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University of Cape Town



Department of Environmental and Geographical Sciences

Urban Growth in Southern Africa:

Comparing 30 years of decadal imagery to census data

Towards a Master of Science Degree

In

Environmental Geographical Sciences

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Final Submission: November 2011

Plagiarism Declaration

I, **Lauren Lyn Lewis** hereby declare that the **Urban Growth in Southern Africa: Comparing 30 years of decadal imagery to census data** is my own work and has not been submitted before for any other degree or to any other university. All the sources I have used or quoted have been indicated and acknowledged as complete references.

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Date

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Abstract

Global urban studies tend to underrepresent African cities, in particular due to data constraints. Utilising the available information for five study sites, namely Cape Town, Durban, Johannesburg, Windhoek and Gaborone, this study uses remote sensing and GIS to devise a feasible methodology to monitor urban expansion in a Sub-Saharan Africa context by drawing on Landsat decadal time slices for the period 1970 - 2002. For the purpose of this study, urban was defined as built-up or impervious areas, including residential, commercial, industrial complexes and transport infrastructure, while census data was also incorporated in order to compare urban expansion to population growth. GIS administrative boundaries were used to spatially define the study sites throughout the time series. The methodology involved using unsupervised classifications on the Landsat data to extract urban areas. Due to the reference data being in vector format, the classification results were converted to shapefiles to allow for an accuracy assessment to be conducted. The total urban area of each study site was calculated for each time slice and the results were represented as maps depicting urban expansion. Graphs were also created depicting the total urban area vs. total population for each time slice (1970s, 1990s and 2000s). The general trend regarding the South African study sites show that initially the populations seemed to be increasing at a faster rate than the urban areas were expanding, while later urban expansion seemed to occur at a faster rate. The classification results show the total increase in urban areas to be: Cape Town (223.3 km² (51.8%)), Durban (91.4km² (67.1%)), Johannesburg (692.9km² (87.0%)), Windhoek (29.2km² (74.9%)) and Gaborone (63.2km² (87.2%)). The results also showed that the most variation occurred in Durban where the informal areas remained undetected by the classification throughout the time series. Interestingly, Windhoek and more so Gaborone produced very linear graphs when comparing urban expansion to population growth. Comparing these results to the reference data, the total urban expansion occurring over the time series was: Cape Town (468.99km² (76.0%)), Durban (454.7km² (71.1%)), Johannesburg 356.3km² (56.2%), Windhoek (1.7km² (13.9%)) and Gaborone (17.3km² (91.2%)). The accuracy assessment was only conducted on the South African study sites, as no suitable reference data could be secured for Windhoek and Gaborone. The National Land Cover datasets were used as reference data for 1994 and 2001, while urban areas were extracted from 1:250000 topographic maps to serve as reference data for that period (due to the lack of electronic spatial data). The end points in the time series (2001 reference data) had the closest corresponding temporal data and also resulted in the most accurate results being produced. The accuracy assessment revealed Johannesburg's 2002 classification to be 91.6% accurate, Cape Town (2000) being 72.4% and Durban (2001) the least accurate with 20.9%. Space has become increasingly important in understanding the coupling of social and physical processes occurring on landscapes. The methodology thus proved to be feasible in analysing and combining spatial and social temporal data in a Sub-Saharan African context.

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Abbreviations

CD:NGI	Chief Directorate: National Geospatial Information
ERDAS	Earth Resource Data Analysis System
ETM	Enhanced Thematic Mapper
GCP	Ground Control points
GIS	Geographic Information Systems
GLCF	Global Land Cover Facility
ISODATA	Iterative Self-Organizing Data Analysis Technique
LULC	Land Use/ Land Cover
MSS	Multi-Spectral Scanner
NLC	National Land Cover
PCA	Principal Component Analysis
RDP	Reconstruction and Development Programme
TM	Thematic Mapper
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

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Definitions

Cartographic generalisation	The interaction between individual operators that is concerned with processes such as object elimination, detail reduction amalgamation, typification and displacement.
Infrastructure	The basic physical and organizational structures (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise
Urban	Settlements are usually designated as urban once they have grown large enough to support industries which are not rural in nature. However, no common figure can be put on the necessary size as settlements function differently in different areas due to local circumstances. For the purpose of this thesis, urban will be defined as built-up or impervious areas, including residential, commercial, industrial complexes and transport infrastructure such as roads.
Urban edge	A demarcated line to manage, direct and control the outer limits of development. The intention of the urban edge is to establish limits beyond which urban development should not be permitted.
Urban sprawl	An unplanned and unexpected expansion of development in an area where homes, strip malls and roadways take over natural areas; The unplanned uncontrolled growth of urban areas into the surrounding countryside.
Urbanisation	The process by which an increasing proportion of an area's population becomes concentrated in (legally or statistically defined) urban areas; The social process whereby cities grow and societies become more urban; The economic and demographic processes involved in the growth of towns and cities.
x:y coordinates	The horizontal (x) and vertical (y) addresses of any point on the earth's surface relative to other locations.

1 Introduction

This study will make use of population census data as well as Landsat images in order to determine the correlation between urban growth and population growth. Five study sites located in Sub-Saharan Africa were chosen based on their status as being primary urban centres, namely Cape Town, Durban, Johannesburg, Windhoek and Gaborone. In South Africa, Cape Town, and Johannesburg are both provincial capitals in their respective provinces namely the Western Cape and Gauteng, while Durban is the largest city in Kwa-Zulu Natal. Gaborone and Windhoek were selected as additional cities in the Sub-Saharan African region, both of which are national capital cities in Botswana and Namibia respectively. The availability of data, particularly spatial and temporal data, for these cities provided strong motivation in order to incorporate these major cities into the study. Further motivation regarding the choice of study sites is discussed in Section 1.3.

Space has become increasingly important in understanding the coupling of social and physical processes occurring on landscapes (Goodchild and Janelle, 2004). Infrastructure, employment, resources, services and facilities are all vital components in the effective functioning of a city. Spatial and population growth do not always occur at the same rate. Spatial growth is the area that is occupied by infrastructure¹, while population growth is the increase in population due to varying factors e.g. increased birth rate or an influx of people from other areas.

Figure 1 illustrates the increase in population and the amount of urban land occupied between 1990 and 2000 on a global scale. African cities are noticeably underrepresented which could be due to a variety of reasons, the most probable being the lack of data (both spatial and census data) for African cities. The spatial extent of urban areas is not always easily determined due to the varying definitions as to what actually defines an urban area and also rural urban fringe developments that are occurring.

¹Refer to definitions

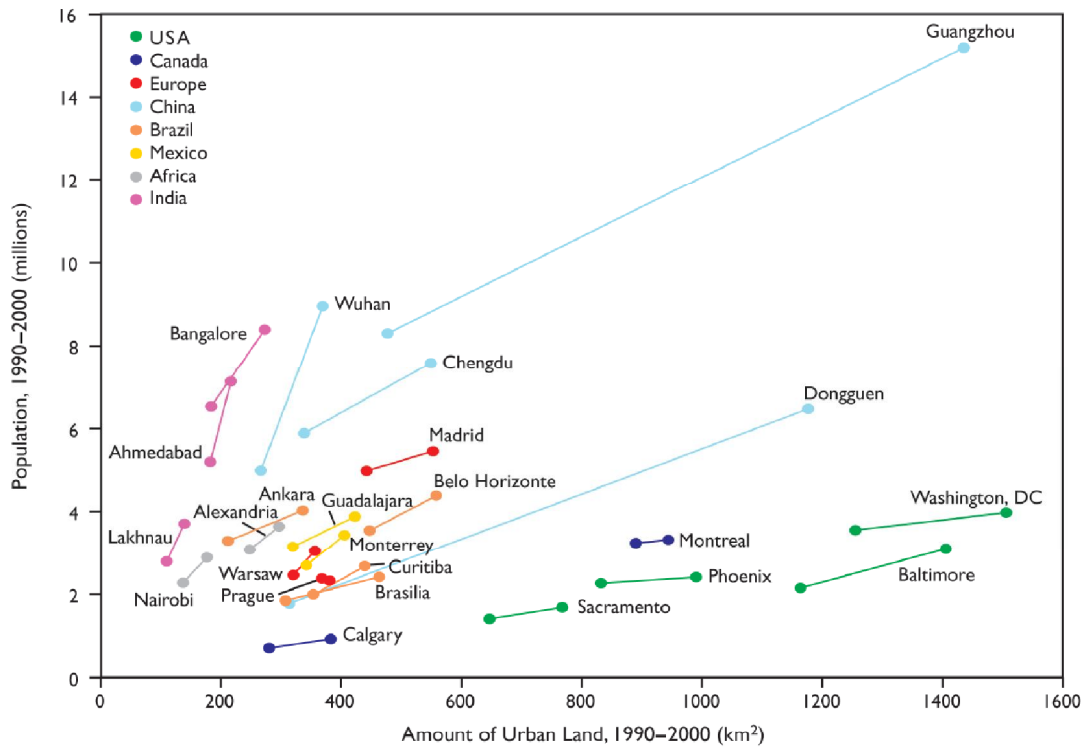


Figure 1: Graph illustrating total population vs. total urban land

(Source: Schneider, 2007, p. 287)

Since 1950, the urban populations in Africa, Asia and Latin America have increased more than fivefold, resulting in approximately two thirds of the world's urban populations being located in these regions. The rapid urban growth brought about a large increase in the amount of large cities, many of which have reached sizes that are historically unparalleled (Satterthwaite, 2000). Two centuries ago, London and Beijing were the world's only million cities i.e. only 2 cities had more than one million inhabitants. By 1950, there were 80 and by the year 2000 there were over 300, most of which are in Africa, Asia and Latin America. Most of these cities also have populations that have increased more than tenfold since 1950. Brasilia (the federal capital of Brazil) for example, did not even exist in 1950, but is home to more than 2 million inhabitants today (Satterthwaite, 2000).

Urbanisation rates vary significantly across regions. On a global scale, Africa has been identified as the least urbanised region, and having the fastest rate of urbanisation, these trends are illustrated in Table 1 (Sandbrooks, 1985; United Nation Population Division, 2002). In addition, Africa also has the lowest economic growth rate (Gantsho, 2008). The main influences have been the effects of slavery, corrupt governments, failed central planning, the international trade regime, geopolitics, human rights violations, negative effects of colonialism, despotism, illiteracy,

cultural beliefs (superstition) and conflict (military and tribal conflict) (Sandbrooks, 1985). The 2003 Human Development Report had the bottom 25 ranked nations (151 to 175) all from Africa (United Nations, 2003). Urbanization² is usually associated with the rate of economic and industrial growth, however, in Africa, the city growth is attributed to the high rate of population growth rather than to economic development (Montgomery et al, 2003, p. 93).

Table 1: Global Urbanisation Trends

(Source: United Nations Population Division, 2002)

Region	Percentage Urban Area (%)				Urbanisation rate (%)	
	1950	1975	2000	2030	1950 - 2000	2000 - 2030
North America	63.9	73.8	77.4	84.5	0.38	0.3
Latin America & Caribbean	41.9	61.4	75.4	84	1.18	0.36
Oceania	61.6	72.2	74.1	77.3	0.37	0.14
Europe	52.4	67.3	73.4	80.5	0.68	0.31
Asia	17.4	24.7	37.5	54.1	1.53	1.23
Africa	14.7	25.2	37.2	52.9	1.86	1.17

In Sub-Saharan Africa, the colonial influence on cities is ever-present. Segregation in these areas was present even before apartheid laws were enforced in South Africa (Dubresson and Jaglin, 2002, p. 7-8). During the post-apartheid period, in-migration to historically large urban areas tends to be increasing, contributing to the increase in urban populations (Posel, 2003). Besides the influence of past events, present events are causing immigration from neighbouring countries such as Zimbabwe.

The term urban is generally understood to refer to a built up area where basic services such as water and sanitation are available to the population. However, there is no formal, interchangeable, universal definition of what urban actually is (Montgomery et al, 2003, p. 132). According to the United Nations Demographic Yearbook, each country has its own definition. With this being said, the results of the study will largely be based on the assumption that the area being analysed is in fact an urban area as defined in terms of this study. The complexity of defining urban exists in literature from all parts of the world and remains a continuous challenge experienced by everyone from independent academics to the United Nations (UN) (Cohen, 2004).

