area has grown by 47 km² during the period 1976–2000. The spatial patterns of urban expansion show temporal variations in that during the period 1976–1988 the urban expansion was mainly to the east and north-east, while the expansion direction during the 1988–2000 period shifted mainly to the west but still continued towards the north-east (see figures 3 and 5). The rate of encroachment of urban areas on other land uses has been quite rapid, with discontinuous patches (figure 5) of urban development characterizing the urban sprawl. These discontinuous patches have been described as economically inefficient and aesthetically unattractive (Cadwallader 1996). This form of urban sprawl, with its uneven spatial directions, could have been promoted by non-adherence to the local government regulations. The freehold land tenure system could also have contributed to this form of sprawl since private land has been subdivided and used for development of unplanned residential areas (Lamba 1994).

The urban growth of Nairobi city cannot be said to have followed the classical models such as the concentric zone model (Burgess 1925), the sector model (Hoyt 1939), or the multiple-nuclei (Harris and Ulman 1945) theories of urban spatial structure. However, elements of both concentric and sector models are discernible. The growth has not taken place evenly in all directions but has occurred much faster and further along certain directions. The expansion of the city (figure 5) has taken an accretive growth, where new developments have occurred around the periphery, as well as by increasing the density in the centre. Like most of the European cities, Nairobi shows a characteristic pattern of star-shaped urban sprawl where urban
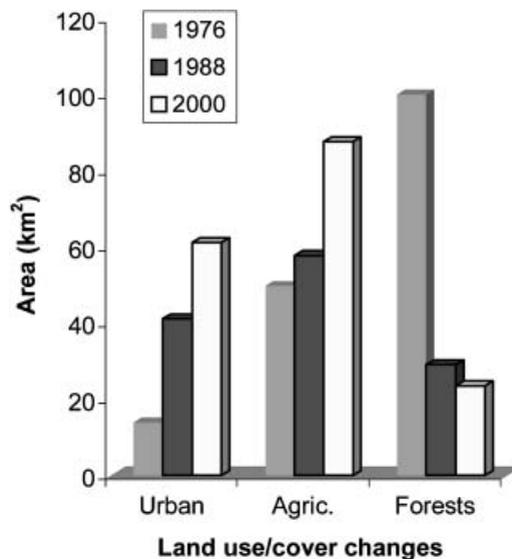

Figure 4. Trends in land use/cover changes for urban, agriculture and forested areas from 1976 to 2000.
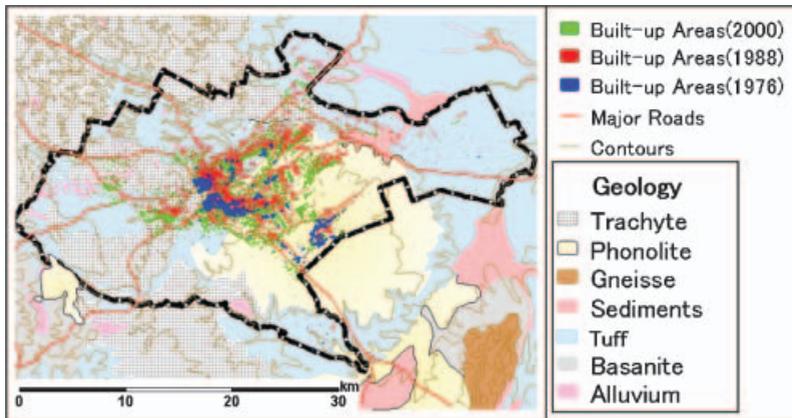
Figure 5.   Map showing the roads, the general geology and topography for Nairobi city.

development has evolved around the nexus of the main transport routes emanating from the city centre. These routes represent lines of greater access and the expansion pattern has tended to grow in sectors, emanating from the city centre and centred on these major roads. Accessibility and transport are perhaps the most important factors in the urbanization process of Nairobi city. Like many African cities, Nairobi's rate of change has been very fast, mainly because of the big number of immigrants from rural areas. Urban expansion has taken place against a background of stagnant living standards rather than one of growth. This has led to mushrooming of unplanned, chaotic squatter settlements of high densities, which represent over a third of urban residences.

Viewed as a time series, the urban growth has varied substantially over the study period. Nairobi city expanded by 28 km^2 during the 12-year period from 1976 to 1988 compared to the 19 km^2 for a similar 12-year period between 1988 and 2000.