Urbanisation is becoming increasingly evident in cities in developing countries. The interest in the urbanisation of the developing world, coupled with advances in technologies such as remote

² Refer to definitions

sensing and geographic information systems (GIS), has resulted in the development of various methods to analyse the urban growth of these cities. Most previous studies using these methods have only take the physical changes of urban areas into account. A further aspect to the study will be the analysis over a time series where the data will be linked as closely as possible to the dates the remotely sensed images were taken. This will provide insight as to whether there has been acceleration in either urban growth or population growth over the time period.

The study attempts to illustrate how urban expansion can be monitored in a Sub-Saharan Africa context using the available temporal spatial (satellite images) and census data. Remote sensing and GIS will be demonstrated as the analysis tools to monitor urban expansion in a Sub-Saharan Africa context using the available temporal spatial data. Also how the spatial data relates to the census data, similar to the graph (Figure 1). In order to keep the total area of each study site consistent for each period in the time series, the municipal administration boundaries, as defined by the South African Demarcation Board, will be used to define the boundaries of each study site. These boundaries encompass urban areas, open spaces and in some cases, rural landscapes. Remote Sensing will be used as a tool to extract the urban³ areas.

1.1 Problems with defining 'Urban' in a global context

The definition of urban as stated previously, is not uniform for all areas, and there does not seem to be any prospects of national governments adapting a universal definition (Montgomery et al, 2003, p. 132; Hinrichsen et al, 2002, p. 3). To briefly illustrate this, the United Nations Statistical Office compiles data from 228 countries, for just over half of these countries the urban definition are based on governmental considerations which associates urban areas with provincial capitals or with areas under the jurisdiction of certain local authorities. In approximately 22% of the countries, the urban areas are determined by the size and density of the population. These countries have a lower limit varying from 200 to 50 000 inhabitants, at which a settlement is considered to be urban. 39 Countries emphasise the socioeconomic criteria, including the proportion of labourers employed in non-agricultural activities and the availability of urban-type-facilities such as electricity, sewage systems, water supply, roads etc. Approximately 24 countries do not have (or have not provided to the United Nations) any defining urban criteria (Montgomery et al, 2003, p. 132-133).

³ Refer to definitions

Having a common definition of urban would not be appropriate for a variety of reasons, but more simply because even cities from the same country are at different levels of development with regard to service delivery, infrastructure planning, and maintenance and also on social levels. There would have to be uniform defining criteria as to what would constitute an urban area. For example, India would be predominantly urban if it used the same definition that Sweden and Peru used to define the term (Satterthwaite, 2000). Conversely, and using the same example, the problem of there being no uniform definition creates a challenge when comparing urban areas as in many instances they will not have the same defining criteria, resulting in no comparison being 100% accurate.

The United Nations Demographic Year Book (2001) lists definitions used by different countries on each continent. 11 out of 27 surveyed countries in Africa do not have a definition for urban. South Africa defines urban as places with some form of local authority Botswana states urban is an Agglomeration of 5 000 or more inhabitants where 75 per cent of the economic activity is non-agricultural while Namibia does not have a definition. Having a variety of definitions for the term urban would mean that any nation can increase or decrease its level of urbanisation by simply changing its definition (Satterthwaite, 2000). This project defines urban as areas built-up or impervious areas, including residential, commercial, industrial complexes and transport infrastructure such as roads.

1.2 Urban Population Dynamics and the Growth of Cities

In developed countries (and most developing countries), the general trend is that non-agricultural production occurs in the cities. This makes the cities economic growth engines in an economy (Black, 1999). Urbanisation is defined by Schneider (2007, p. 286) as the transformation of land to urban use and is considered to be one of the most significant and irreversible alterations to the surface of the earth. The level of urbanisation has a strong influence on economic growth, influencing both the efficiency of growth and the degree of income inequality in an economy. Conversely, economic growth has an influence on urbanisation as it drives the spatial evolution of production and population concentration in and around areas (Black, 1999). Africa, Asia and Latin America will see most of the world's urban population growth in the near future. Two important contributing factors to urban growth are rural-to-urban migration and natural urban increase. The latter is more evident in modernised regions where the mortality rate

has noticeably decreased when compared to the area's historic record (Montgomery et al, 2003, p. 3).

1.3 The Selection of the Study Sites

Sub-Saharan African cities underrepresented on a global scale in studies such as Schneider (2007; Figure 1). Alexandria (Egypt) and Nairobi (Kenya) are the only two African cities represented in the study, with Nairobi being in Sub-Saharan Africa. This study focuses on five major cities in Sub-Saharan Africa, namely Cape Town, Johannesburg, Durban (South Africa), Gaborone (Botswana) and Windhoek (Namibia), all of which are developing countries.

The sites were selected on the basis that they are primary urban centres and large economic centres and thus important contributors to the GDP in their respective countries. This is considered important as economic centres are generally well planned and managed areas. Cape Town (Western Cape) and Johannesburg (Gauteng) are both provincial capitals and Durban is the largest city in Kwa-Zulu Natal. Data for these areas e.g. historical data, topographic maps, satellite imagery, census data, are found to be more abundant (especially with regard to data required for time series analysis) and freely available. In terms of the South African sites, the selected areas were limited to three large cities as the selected areas would provide adequate data for the analysis. An additional criterion for the selection of the five study sites (other than being large economic centres) was their location which influenced their geophysical complexity. Durban was immediately identified as having the most diverse landscape due to the undulating terrain, abundance of rivers and river valleys and dense vegetation. Johannesburg was considered unique as it has an abundance of mining areas. Local knowledge and familiarity with Cape Town was considered as strong motivation for inclusion in the study, while Windhoek and Gaborone were located in Namibia and Botswana respectively which would allow for different definitions of urban to be incorporated into the studies. They were also historically different cities which would have influenced spatial planning and social factors making them considerably different to the South African study sites. Figure 2 shows a locality map of the study sites.

Gaborone and Windhoek added value to the study as the cities are located in Botswana and Namibia respectively, thereby introducing study areas from additional Sub-Saharan African countries, both capital cities in their respective countries. Besides having differing definitions of urban (according to the United Nations Demographic Yearbook, 2001), they are also younger

cities than the South African study sites having less historical influence. A major contrast regarding the history of the two study sites is that Windhoek's spatial plan and politics were influenced by South Africa's occupation from 1915 to 1977, while Gaborone remained independent from the Apartheid influence. The two cities were ideal choices to be incorporated into the study as they allowed for a larger area of the Sub-Saharan African region to be represented in the global context (e.g. Figure 1) and compared on a local scale to the other study sites.

1.3.1 Cape Town, Durban and Johannesburg

The South African study sites generally have very similar histories in that they were all influenced by Apartheid. This has led to their being a defined urban form where urban boundaries such as railways, roads or natural features such as rivers, were used in order to segregate different racial areas.

The urban racial segregation was enforced as the Group Areas Act (1950). City racial structures changed in all South African study sites. The white population was given large plots near the central business district in areas that were often considered elite. Coloureds were forced into more densely populated areas away from the central business district (CBD), which were still considered as a privilege compared to the black population. The black population were forced into homeland areas and in many cases were denied access to the urban areas if they did not have employment. They were also expelled to live in the peripheral areas of the city, if they were not sent to the homelands.

1.3.2 Gaborone

Gaborone is the capital of Botswana, which was relocated from Mafikeng (South Africa) in 1965 (Maundeni, 2003, p. 11; Njeru, 2009). The area was mainly chosen as the location for the capital of Botswana, due to the accessibility to a fresh water source, close proximity to a railway line to Pretoria (South Africa), its central location among tribes, as well as the lack of association with those surrounding tribes (Njeru, 2009; Seth, 2008). The area was ideal in order to accommodate expansion (Maundeni, 2003, p. 11). At the time, Gaborone had the lowest population density of all Botswana's cities. In 1963 the development plan that launched the new capital was polarised with high and medium income groups residing on one side and low income groups on the other (Ministry of Local Government et al, 1991; Tlou and Campbell, 1984). The country became

independent on 30 September 1966 (Tlou and Campbell, 1984). In 1984, the central government sought to reverse the segregation of income groups and insisted on integrated development. Since then a policy of non-centralisation has been adopted in the design of the development plan in order to prevent spatial polarisation occurring within the city (Maudeni, 2003, p. 15). The Ministry of Lands, Housing and Environment (2001) has stated that the implementation of the policy has resulted in a balance, well-integrated and socially healthy community (Maudeni, 2003, p. 15).

1.3.3 Windhoek

Namibia is the most arid country in Sub-Saharan Africa. The harsh conditions led to the area being colonised at a much later stage than the rest of Southern Africa. In 1884 merchants from Lüderitzbucht requested a German protectorate over German West Africa, resulting in the establishment of the German colony's borders in 1890. Windhoek was founded on 18 October 1890. In 1915, South Africa seized Namibia from the Germans, which led to the region being run on South Africa's apartheid political system (Thornberry, 2004).

Spatially, Windhoek is approximately ten times greater than any other urban area in Namibia and is home to approximately 13% of the country's total population (Simon, 1995). The influence of apartheid is evident in the structure and racial distribution in the city (Simon, 1995). Racial segregation laws were applied in full effect and, like in South Africa, homelands were established to accommodate the black population while the white minority received the benefits of owning their own land in urban areas (Thornberry, 2004).



Figure 2: Map illustrating the distribution of the study sites

1.4 Scope

The purpose of the thesis is not aimed at improving remote sensing and image processing techniques, but rather an attempt to populate the graph produced by Schneider (2007, Figure 1), and provide representation of the Sub-Saharan African region, which is clearly absent from the graph. The method employed in this study therefore requires the comparison of remotely sensed data with social data. From a social perspective, it is also not the intention to be able to define the term urban in a Sub-Saharan Africa context, but rather to test the viability of the devised methodology in identifying the urban areas in satellite imagery and to determine the amount of land that the urban area occupies. For the purpose of this research project, urban is defined as built up areas including residential, industrial and transport infrastructure⁴. The viability of the methodology is considered important as it will provide a potential method of being able to analyse

⁴ Elaborated in the definitions section

urban expansion in a Sub-Saharan African context, given the limited availability of data. The results will be illustrated graphically and will allow the fastest and slowest growing urban areas and populations to be identified.

This study will use remote sensing and GIS techniques, in order to determine the urban expansion over a time series for five Sub-Saharan African cities and to relate the urban area with the total population for the given period. A variety of different datasets will be used, of which the purposes are highlighted below:

- Census data (tabular data) . Provide the total populations of each study site throughout the time series.
- Satellite imagery (raster data i.e. Landsat images) - Perform an unsupervised classification to extract urban areas in each study site throughout the time series.
- GIS administrative boundaries (vector data) . Define the boundaries of the study areas as to not create any variability in the total area of each study site being used in the study. The problem of potentially overstepping boundaries was initially identified in Johannesburg due to the extensive development that has occurred, thus creating the need to utilise administrative boundaries.
- CD:NGI National Land Cover Datasets (NLC) (1994 and 2001) . Serve as reference data for the 1994 and 2001 periods in the time series regarding the South African study sites. The datasets were provided as GIS vector data.
- Topographic maps . Serve as a comparison for the Landsat imagery in identifying urban areas for Windhoek and Gaborone as well as for the 1970s period of the time series for the South African study sites.

Since the Landsat imagery is available from 1972, this would mark the beginning of the time series which will end in the year 2001 (the year the last South African census record was produced). Only total population counts will be extracted from the census data. One of the challenges will be to determine and extract urban areas in the satellite images; therefore much of the analysis will be based on the assumption that the areas identified are in fact urban⁵. The latest available administrative boundaries will be used in the form of GIS data to define the study sites. The boundaries will provide the spatial framework for measuring urban areas in the selected study areas. In order to use the topographic maps as reference data, the urban areas

⁵ Refer to definitions

will be extracted for each study site prior to the year 1994 (for the South African study sites) as historic urban shapefiles were unavailable. Windhoek and Gaborone will only make use of topographic maps as reference data as no alternative information was available. For the 1991 and 2001 time periods, the South African study sites will be assessed using the NLC datasets as reference data.

Although GIS and remote sensing are used as analysis tool, it is not the purpose of this thesis to test different classification methods. After much consideration, it was decided that the unsupervised classification techniques would be implement and tested against reference data obtained from the CD:NGI. The results would therefore demonstrate the viability of this methodology, including successes and short-coming. In addition, the time series analysis will provide a historical account of each study site. The influence of political regimes such as apartheid will be investigated and used in attempt to account for the results obtained. This study therefore aims to use social studies to explain spatial trends obtained from the GIS and remote sensing analysis.

1.5 Aims, Objectives and Hypotheses

The analysis aims to address the urban debate, providing a broad social analysis of the selected study sites to explain the trends of urban expansion using GIS and remote sensing as monitoring tools that can be used to devise a feasible methodology to determine physical urban expansion over a time series, within demarcated boundaries. The materials used in the analysis should therefore be cost effective and easily accessible to the broader community⁶. The selection of the study sites is based on the under representation and lack of analyses in an African and specifically Sub-Saharan African context, in global studies e.g. Figure 1. GIS and remote sensing will be used as the analysis tools, to extract urban areas from Landsat TM, MSS and ETM+ images. The spatial data will be used to determine if a correlation exists between urban expansion and total population, thus providing a graphical interpretation of urban expansion and population growth over a time series, similar to the graph produced by Schneider (2007), presented in Figure 1.

⁶ Independent researchers, planners, government departments etc.

For the purpose of this study, urban areas in the Landsat satellite imagery, topographic maps, NLC datasets will be defined as⁷:

*'Built-up or impervious areas, including residential, commercial, industrial complexes and transport infrastructure e.g. roads.'*⁸

This definition (including variations thereof) has also been adopted by many researchers and authors, some of whom are referred to in this study e.g. Epstein (2001), Angel et al (2005) and Schneider et al (2003). For the project undertaken by the CD:NGI in 1994 to compile South Africa's first National Land Cover Dataset (and subsequently revised the data in 2001), the CD:NGI defined urban as areas within the urban edge of each municipality. The larger original land parcels (erf, farm portion or holding) would be subdivided to reflect the primary land uses e.g. restaurants in the Kirstenbosch Botanical Gardens would be a secondary use, whereas botanical gardens would be the main use, however, if there was large office park situated in the botanical gardens, the land parcel would be divided to reflect the botanical gardens as a main use and the office park as a separate main land use (CD:NGI, 2009). For this study, the 1994 and 2001 National Land Cover Datasets will be referred to and used as Reference Data⁹, particularly for the required accuracy assessment.

Administration boundaries from the South African Demarcation Board will be used as the boundaries of the study sites throughout the respective time series. These boundaries encompass the urban regions of each South African study site, including the urban edge (as defined in the respective Spatial Development Frameworks), as well as open spaces and in some areas, rural landscapes. Remote sensing will be used to extract the urban areas. The administrative boundaries will play an important role in this study as they will ensure:

- Study sites have a constant total area throughout the time series, thereby providing the spatial framework for measuring urban areas within each study site;
- A constant scale will be used throughout the time series for each of the study sites, therefore allowing for comparative analyses to be made across the time series without changing the scale;

⁷ The census data will use this same definition to represent urban populations i.e. the populations residing in regions in the study sites as defined above.

⁸ An elaboration of this definition can be found in the definitions section.

⁹ Reference data is typically assumed to be correct and used to evaluate results (particularly of land cover mapping)

- The issue of urban sprawl¹⁰ is eliminated whereby all areas occurring outside the municipal administrative boundary is excluded from the study e.g. the rapidly developing and expanding Midrand corridor between Johannesburg and Pretoria;
- The area being analysed occurs within a politically defined boundary; and
- Allow the methodology and remote sensing techniques (ability to extract urban areas) to be tested as the administrative boundaries encompass a variety of different land cover types including urban regions, open spaces and in some areas, rural landscapes.

This study is focussed on integrating urban geography with remote sensing and GIS in order to explain urban expansion over a time series in a Sub-Saharan African context. The formulated hypothesis states that if low-cost technical data such as census data, satellite imagery and GIS vector data as well as resources such as remote sensing and GIS software is readily available and easily accessible to Sub-Saharan African countries, then a feasible and practical methodology can be formulated in order to monitor urban expansion in these developing countries. Also, if social factors are encouraging migration towards larger city centres then the urban population will be increasing at a faster rate than urban areas are developing.

The study can thus be divided into three primary objectives that aim to answer whether remote sensing can be used as a cost effective feasible tool to analyse urban expansion over a time series in a Sub-Saharan African context and if historical information be used to explain the current spatial development trends? The results would also be able to show whether urban populations are increasing at a faster rate than the rate at which the urban areas are expanding. Based on these primary questions, the research objectives identified in this thesis are:

- To explore low-cost techniques to devise a practical methodology to analyse urban expansion in a Sub-Saharan African context using Remote Sensing and GIS;
- To test the feasibility of the devised methodology for mapping urban expansion in five Sub-Saharan African cities, within defined boundaries and at a fixed scale; and
- To understand the relationship between urban expansion (conversion of land to urban use) and urban population growth (by using cross-disciplinary techniques to assess demographic, historic and urban expansion trends) in the selected study areas.

¹⁰ Refer to definitions

2 Review of the literature

The use of remotely sensed imagery and census data immediately combines two disciplines, namely remote sensing and social sciences, which have previously been considerably independent of each other. The reason behind their isolated studies is the questions that the respective researchers chose to address (Liverman et al, 1998, p. 1). Social scientist tend to focus on abstract variables that would explain spatial appearances and transformations such as distribution of wealth and power, land tenure rules, governmental policies and social customs, which are not at all related to the reflected bands in the electromagnetic spectrum. Similarly, social scientists tend to question why things happen, rather than where things happen, making some studies very aspatial (Liverman et al, 1998, p. 2).

As noted earlier, the literature shows that the actual concept of 'urban' is highly contested (Cohen, 2004, Montgomery et al, 2003, p. 132-135). For this reason, the United Nations has published Demographic Yearbooks to provide the definition each country uses to define urban areas (United Nations, 2001). The definitions provided are unique and not interchangeable. Part of the literature review will discuss this issue as a contributor to the difficulty in defining what an urban area actually is.

2.1 *The Urban debate*

What is urban? What is a city? Where does the city end and where does the rural area begin? In an ever-changing, urbanizing world, the answer to this question seems very evasive. The term 'urban' and 'city' are frequently used interchangeably (Hinrichsen et al, 2002, p. 3), neither having an internationally agreed upon definition (Hinrichsen et al, 2002, p. 3; Montgomery et al, 2003, p. 132; Satterthwaite, 2000; United Nations Demographic Yearbook, 2001). Commonly people reserve 'city' for urban centre with larger populations, while 'urban' is used more generally and refers to settlements of varying population sizes (Hinrichsen et al, 2002, p. 3).

Today the challenge lies in determining populations and urban areas of large modern metropolises that extend in all directions. In some cases rural villages and towns get absorbed into the expanding urban area (Angel et al, 2005). Satterthwaite (2003) supports this statement

saying that the extension of city or metropolitan boundaries changes the status of many settlements and residents within the new, extended area from rural to urban.

Many countries use administrative boundaries to demarcate urban areas, however, even this definition has been found to have flaws. Best (1981) illustrates this in a problem when it was applied in Britain: prior to 1974, the area actually being utilized as urban land was considerably less than the area within the administrative boundary. Conversely, in African cities the reverse may be more applicable, where urban areas extend beyond the city boundaries. The administrative boundaries that outline cities also affect population counts and growth rates. The city limits are becoming increasingly difficult to define. One of the major realities that urban researchers are faced with is that the simplicity of determining the population and urban extent of walled medieval cities no longer exists (Angel et al, 2005, p. 50). Describing whether the population of a city is increasing or decreasing depends on how their boundaries are defined at the given time (Montgomery et al, 2003, p. 136). This is an important factor that needs to be considered when analysing urban populations over a time series especially. The UN takes this into account in its reports by reporting urban population counts for many kinds of boundaries or city concepts (Montgomery et al, 2003, p. 136).

The differences between urban and rural are becoming less obvious as advancements in technology and the global economy infiltrates formally isolated areas. There is also an increase in the interdependency between the two. While some authors still argue for the use of the terms rural and urban (Montgomery et al, 2003, p. 63), there is a more recent argument developing that the terms be disbanded (Trzyna 2007, Bass 2004). The two way urban-rural split is thought to be a very crude way to classify places and many researchers agree on the increasingly obsolescence of the dichotomy (Champion, 2004, Trzyna, 2007, Bass, 2004). The blurring distinction between rural and urban is giving rise to partially built-up areas called *semi-urban* and *transitional* areas on the periphery of larger cities. This fringe development is causing the evolution of a new kind of urbanization such as 'edge cities', 'exurbia', 'polycentric urban configurations', 'extended metropolitan regions' and 'desakota' (literally village city) (Champion, 2004).

2.2 Urbanisation

2.2.1 The scale of global urbanisation

The world population is projected to reach 7 billion people in early 2012, which is an increase since the previous estimate of 6.8 billion people. The most recent projection from the United Nations Population Division reveals that by 2050 the Earth will be home to more than 9 billion people (United Nations, 2009).

Most of the 2.3 billion people increase is expected to enlarge the populations of developing countries, which is expected to increase from 5.6 billion people in 2009 to 7.9 billion people in 2050 (United Nations, 2009). Angel et al (2005, p. 1) estimates that cities in developing countries will more than triple their land use by 2030, with each new resident converting approximately 160m² of non-urban to urban land over the next few years.

Similarly, urban populations in industrialised countries are expected to increase by approximately 11% by 2030 from 0.9 billion to 1 billion people (United Nations, 2004). By 2030, the populations in industrialised cities would increase by 20%, converting approximately 500m² per person, of land from non-urban to urban (Angel et al, 2005, p. 1).

Since the 1950s, most countries have urbanised quite substantially, which is a trend that continued through the middle of the 21st century. In 2008, the world's population living in urban areas surpassed the 50% mark. Developing countries show patterns of increasing proportions of the total populations living in cities, similar to historic patterns of Europe and North America, with increasing urbanisation accompanying rising GDP levels (UN-Habitat, 2008). Some of the main observed differences between the trends are that presently, urban expansion in developing countries is being experienced at much faster pace, creating total urban populations which exceed the estimated levels. This is observed in the concentration of people living in mega-cities (urban areas with total populations exceeding 10 million people) and the increasing numbers of medium sized cities, with approximately 3 million people (UN-Habitat, 2008).

2.2.2 Urbanisation in developing countries

Great Britain and some European countries were among the first countries to become urbanised. Due to the slow pace at which urbanisation was occurring, governments had time to plan and provide for the increasing demands of the growing urban populations. Developing countries differ in that urbanisation is experienced at a much more rapid pace (See examples in Cohen, 2004; Collins, 2001).

The developing world has previously been predominantly rural, relying mainly on primary activities such as mining and agriculture. This trend has notably shifted towards an urban way of life. In 1975, 27% of people in developing countries lived in urban areas, but by 2000, the proportion increased to 40% (Hinrichsen et al, 2002, p. 2). By 2030, projections suggest that 56% of the developing world will be urban (Hinrichsen et al, 2002, p. 2; Angel et al, 2005, p. 1). The rapid urban growth in developing countries is a result of rural-urban migration as well as natural population increase. Rural populations have virtually stopped growing. Sub-Saharan Africa and Oceania are the two main regions where future actual rural population growth will be evident (Hinrichsen et al, 2002, p. 2).

Urban areas in developing countries are at the core of the struggle to achieve improved living conditions. Globally, urban areas have become economic growth engines in the world's economy, as well as being centres of change and diversity (Hinrichsen et al, 2002, p. 1). However, the rapid population growth experienced in these areas is causing increased poverty levels, lack of infrastructure, housing and opportunities, as well as inadequate critical public facilities e.g. schools, hospitals. The inability to meet these public needs will result in much higher poverty levels and morbidity (Hinrichsen et al, 2002, p. 1; UN-Habitat, 2008).