6.1   *Factors influencing urban expansion*

The land use/cover changes revealed for Nairobi city occurred as a result of the interactions of a number of environmental as well as demographic and socio-economic forces. The urbanization speed of Nairobi city has been rapid compared to other major African cities. Some factors that have influenced this expansion are as follows.

6.1.1   Rapid economic development. Economic development has been one of the dominant driving forces. Nairobi's gross domestic product (GDP) was about sterling £254 million in 1975, £645 million in 1985 and £1.1 billion in 1995 (Kenya 2002). The national economic survey of the year 2000 put Nairobi's GDP at £1.5 billion (Kenya 2002). The economic development has led to the establishment of more industries, the boom of real estate and subsequently to the expansion of the city area. The unregulated small-scale businesses have expanded rapidly and the employment in this sector is estimated at 500 000 people (Kenya 2002). The increase in economic development as measured by the changes in the GDP values reflects in the change in urban expansion (see figure 4). The economic development, which grew much faster in the period 1975–1985 (153% growth) led to a higher rate of urban expansion. The period 1988–2000 had a lower rate of urban expansion, which

can be explained by the slower economic development (70% growth) during the period 1985–1995.

6.1.2   Urban population growth. The 1969 population census put Nairobi's population at slightly over half a million. The population rose to 1.35 million by 1989 against a national total population of 23 million (Development Solutions for Africa 1992). The current population is estimated at 3 million, a fivefold increase over the 1969 population. This rapid urban population growth reflects a natural population increase among the urban residents (52%) as well as migration of people from rural areas to the city (48%). The substantial population growth in Nairobi area during the 24 years is responsible for the land use/cover changes shown in figure 3. This population growth has increased the demand for food and has led to intensification of agriculture and expansion of cultivated land (Freeman 1991). Nairobi's economy, public services and infrastructure have not managed to keep up with the increasing population. The city management has been unable to cope with the increasing demand for efficient city services since the rapid urban growth has outpaced the capacity of local authorities to provide and maintain infrastructure and basic services (Stren and White 1989). The population, which is growing at a rate of 4% per annum, has contributed to the urban sprawl, the mushrooming slums, and the increased land use changes. This population increase together with poor planning have interacted with each other and made worse the already existing physical, social, economic and environmental problems.

6.1.3   Traffic infrastructure. The spatial pattern of built-up areas has a geometry that has mainly been shaped by roads. Nairobi is at the centre of a series of radial roads and these roads (see figure 1 and 4) link Nairobi to other parts of the country. Although Nairobi started as the headquarters of the Kenya–Uganda railway, transport by the railway seems to have been abandoned and the network has not been upgraded to serve the transport needs for Nairobi. As can be seen in figure 5, the transportation routes have promoted the urban sprawl, resulting in star-shaped linear growth along the major roads.

6.1.4   Topographical and geological factors. The physical setting of Nairobi city has also influenced the expansion directions. From figure 5, the north-east and westward expansions have tended to follow the flat areas. In the areas to the east, where at first sight the flat land and the general topography appear to offer lower land and residential building costs, the poor road network, the greater prevalence of clay soils, and the drainage problems have reduced these advantages. In the western part of Nairobi, where the ground is higher with rugged topography, expansion is constrained by the existence of steep slopes.

   The presence of volcanic rocks such as trachyte, phonolite, tuffs and basanite (see figure 5) has provided cheap and easily available building materials and has contributed to the growth of Nairobi city. The tuffs are excellent building stones and are extensively used in Nairobi in the building and construction industry.

6.2   *Constraints to the expansion of Nairobi city*

As shown in the expansion analysis, there are several preferred directions for the urban expansion, for which there are favourable factors. On the other hand, there

are negative factors that would discourage the urban expansion. Soils are one of the major influencing factors in the expansion of Nairobi city. Deep, well-drained red soils of volcanic origin, covering the western and northern areas have promoted the urban expansion in these directions (figure 6). On the other hand, the brown and black clay soils to the east are difficult to build on and have poor drainage. These soils have played a role in restricting the eastward expansion of Nairobi city.

Other major constraints to the expansion of Nairobi city include the Nairobi national park to the south of the city, and the safety zone and noise corridor around Nairobi International airport (figure 6).