The urban population growth rate in Africa is historically unparalleled at almost 5% per annum in the past decade (although in some cases official estimates have been found to be quite tentative) (Kessides, 2006, p. 5). Estimates suggest that the amount of new urban residents is set to sharply increase between 2000 and 2030, increasing by more than 300 million people (Figure 3). This is more than twice the rate of rural population increase. Predictably, urban areas will be put under severe pressure as the demand for services, jobs and land increases (Kessides, 2006, p. 5).

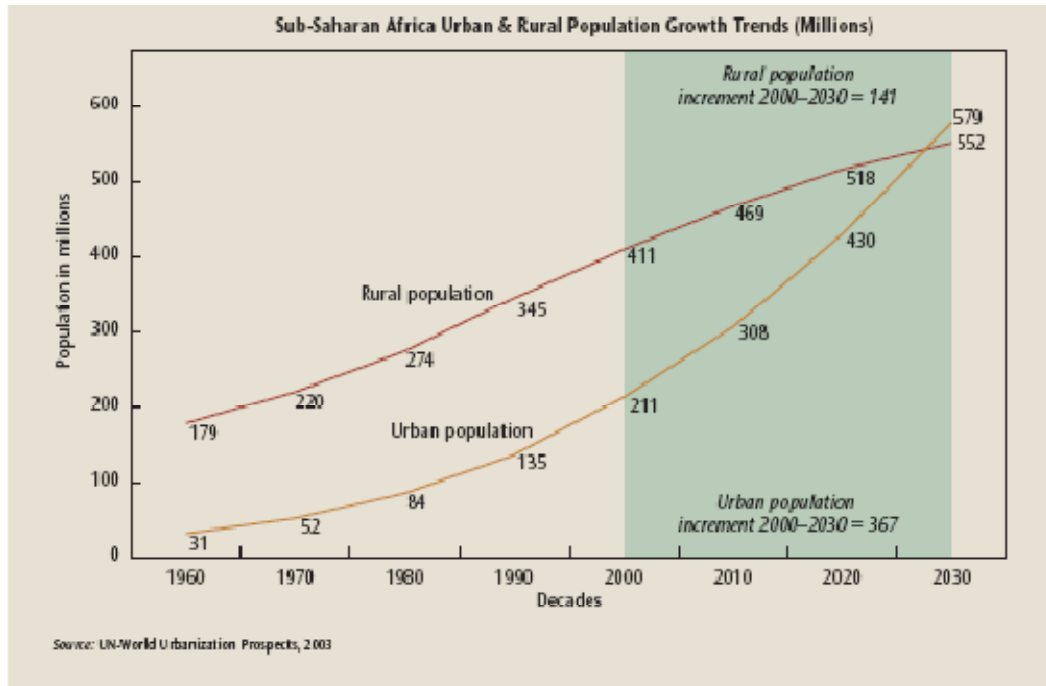


Figure 3: Population growth estimates 2000 - 2030

(Source: Kessides, 2006, p. 5)

Africa's colonial cities were developed to ease the extraction of commodities for European colonisers in the politico-administrative system. Johannesburg in South Africa was an important gold mining centre where raw gold ore was extracted and exported for manufacturing. This resulted in the expansion of many coastal cities that were already involved in international trade such as Cape Town and Durban, which were important trading ports prior to the discovery of gold (Rakodi, 1997). Traditional manufacturing managed to survive in some areas of Africa, but industrialized manufacturing was very rarely introduced, except in settler societies (Rakodi, 1997). Areas that were never directly colonised have evidence of links between their economies and the outside world and also European influence in their urban form e.g. Addis Ababa in Ethiopia. The main decolonisation period began around 1950. Cairo and Johannesburg were the largest cities with populations of 2.41 million and 915,000 respectively. They were followed by Casablanca, Cape Town, Durban, the East Rand, Tunis, Algiers and Ibadan, all with populations exceeding 400,000. Ultimately, only 15% of Africa's population resided in urban areas (Rakodi, 1997).

The urban population in African countries was highly concentrated in one or two cities, which normally included the colonial capital (Rakodi, 1997). According to Montgomery et al (2003, p. 99), these levels of urbanisation are low compared to other third world countries across the world.

The low levels of urbanisation is because many African economies are still reliant on primary economic activities such as agriculture, which is also primarily on a subsistence level (Montgomery et al, 2003, p. 99). The majority of the each country's populations are situated in the study sites due to the colonial influence in Africa. Windhoek and Gaborone are the capital cities of Namibia and Botswana respectively. Johannesburg is South Africa's economic centre due to the mining industry and its large central business district. Cape Town and Durban are important ports that also date back to the colonial period.

The urbanisation rate in South Africa has been rapid since the 1950s. By 2010, an estimated 73% of the South African population will be living in urban areas (Collins, 2001). Some of the problems associated with rapid urbanisation are increasing demand on land, water, transport services, housing and employment (Collins, 2001). This results in varying living standards throughout the cities. Apartheid has made urbanisation in South Africa even more complex, where the urbanisation of black people forced them to settle in areas on the city peripheries, far from the central business districts of main cities e.g. Khayelitsha in Cape Town, Alexandra in Johannesburg and Phoenix in Durban (Collins, 2001). The influx of black people, the majority of which were men in search of work (leaving their families in the homelands) often resulted in unplanned settlement in the peripheral areas of the city because the pass laws made it illegal for most black migrants to live in white cities. Some resorted to living in informal backyard dwellings (Christopher, 1994, p. 122; Collins, 2001).

2.2.3 Migration and Urbanisation: The urban challenge in developing countries

Migration in developing countries mainly arises from the attraction of the city compared to the rural areas from where migrants move. The attraction lies in the hopes of better access to public services e.g. clinics, schools, electricity and sanitation, as well as recreational prospects and employment. These are all considered as 'pull factors' (Wahba, 1996). These attractions are not the only factors influencing migration, some migrants move from poorer areas purely in search of economic gain. This is largely evident in the study sites e.g. Windhoek is the largest economic centre in Namibia, attracting many people who eventually settle in Katutura, a black township on the outskirts of the city (further examples from the other study sites are discussed in section 2.3). The World Bank has stated that there is a large urban-rural wage gap in developing countries (Wahba, 1996). In Africa, during the 1960s and 1970s, migration from rural areas accounted for

approximately 50% of urban growth and for approximately 25% during the 1980s and 1990s (United Nations, 1996; Brockhoff, 1996).

In 1990 the Intergovernmental Panel on Climate Change (IPCC) stated that human migration will be greatly influenced by climate change in the near future (Brown, 2007, p. 4). Climate change will influence population movement, making certain parts of the world much less viable places to live. The effects are estimated to displace millions of people, the most widely repeated prediction being 200 million forced climate migrants by 2050 (Brown, 2007, p. 4).

2.2.3.1 Socio-economic migration factors

Economic factors influence rural-urban migration, which in turn impacts on urbanisation and city growth (Wahba, 1996). Urban challenges are shared on a global scale, although characteristics of individual regions determine the urbanisation patterns and specific development challenges. UN-Habitat (2008) and the Department for International Development (DFID) (2001) has identified the major urban challenges facing Latin America, the Caribbean, Asia, the Middle-east and North Africa as well as Sub-Saharan Africa. Poverty and inequality in urban areas are an increasing phenomenon in developing countries. In 1988 the World Bank estimated that approximately 330 million urban residents were living below the poverty line, which is less than US\$1 per day. This figure has increased to 495 million people in 2000 (World Bank, 1999). Some of the highest levels of urban poverty can be traced to Sub-Saharan Africa where over 50% of the urban population lives below the poverty line (Hinrichsen et al, 2002, p. 7).

The availability of urban land is considerably important in terms of meeting the demand for housing, as well as linking the areas to networks of public infrastructure and services and recognising the need to mitigate and adapt to the impacts of climate change (UN-Habitat, 2008). High population growth rates and government control over land has influenced the demand for housing. The costs involved in conventional housing construction are frequently beyond what the majority of the poor can afford (DFID, 2001, p. 18). The Sub-Saharan Africa situation is considered one of the worst regions in the world in terms of housing. Approximately 60% of urban housing units are temporary structures, half of which do not conform to building regulations (UN-Habitat, 2001).

Other challenges include the need for employment opportunities to be created to serve as a sustainable means of income for urban residents, especially the youth. Although, one of the shortcomings of job creation is the lack of access to knowledge as well as lack of knowledge of their current situation, serving as a further disadvantage for the urban poor (DFID, 2001, p. 19).

2.2.3.2 Environmental migration factors

Urban slums such as high density dwellings e.g. high-rise apartments, squatter camps and shanty towns are areas where people illegally occupy vacant land, in most cases the areas are regarded as high risk areas unsuitable for human settlement such as flood prone regions (e.g. Khayelitsha on the Cape Flats), steep hill slopes and gullies, making them particularly vulnerable to extreme weather events, natural disasters, environmental processes and climate change. Environmental impacts on human settlements in developing countries could be far more severe than in the developed world (UN-Habitat, 2008).

Climate change is arising as a major concern for developing countries, placing increasing demands on cities (UN-Habitat, 2008). Lankao (2008) and Bigio (2003) state that rising sea levels, stronger tropical cyclones, flooding, landslides, heat and cold waves and the quality and storage of urban water is set to become an increasing challenge for urban populations. Further impacts include shoreline erosion, coastal flooding, saline intrusion of aquifers (due to sea level rise), and agricultural disruption (Brown, 2007, p. 2).

Extreme weather events mainly affect areas situated on coastlines. Between 1950 and 1990, extreme weather events associated with global warming has increased by 50% (UN-Habitat, 2008). Approximately 40% of the world's population lives within 100km of the coast and is considered to be within range of severe coastal storms. Research also shows that 13% of the world's urban population lives in low lying coastal areas, less than 10m above sea level (Lankao, 2008, p. 52), with almost 100 million people of the global population living less than 1m above sea level (UN-Habitat, 2008). This would mean that if the sea level were to rise by even 1m, many major coastal cities e.g. New York, Tokyo, Osaka, Cairo, Los Angeles, Lagos and Rio de Janeiro would be under threat (UN-Habitat, 2008).

In-migration from rural to urban areas can also be stimulated by climate change and in some cases can be regarded as 'push factors' as the change in climatic conditions could be

unfavourable to the agricultural sector, forcing people to find work in urban areas. Lower income subsistence farmers will be obligated to reside in areas such as informal settlements if they are unable to afford proper urban dwellings. The informal areas in the study sites are most severely affected by climatic events. In most cases they are situated in areas that are unsuitable for development e.g. floodplains, as they have only been chosen due to their vacancy and location e.g. along main transport routes in order to have access to central business districts and prospective employment opportunities.

2.3 The historical influence on the spatial planning of the study sites

Apartheid played an important role in the urban form and segregation of the different racial groups, particularly in South Africa. It is thus important to recognise the various Acts that were implemented during the pre-apartheid, apartheid and post-apartheid eras. Table 2 highlights the Acts that are further discussed in the literature, which influenced the South African study sites.

Table 2: Description of Acts (ranging from pre to post-apartheid) referred to in the literature
(Source: S.A. History)

Year	Date	Act	Description
1913	19-Jun	Black Land Act No 27	Prohibited blacks from owning or renting land outside designated reserves (approximately 7 per cent of land in the country).
1950	07-Jul	Group Areas Act No 41	Provided for areas to be declared for exclusive use of one particular racial group. It became compulsory for people to live in an area designated for their classification group.
1951	06-Jul	Prevention of Illegal Squatting Act No 52	Prohibited persons from entering land or a building without lawful reason, or remaining there without the owner's permission. Magistrates were granted powers to order squatters out of urban areas, demolish their dwellings and move them to a place as might be determined.
1953	09-Oct	Reservation of Separate Amenities Act No 49	Allowed for public facilities and transport to be reserved for particular race groups.
1954	01-Aug	Blacks Resettlement Act No 19	Established a Resettlement Board which would remove blacks from townships. This authorised the Sophiatown and other removals.
1986	01-Jul	Abolition of Influx Control Act No 68	Amended the 1927 Black Administration Act in order to repeal sections relating to the removal of black communities as well as individual black persons.
1990	15-Oct	Discriminatory Legislation Regarding Public Amenities Repeal Act No 100	Repealed the 1953 Reservation of Separate Amenities Act as well as various other Acts '...so as to abolish the distinction made therein between persons belonging to different races or population groups'.

In many cases, the literature refers to particular areas in the study sites e.g. Khayelitsha in Cape Town, this is because the influence of apartheid on these areas was much greater. In many cases these regions were sites where people were forced to settle when they were evicted from

other areas, giving them particular historical significance. This study however, does not attempt to address the dynamics within each city.

2.3.1 Apartheid and Urbanisation

The development of apartheid, which influenced all the South African cities, was firmly rooted in the colonial era (Christopher, 1994, p. 9). Apartheid laws enforced racial segregation on all levels of planning. The concept was to divide towns and cities into areas that were racially specific. This would force people out of their current locations and into areas designated for particular races. The desired result was total segregation to preserve white South Africa (Apartheid), which was a step above the initial segregation induced by colonial and union segregation. The black population was also subjected to further control under a separate legislation, The Natives Resettlement Act of 1954. Many blacks were forced to move to designated homeland areas, and those that remained in the city had to reside on the periphery (Christopher, 1994, p. 105).

Figure 4 illustrates a model for an apartheid city. The guidelines for demarcating boundaries were drawn up by the Durban Corporation as they have had previous experience in segregating Indian residents in the years prior to 1950. The guidelines were then adopted by the Land Tenure Advisory Board. The guidelines suggested that a sectoral pattern be adopted for each group area; each sector should also be capable of outward expansion. Each Group Area had to be separated by a buffer strip of at least 30m of open land. These buffers were to limit social contact and in many areas, rivers, ravines, industrial areas, railways and roads were incorporated into the segregation plan. The transportation routes were also limited in only having access to the most common parts of the city. The intention was for each group area to be self-sufficient in having localised facilities (Christopher, 1994, p. 106). The shape of the Apartheid cities is likely to be apparent in the earlier satellite imagery in this study, although as time progresses, the buffer areas may be less obvious.

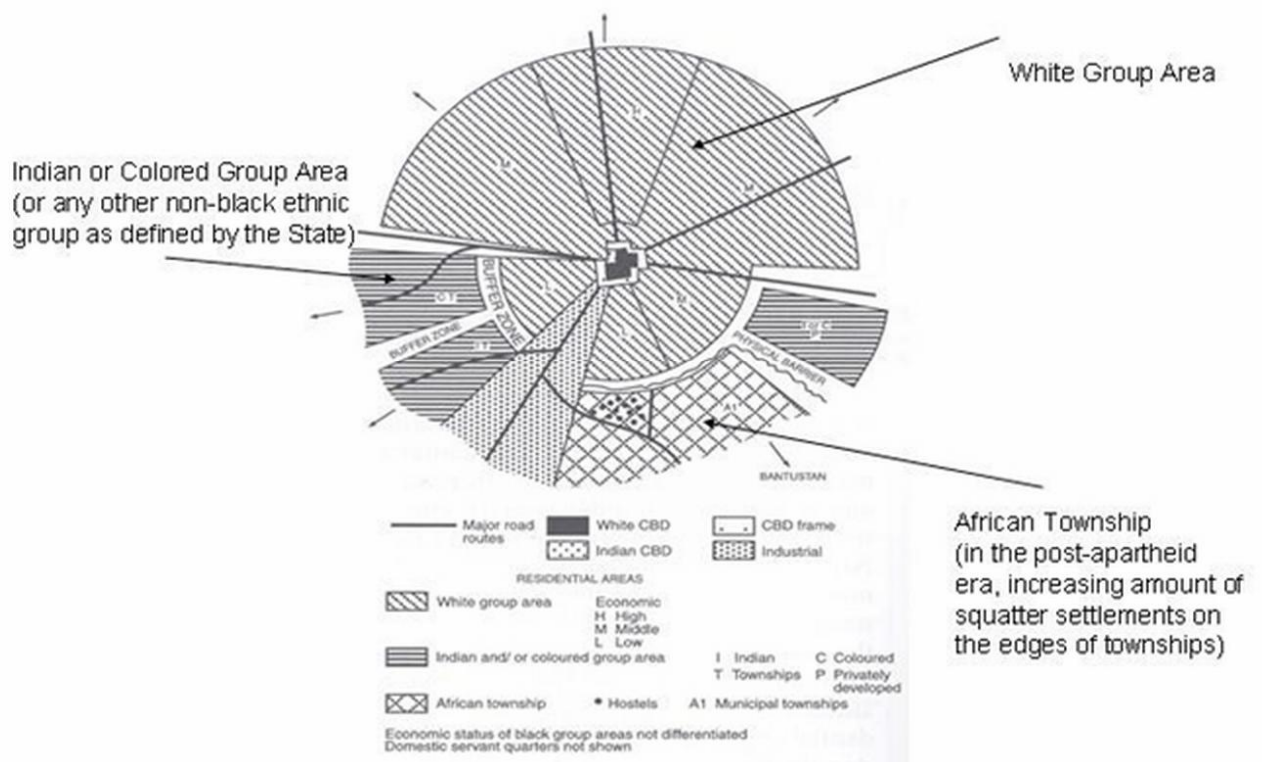


Figure 4: A model Apartheid City

(Source: Davies, 1981 taken from Christopher, 1994, p. 107)

The white population in Cape Town, Johannesburg and Durban were located nearest towards the city centre and were thus spatially as well as socially divided from the black (and coloured) populations (Spinks, 2001). The white inner-city had low population densities and was well serviced. The black and coloured areas however, were built within strict borders. High densities made living conditions uncomfortable with the majority of people living in rented state owned houses (Bertaud, 2001).

Apartheid enforced influx control systems, limiting internal migration in South Africa, especially the migration of blacks to metropolitan areas, thus affecting urbanisation levels. In most cases, only a small amount of migrant workers were permitted to move their families to the urban areas, where non-whites were settled in peripheral areas. Since 1994, the flow of internal migrants as well as migrants from other countries has increased considerably, increasing the rate of urbanisation in the post-apartheid era (Kok et al, 2006, p. 17-18). The current South African city still reflects apartheid urban planning as racial fragmentation and discontinuous land use and settlement are still evident. The spatial ordering in itself is inefficient and dysfunctional, land uses

are evidently mismatched and poor communities, usually with people of the same race, are concentrated in high density areas on the periphery (Hindson et al, 1992, p. 6).

Since 1990, South Africa has been embarking on the journey towards reconstruction, development and planning. McCarthy (1991, p. 23) states that the success of the process would be dependent on the understanding of the geographical legacy of apartheid and the scars it has left behind, and also the complex local, regional and environmental diversity that characterises the South African whole. The abolishment of apartheid has made free movement within the country possible for all residents. This has allowed for large scale migration into larger urban centres, causing large scale urban population growth and the densification and expansion of existing informal settlements, as well as the development of new informal settlements on vacant land.

The following city profiles describe the historical and present factors influencing the population and spatial planning of the study sites.

2.3.1.1 Cape Town

Cape Town was founded in 1652 by the Dutch East India Company, making it South Africa's oldest urban settlement. The area supported a variety of wetlands and rivers. The lowland portion of Cape Town was strewn with seasonal and perennial wetlands which were fed and interconnected via the groundwater system (Day, 1987). Urbanisation has resulted in most vleis to be drained and the rivers canalized. The Kuils River once meandered across the landscape with many adjacent oxbow lakes. Development resulted in the river being straightened and canalized, which also discontinued the connectivity between systems. Many vleis have subsequently dried up or have been drained and filled for the land to be developed (Holmes and Wood, 2008).

Cape Town's demographics differ to the rest of the country in that the black population does not make up the majority of the residents (Spinks, 2001). The racial distribution is predominantly coloured (44%), followed by black (34.9%), a relatively dominant white group (19.3%) and Asians (1.8%) in the minority (City of Cape Town, 2008, p. 6). The coloured majority can be partially attributed to the Coloured Labour Preference Policy (1955) and the limitation on black urbanisation. Cape Town is also the birthplace of coloured people who are the descendants of

the racial mixing. The population composition reflects the segregated history and the political influence in the area (Spinks, 2001).

Although apartheid was highly prevalent in Cape Town, some suburbs were evidently more affected than others. This is particularly noticeable in areas where people were forcibly relocated e.g. Mitchell's Plain or areas that faced total destruction such as District Six. Some of the more affected areas are discussed in this section below:

As the need for development land increased from 1973 the urban infrastructure started expanding in a northward and also north-easterly direction. The area extending north from Cape Town CBD to the urban edge, including Atlantis, Mamre, Melkbosstrand and Table View is known as the Northern Growth Corridor (NGC). The area, especially Atlantis is known for its politically motivated establishments. Atlantis was established between 1976 and 1986. At the time it fitted in with the government's decentralization policy, as well as the housing shortage the coloured community experienced in Cape Town (Warnich and Verster, 2004). Atlantis was the only land seen as suitable for the development of a coloured township as it was considered to be suitable for low income housing due to its poor agricultural and land value, also it was located relatively close to Cape Town CBD, but is also far enough to develop independently. In 1976 Koeberg Nuclear Power Station was established approximately 30 km outside Cape Town to cope with the increase in the demand for electricity in the city. Employees for Koeberg and Atlantis's adjacent industrial area were sourced from the newly established township (Eskom, 2008). Similarly the establishment of Duynfontein and Melkbosstrand into residential areas only began after the construction of the Koeberg Power Plant (Hart, 2008). The promise of housing and employment opportunities for the coloured community drew many families to the area (Warnich and Verster, 2004). The current reality is that the area has remained underdeveloped and unemployment is highly prevalent. It is a living example of the apartheid era and the policies of separate development (Warnich and Verster, 2004).

The Group Areas Act (1950) led to Cape Town becoming South Africa's most racially segregated city. More than a tenth of Cape Town's population resided in District Six up until the 1970s. In 1965 the Apartheid government declared many well established coloured areas such as District Six, Rondebosch, Observatory and Harfield Village as a white only area. More than 60 000 people were relocated from District Six alone to live on the Cape Flats (Vanderschuren, 2003). The

coloured group was forced to live in areas such as Manenberg, Heideveld and surrounding areas, with virtually no provision of basic services and long distances to travel to their places of work (Spinks, 2001). Initially blacks were already living in peripheral areas, so the initial phases of Apartheid had a minimal effect. Those that were relocated from District Six were sent to Langa and Gugulethu and in some cases back to their places of origin (Vanderschuren, 2003). By 1955 however, they were expelled to further areas such as the homelands in the Eastern Cape due to the preference of coloured labourers (Coloured Labour Preference Policy (1955)).

Mitchell's Plain was established during Apartheid in 1975 as a coloured township in order to accommodate families who were forcibly relocated to the Cape Flats according to the Group Areas Act. Initially the area was intended to provide 40 000 housing units for the families, but since then the number of residents has increased substantially with more than 300 000 people occupying the area (Ndegwa et al, 2006). Mitchell's Plain is not well integrated into the urban context. Test sites of arms manufacturers are located in the east and a waste site and perennial wetland separates the area from Khayelitsha, the neighbouring African township (Ndegwa et al, 2006).