7. Conclusions

Post-classification techniques with the GIS approaches to integrating satellite remote sensing data with demographic and socio-economic data were adopted to examine land use/cover changes and the dynamics of urban expansion. This information is necessary for urban planning purposes and for the appropriate allocation of services and infrastructures. The land use/cover in the study area was found to have changed significantly. In particular, the urban/built-up areas have increased by $47\,km^2$ over the period from 1976 to 2000, representing an increase in area of over 300%. Loss of forests and the problem of urban sprawl have accompanied the urban expansion. It was noted that population, economic development and site location characteristics were important in determining the land use/cover changes. Spatial expansion directions have changed over the study period. The north-east expansion, witnessed in the 1976–1988 period, was followed by westward expansion during the 1988–2000 period. The road network has influenced the structure of urban development, so that the expansion has assumed an accretive growth along the major roads. Soils, geology and topography are some of the other physical factors that have influenced the expansion of Nairobi city.

The master plan for the Nairobi growth commissioned in 1948 and revised in 1978 laid down guidelines earmarking land for future urban expansion. The plan, which was supposed to guide the spatial growth of the city, indicated that a substantial portion of the new urban expansion would be concentrated on the periphery of the already built-up areas and accretive growth in which additions would be made
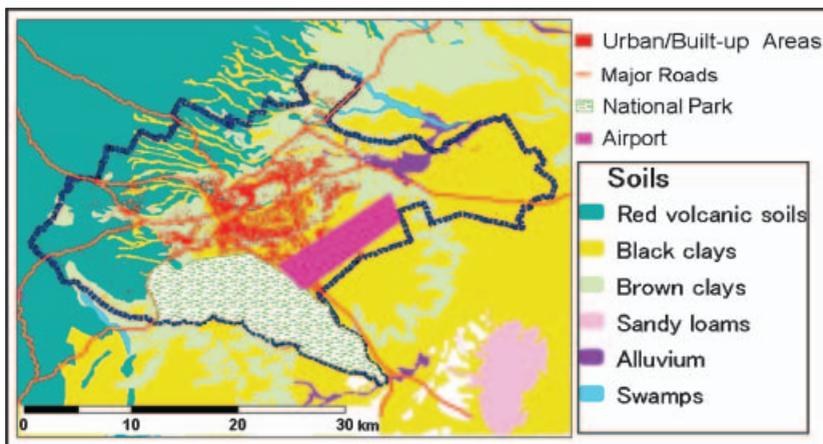

Figure 6. Map showing the main constraining factors to the expansion of Nairobi city.

around the periphery as well as by increasing density in the centre. This study shows that this has not come to be. Instead, highway driven sub-urbanization and also expansion to the east, north and to the west have taken place. The analysis of the urban sprawl directions and land use conversions indicates that deliberate planning is largely lacking in Nairobi's urbanization process, and that the general urban planning principles encoded in various laws and local government regulations have not been adhered to or enforced. The environmental and social consequences of a rapidly growing population in a poorly planned urban system have been dramatic because the city has experienced tremendous growth in a short period of time.

Comprehensive planning is needed to help the city manage the available resources efficiently. The local government is confronted by various challenges such as loss of forests, urban sprawl and negative environmental and social changes, in its effort to realize sustainable development. The increasing population has put pressure on the capacity of local authority to provide services to the residents and this has led to new challenges of unplanned structures, mushrooming of slums and uncoordinated development. The analysis of land use changes shows that the biggest challenge to Nairobi's city planners is perhaps to maintain an internal equilibrium balance between economic activity, population growth, infrastructures and services in such a way that the urban system and its dynamics evolve in harmony, internally limiting, as much as possible, impacts on the natural environment.

This study has presented the dynamics of urban expansion and demonstrated the interplay between biophysical, location site and socio-economic characteristics in shaping the growth of Nairobi city. More importantly, this study has demonstrated the usefulness of satellite remote sensing, digital image processing, and GIS techniques in providing accurate land use/cover maps and comprehensive change information, which are very valuable for planning and research. This study has contributed to the understanding of spatial and temporal dynamics of urban growth of Nairobi city, and will form a basis for better planning and effective spatial organization of urban activities, which is necessary for future development of Nairobi. The kind of approach adopted in this study can be used for analysis of land use/cover changes in developing countries where the amount and quality of geographic information and other ancillary data are often outdated and inaccurate, or very limited where they do exist.

Acknowledgments

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