Phillipi is a relatively new township which was developed in the early eighties with both its history and development linked to apartheid policies. Despite being considered a young township, the 2007 population estimate was 150,000 people, making it one of the largest townships in Cape Town (Adlard, 2009). The area was considered a place of refuge particularly for residents of the former Ciskei and Transkei homelands who fled to Cape Town to escape the political conflict and violence during apartheid (City of Cape Town, 2007). Another major contributor to the growth in population was when farmers in Mitchell's Plain were removed, resulting in many labourers having to relocate as they did not fall under categories of the apartheid's state racial housing relocation process (Adlard, 2009). In 1974 the first informal dwellings were erected in the northern areas of Phillipi resulting in the establishment of Crossroads and also accommodated former Transkei residents as well as people who were rejected by residents of Brown's Farm. By August 1975 approximately 1100 people were living in Crossroads, increasing to 18000 people by 1977. In attempt to control the demand for space in the area, in 1983 the government decided to create Khayelitsha to accommodate Cape Town's entire legal black population (Adlard, 2009). This involved moving all of Crossroads residents to settle in Khayelitsha. This was unsuccessful resulting in more squatters settled in Crossroads and an increase in internal conflict amongst

different groups. As Crossroads expanded, Phillipi was directly affected with the original residents being most severely impacted. As a result, Phillipi had been transformed to an apartheid battleground characterised by black urbanism (Anderson et al, 2009). Weltevreden Valley is situated in the south-west corner of Phillipi and was unaffected by the chaos and conflict occurring in Crossroads. In the north-west corner, Samora Machel was established in February 1994 with 245 informal households which increased to 425 in June 1994 and by November that year 735 shacks existed. This further increased to 1010 shacks in June 1995. From 1986 Brown's Farm had been planned by the Cape provincial Administration. The first Villages 2B, 3 and 4 benefitted from the development plans, with village 4A being the next planned development. During 1994 coinciding with the first democratic elections, site 4A was raided and within a weekend, 500 sites were occupied by shacks. Similar to Crossroads, internal tension characterised the area. The rapid influx of new residents was a reaction to the fear of losing housing space. Members of the community mobilised to prevent claimed land from being stolen (Anderson et al, 2009).

Khayelitsha was formed on the south east edge of the city around 1983 (Spinks, 2001). The black township formation was a result of the over-crowding and squatting in defiance of the Apartheid regime in Crossroads. Minimal water and sanitation services were provided to these areas. Initially, the Khayelitsha area was designated as a formal housing area. By 1993, 16,659 formal houses existed, compared to the 50,000 informal dwellings (Spinks, 2001). Census 2001 shows that the majority (57.4%) of households in Khayelitsha are shacks in the informal settlement (Figure 5; Information and Knowledge Management Department, 2005a).

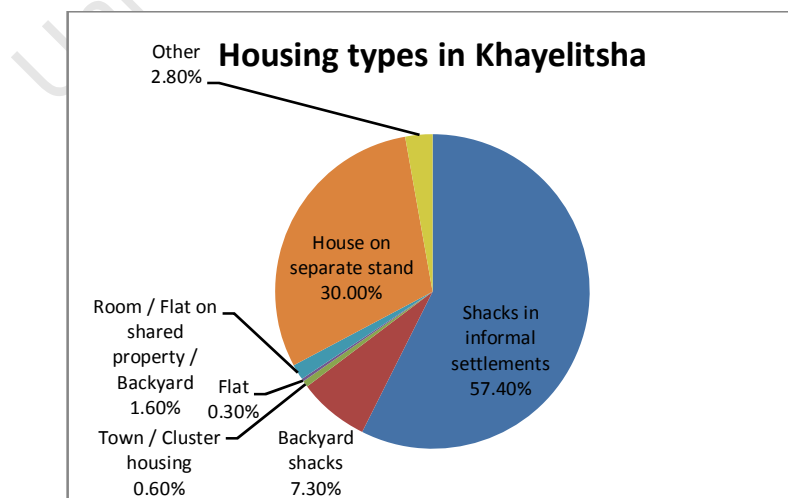


Figure 5: Housing types in Khayelitsha
 (Source: Adapted from Information and Knowledge Management Department, 2005a, p. 34)

More recently, according to Census 1996 and 2001, Khayelitsha has been identified as an area attracting migrants in search of better opportunities in the city. In-migration statistics show that approximately 6000 people are moving to the township per annum, from provinces excluding the Western Cape (Figure 6). 90% of migrants have been shown to have relocated from the Eastern Cape (Information and Knowledge Management Department, 2005a). This type of population movement dramatically impacts on census counts. In Khayelitsha, the 1996 population census indicated 249,540 people living in Khayelitsha, increasing to 329,002 people in the 2001 census. These figures imply a 5.3% per annum growth rate between 1996 and 2001. According to StatsSA (2003), these final figures probably reflect:

- an underestimation of children under the age of 5yrs
- an overestimate of children aged between 10 and 19
- an underestimate of men relative to women
- an underestimate of the white population

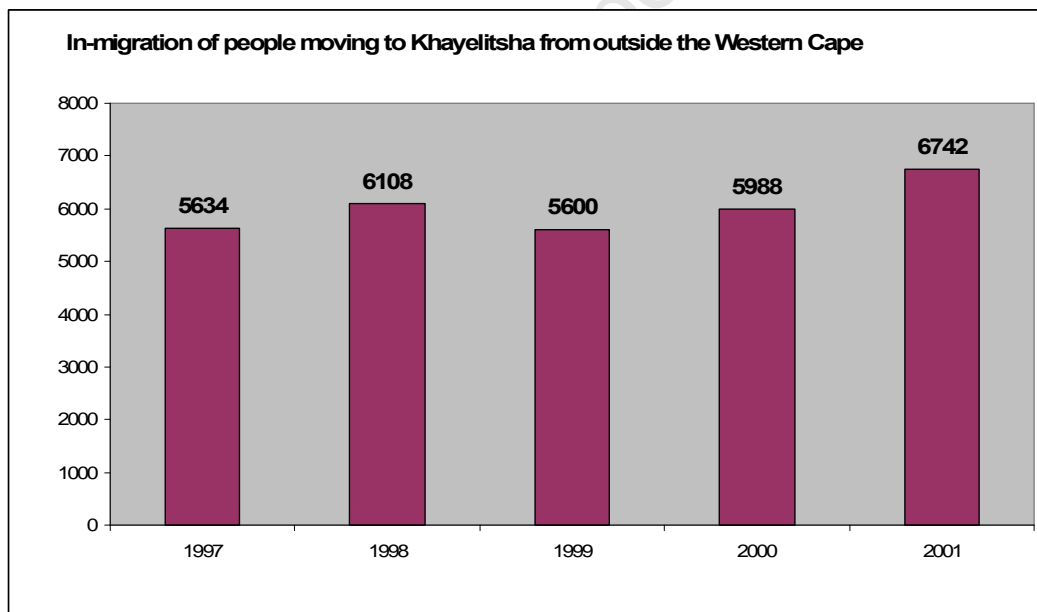


Figure 6: In-migration to Khayelitsha (excluding the Western Cape)
 (Source: Adapted from Information and Knowledge Management Department, 2005a, p. 8)

Similarly, Mitchell’s Plains’ population has also shown to be increasing due to in-migration. Census statistics from 1996 and 2001 indicates that on average, the area receives approximately 3000 new residents per annum due to immigration, 80% of which come from the Eastern Cape (Information and Knowledge Management Department, 2005b). Figure 7 illustrates the in-migration trends to the area.

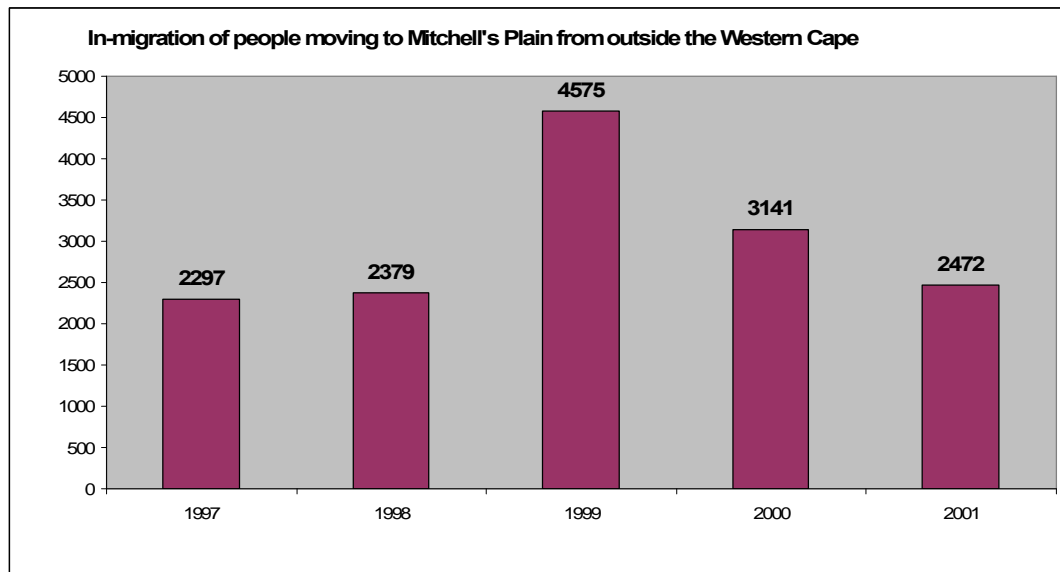


Figure 7: In-migration to Mitchell's Plain (excluding the Western Cape)
 (Source: Adapted from Information and Knowledge Management Department, 2005b, p. 8)

Based on information obtained from Statistics South Africa (StatsSA), the population density of Cape Town from 2001 was represented in figure. From the information it is evident that the Cape Flats is home to much of the population of Greater Cape Town. Particularly significant to note is the high densities in both Mitchell's Plain and Khayelitsha which are both primary areas influenced by in-migration (as discussed above).

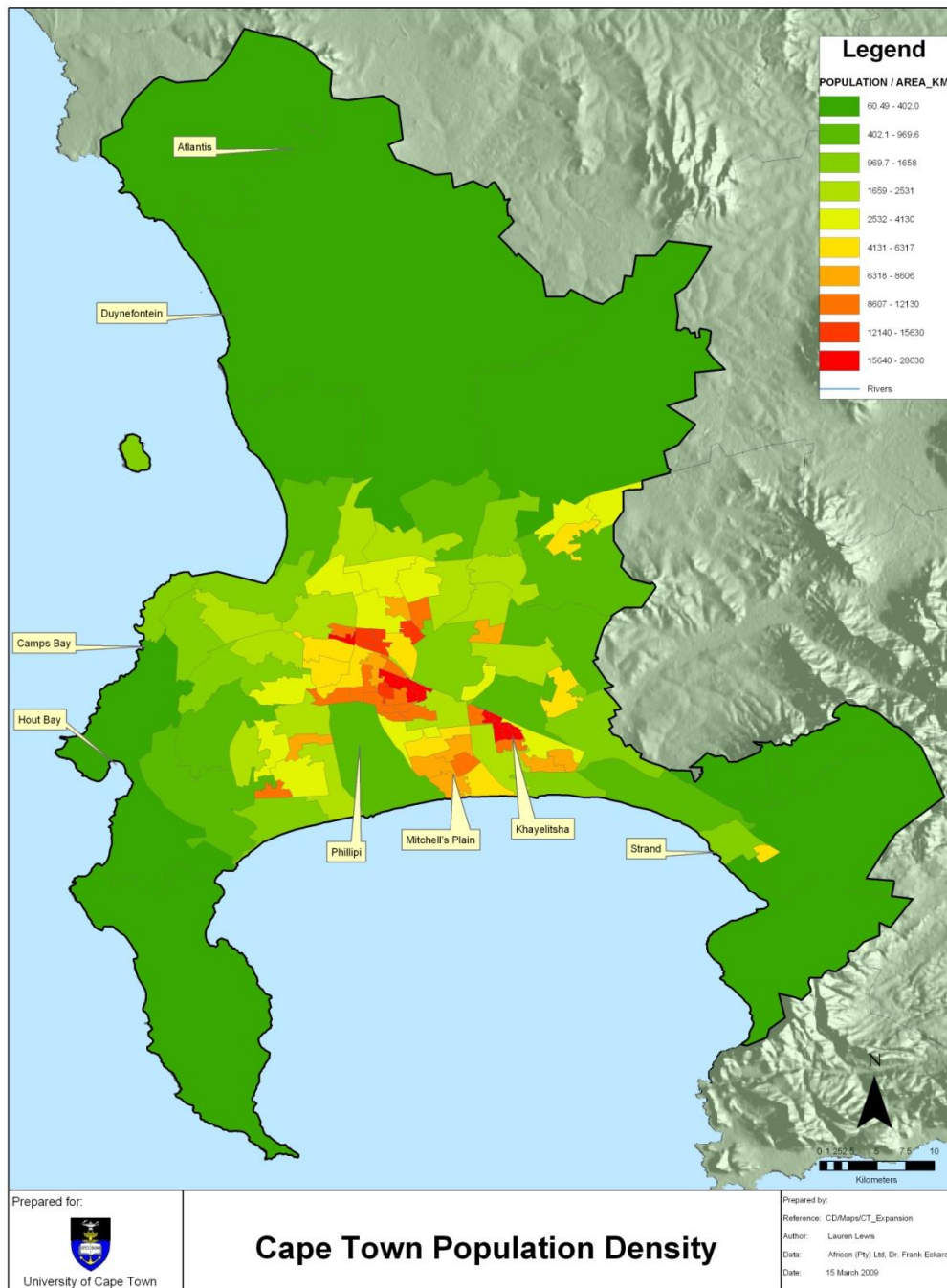


Figure 8: Population density of Cape Town based on Census 2001 data

2.3.1.2 Durban

In the mid-1800s, Durban was established as a small settlement with activities concentrated around the port. The Land Act (1913) alienated black people from most of the land, allowing the colonialists to utilise the land for agriculture and force the natives to seek wage employment as a means of survival (Marx and Charlton, 2003). Despite the suppression and containment of the indigenous Zulu people, their unwillingness to participate in poorly paid wage labour prompted the British authorities to import Indians as labourers for the sugar plantations. The labourers worked according to fixed term contracts, and once the agreed time period elapsed, many began settling around Durban, in informal dwellings, contributing to the present day cultural diversity found in the city (Marx and Charlton, 2003; Pithouse, 2008, p. 1).

From the 1920s, the manufacturing industry began to grow rapidly (Smit, 1997). The city's physical expansion can be attributed to the sugar and food processing industry as well as its transportation link to the economically favourable Witwatersrand (Pithouse, 2008, p. 12; Smit, 1997). In later years the petro-chemical industry became highly dependent on the port for importing and exporting products (Marx and Charlton, 2003).

The white minority felt that boundaries needed to be reasserted in order to better control movement and thus limit interracial interaction (Pithouse, 2008, p. 14). The city boundaries have been expanded several times which was mainly due to the attempt to control the growing informal settlements joining its borders and also to protect the economic privileges that were reserved for the white population (Marx and Charlton, 2003). Expanding the boundaries allowed the municipality to gain control of the growing informal settlements and relocate residents to dormitory locations on the city's periphery (Marx and Charlton, 2003; Pithouse, 2008, p. 16).

In 1949 the Durban City Council (DCC) acquired the power to demolish informal settlements that emerged during the 1920s (Mohammed, 2002). The informal settlements were responses to the deteriorating conditions experienced in the homelands. The Prevention of Illegal Squatting Act was passed in 1951, resulting in the Zanzibari community being the first to be relocated from the Bluff to Umlazi, followed by the shack dwellers from Cato Manor to Kwa Mashu and Lamontville between 1958 and 1966 (Pithouse, 2008, p. 17). The removals were part of a planned established township by the DCC many decades before the introduction of apartheid (Mohammed, 2002).

Four of the main established townships were Phoenix, Chesterville, Umlazi and Kwa Mashu (Mohammed, 2002). Umlazi was located within KwaZulu while Kwa Mashu was initially developed as a relocation camp, eventually being incorporated in 1977. When urban boundaries were proclaimed in the mid-1980s, the DCC directed and manipulated the process of urban exclusion. The Umlazi and Kwa Mashu were designated as 'outsiders' while the residents of Chesterville and Lamontville were threatened with relocation (Mohammed, 2002).

In 1940, Chesterville was established to provide housing for blacks. However, in 1945 all housing developments were halted as residents were threatened with removal for approximately 40 years. In 1959, under the pretext of urban relocation, some of Chesterville's residents were moved to Kwa Mashu (Mohammed, 2002).

The Umlazi Reserve was established in 1862 by the Church of England. The area was to serve as a reserve for progressive rural life for blacks who chose to partake in agricultural practices. In 1962 it was proclaimed a township when residents of Cato Manor were relocated to the area under the slum laws. Today the area is a township of shacks which have expanded outwards, accommodating an estimated 1 million people (Mohammed, 2002).

The first families occupied Kwa Mashu in 1958, managed by the Bantu Administration. In 1977 the area was taken over by the KwaZulu Natal government. Initially sugar plantations owned by Messrs Natal Estates Ltd covered the area. The land was purchased from the company's founder, Sir Marshall Campbell, a well known public figure. Kwa Mashu refers to 'Place of Marshall' (Mohammed, 2002).

Phoenix was established in 1966 with the first families settling in the area in 1976. The low income households were to accommodate families affected by the Group Areas Act and Slum Clearance Act (Mohammed, 2002). The population densities South African cities have a very prominent relationship with city apartheid racial segregation plans. This is evident in Figure 9.

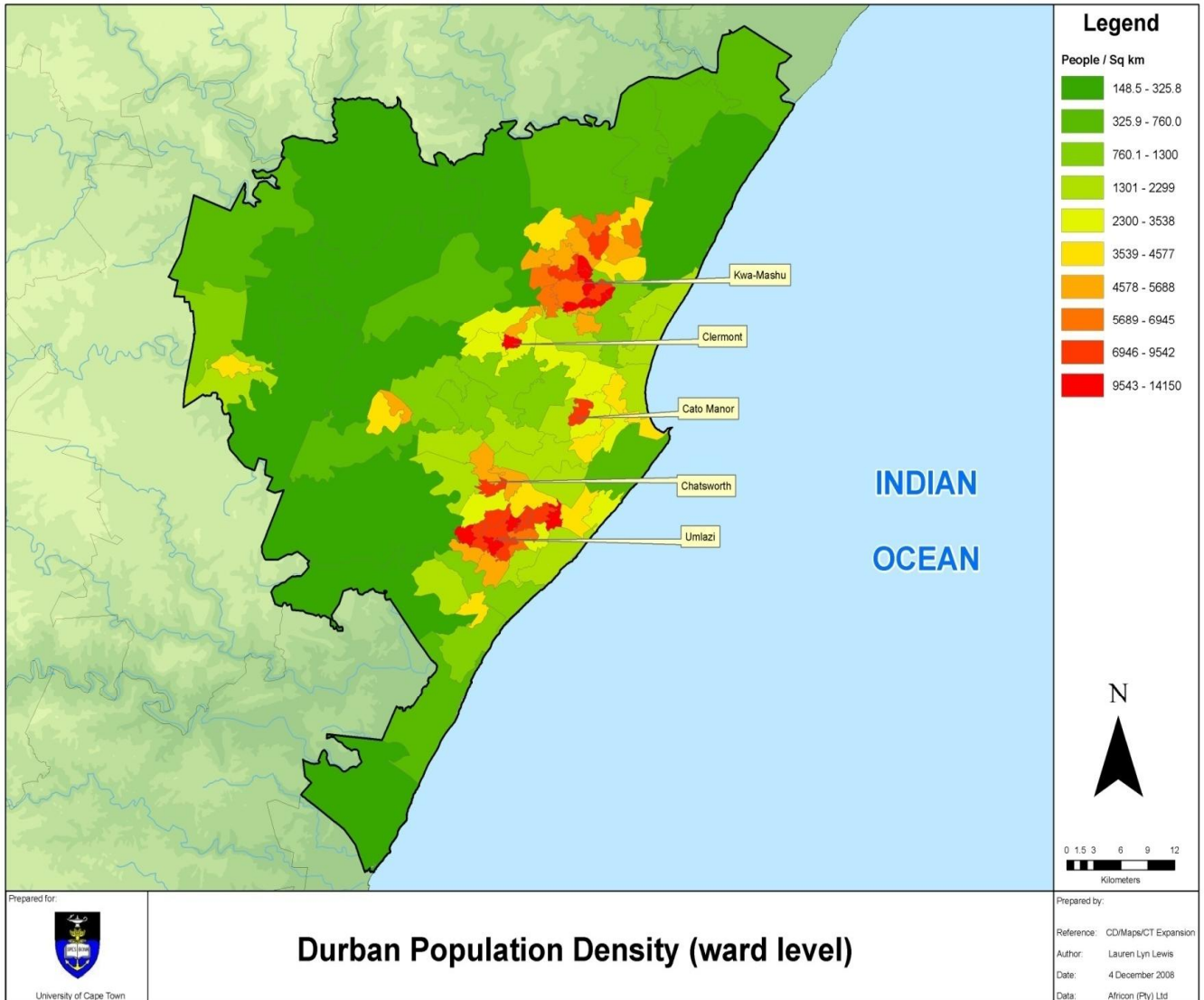


Figure 9: Population density of Durban based on Census 2001 data

Many of Durban's townships were occupied by the military by the mid-1980s, even though by that time the state had lost all the capacity to regulate the movement of black residents (Pithouse, 2008, p. 24). The formal restrictions on African urbanisation were lifted during the late 1980s towards the end of apartheid. This changed the patterns of internal migration in South Africa (Posel, 2003). Temporary circular labour migration was replaced with individuals seeking permanent residence nearer to their place of work; many cases involved the relocation of all the family members as well. This trend was also evident in Cape Town and Johannesburg. The shift towards permanent settlement meant that the payments sent to rural household decreased. The

amount of people that still chose labour migration over permanent migration has decreased since the end of apartheid (Posel, 2003). The result of this meant that the urban areas were increasing in population size and putting pressure on the infrastructure. In many cases the migrants ended up living on the periphery of towns in informal settlements.

The current spatial distribution of different races in Durban is a result of successive attempts at racial segregation. The aim was to create racially homogenous residential areas that were separated by buffers in the form of natural features such as rivers and ravines. This urban form has been achieved by removing black and Indian populations from well located areas over a time period and like in Cape Town, relocating them to the city's periphery (Marx and Charlton, 2003). The central area was also the home to the wealthiest white residents. These areas were well serviced in terms of transportation networks, communication, water and sanitation. Conversely, the poorer populations were located furthest from the amenities and economic centre (Marx and Charlton, 2003).

In terms of tourism, the Group Areas Act (1950) and Separate Amenities Act (1953) meant that the best beaches, accommodation and attractions were reserved for the exclusive use of whites. The Golden Mile is an example of the significant development scale that went into the industry (McCarthy, 1997). The attractions were also aimed at the higher income groups, which excluded the non-white population. The apartheid planning is reflected in the socio-spatial organisation of the city (Pillay, 1996)

In 2000, the post-Apartheid city borders were re-demarcated to identify the need for the redistribution of resources from the wealthy centre to the poorer areas on the periphery (Marx and Charlton, 2003).

2.3.1.3 Johannesburg

Gold was discovered in 1886 in the Witwatersrand area, giving rise to Johannesburg's regional pre-eminence. The gold mining industry's role as being a producer of profit and as an employer did not however last long beyond World War 2 (Scott, 1951). The availability of cheap black labour also contributed to maximising profits. The source areas for miners were men from South Africa (especially the homeland areas), Botswana, Lesotho, Swaziland, Mozambique, Angola, Zambia and Tanzania (Harington, 2004). In 1890, 14 000 miners were employed in the

Johannesburg area, increasing tenfold by the end of the decade. In 1986 the number of miners in the area had peaked to 534 000, decreasing by 42% in 1998 to 255 000. In the post-apartheid era large scale resettlement occurred where miners and their families migrated into Johannesburg and resettled along the Reef (Harington, 2004).

In 1945, 96% of the country's gold was produced in the Witwatersrand. The mines of the Central Rand, which were largely situated within Johannesburg's metropolitan boundaries, were responsible for 34% of the production (Scott, 1951). By 1980 Johannesburg's contribution to the national production dropped to only 3% (Fair and Muller, 1981). This was mainly due to the exhaustion of economically viable ore and the opening of new and more productive mines on the far West Rand and in the Free State. Secondary activities dominated the central Witwatersrand, and were soon followed by the growth of tertiary activities (Beavon, 1997). In recent years the mining industry has been slowly reducing their dependence on migrant labourers, with a large proportion of the currently employed miners residing near the mines (Harington, 2004).

The period between 1950 and 1970 marked the transition from primary industry to secondary industry. During the same period tertiary activities increased dramatically in Johannesburg's CBD (Fair, 1977; Fair and Muller, 1981). By the 1990s actual mining had become insignificant to the Gross Geographic Product (GGP), dropping to only 18% (Mabin and Hunter, 1993, p. 87-88). Up to 1970 tertiary services were concentrated in Johannesburg's CBD. From the mid-1970s onwards offices started to be established in the northern suburbs and neighbouring municipalities, even so, in 1993 the Johannesburg CBD contained 2.7 million m² of the top three grades of offices (Amprops, 1994).

In Johannesburg, the Natives Resettlement Act (1954) forced inner black suburbs to the periphery, and where possible, to the homelands. In some cases black populations were forced out and the land was handed over for coloured or Indian occupation. One of the most notorious removals in Johannesburg was the destruction of Sophiatown. Approximately 750,000 people were relocated to designated black townships on the outskirts of the city, such as Soweto¹¹ (Christopher, 1994, p. 122) (Figure 10).

¹¹ Acronym for South Western Townships

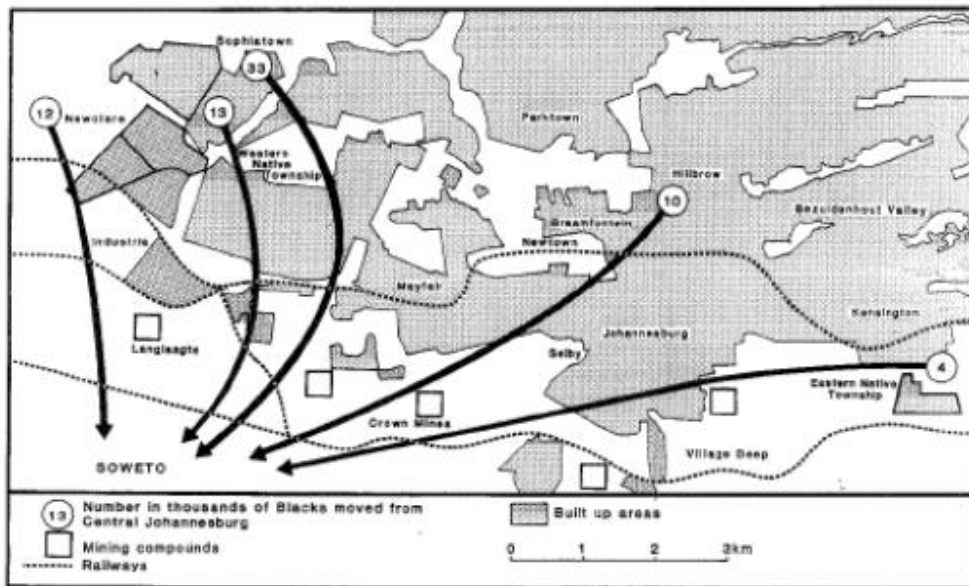


Figure 10: Johannesburg forced black removals

(Source: Christopher, 1994, p. 123)

Between 1923 and 1976, the Act severely restricted the income-earning opportunities for self-employed Black people in the townships. Seven categories of self-employed businesses were available to people residing in the townships, namely, general dealership, native queuing-houses, restaurants, milk shops, butcheries, greengrocers and hawking. These activities were also restricted to only taking place within the townships, where the amounts of these types of business were also strictly controlled (Beavon, 1989, p. 24). The ban was lifted in 1977. In Soweto, occupation of houses was only possible if the resident had worked continuously for one employer for 10 years. If the occupant took a job in another town (other than Johannesburg), they lost their resident rights in Soweto (Hlope, 1977, p. 347; Horrel, 1978, p. 174). Despite these conditions, the township continued to expand (Figure 11).

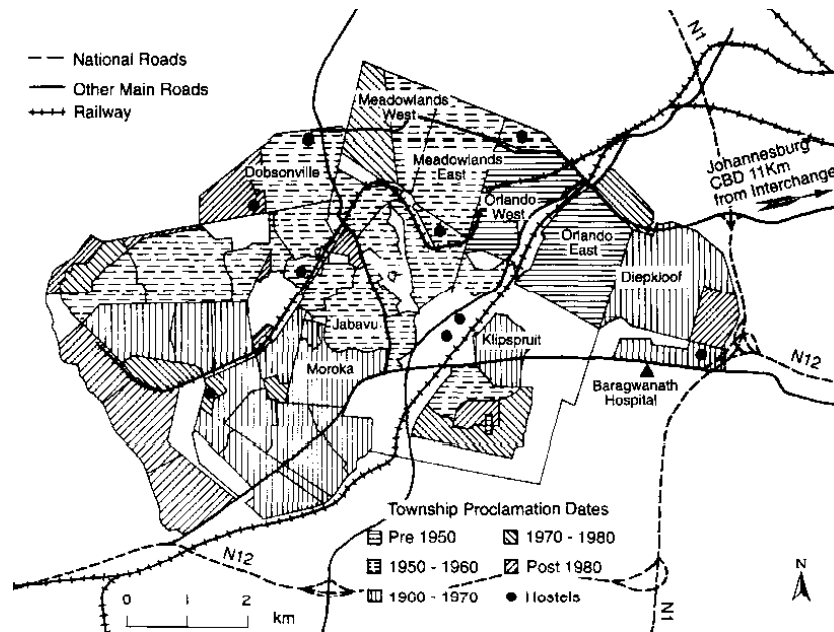


Figure 11: The growth of Soweto

(Source: Morris, 1980)

Alexandra is a township situated north of the Johannesburg CBD that survived apartheid after many negotiations that suggested the black spots amongst white suburbs be bulldozed (Davie, 2003). While many locations on the Witwatersrand were being demolished, many people relocated to Alexandra, rather than to the newly established townships on the urban periphery, such as Soweto, Daveyton, Tembisa and Vosloorus. This was due to Alexandra being less controlled than the new townships (Morris, 2000). During the 1970s, the alternative to the plan of total destruction was a redevelopment plan, whereby all the houses would be bulldozed and hostels erected to accommodate the residents. This also never materialised as many organisations protested against the proposals due to the social problems that would arise out of relocation and hostel living (Morris, 2000). The number of illegal squatters rose dramatically. In 1979, Rev. Sam Buti protested against the proposition of the relocation of black residents. As an alternative, the government decided to redevelop the area, creating a densely populated black suburb (Morris, 2000). The redevelopment plan allowed for the establishment of black middle-class suburbs called East Bank and Far East Bank. During the 1980s and 1990s, the conditions in the Old Town have vastly deteriorated (Morris, 2000).

In the 1890s, Hillbrow and Berea were established as residential neighbourhoods for middle class workers (Morris, 1999; Schmidt, 2004). The attractive location between the Johannesburg CBD

and the northern suburbs drew many property speculators to the area. By the late 1920s, the low-rise detached houses were demolished in order to accommodate three and four storey flat blocks in order to be rented to the public (Schmidt, 2004).

The second drastic change to the area came during the late 1970s due to a combination of forces. White residents began moving out of the area, partially due to the increased recruitment of white males to the military, leading to high vacancy levels (Morris, 1999). This created a pull factor for the coloureds, Indians and black residing in other areas as these population groups were experiencing severe housing shortages. In response, this became a push factor for whites to leave the area (Morris, 1999). Coloureds and Indians began moving into the once whites only suburbs in defiance of the Group Areas Act, followed by black residents (who were eager to move out of the townships) in the 1980s. Landlords who were eager to fill their vacant spaces contributed to what became known as the greying of Hillbrow. The movement drastically changed the area's demographics. By the late 1990s mainly blacks from other African countries occupied the areas (Morris, 1999). Most of these residents are economic refugees from West Africa (Leggett, 2003). The older high-rise apartments were relatively large in size (approximately 133m²), which was mainly due to the prior occupation of white middle-class residents. The space was considered extraordinarily large for the lower income residents, considering the average RDP house occupies 30m², and allowed the opportunity of subletting on a one-room-per-family basis (Silverman and Zack, 2008). These circumstances have led to Hillbrow being one of the most dense areas in the City of Johannesburg and according to Setplan Dladla Development (2004), Hillbrow (and Berea) is one of the highest density urban areas internationally, with 135 000 people living in just under 2 km² (67 500 people per km²).

Census data obtained from StatsSA allowed for Figure 10 to be reproduced illustrating the 2001 population densities. Figure 12 shows that present day populations in Soweto remain high which is a result of enforced apartheid policies and can be directly linked to racial segregation as previously described. Similarly, population densities for Johannesburg are shown in Figure 13.

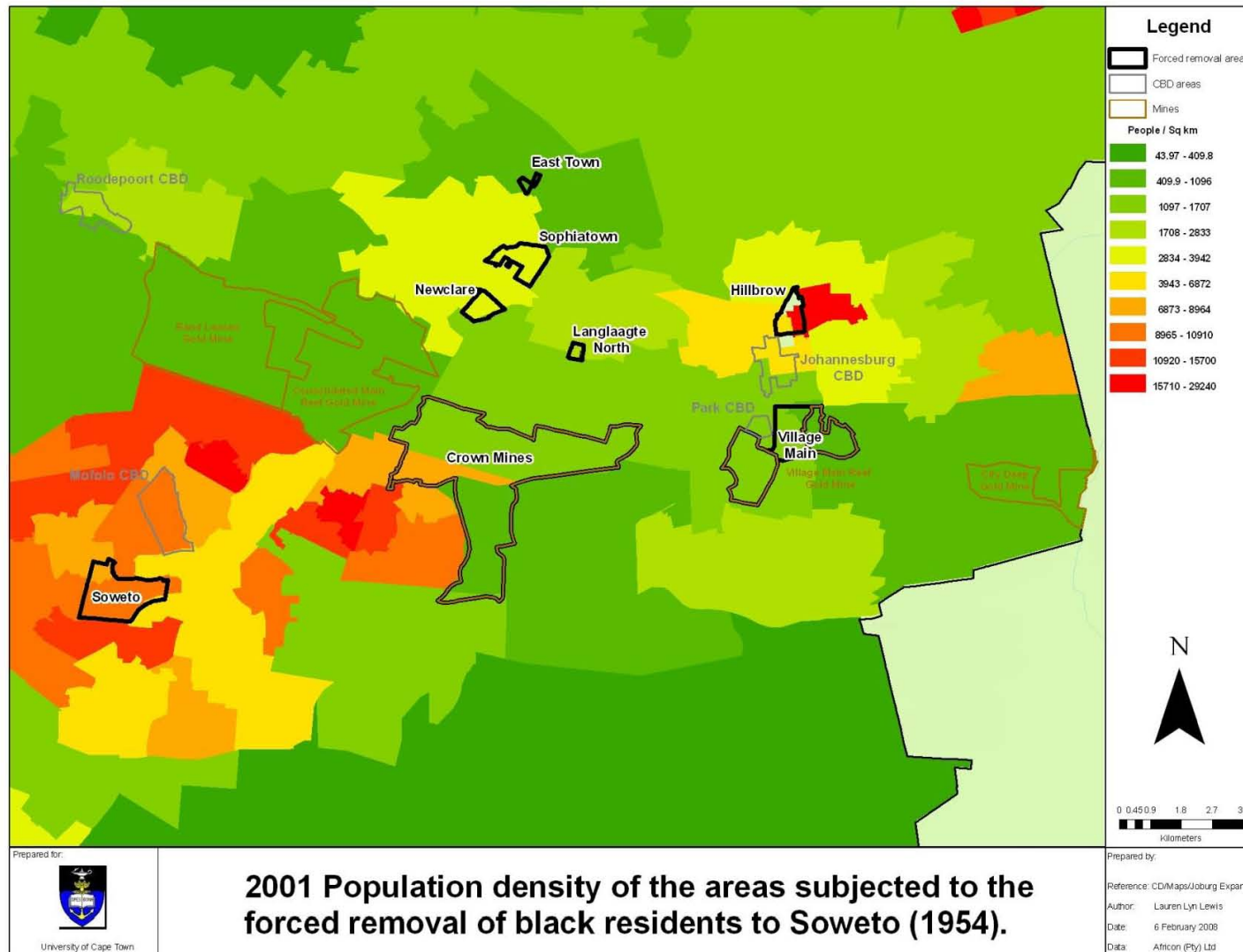


Figure 12: Population density of suburbs in Johannesburg previously subjected to forced removals: A reconstruction of the map produced by Christopher (1994, p. 123)

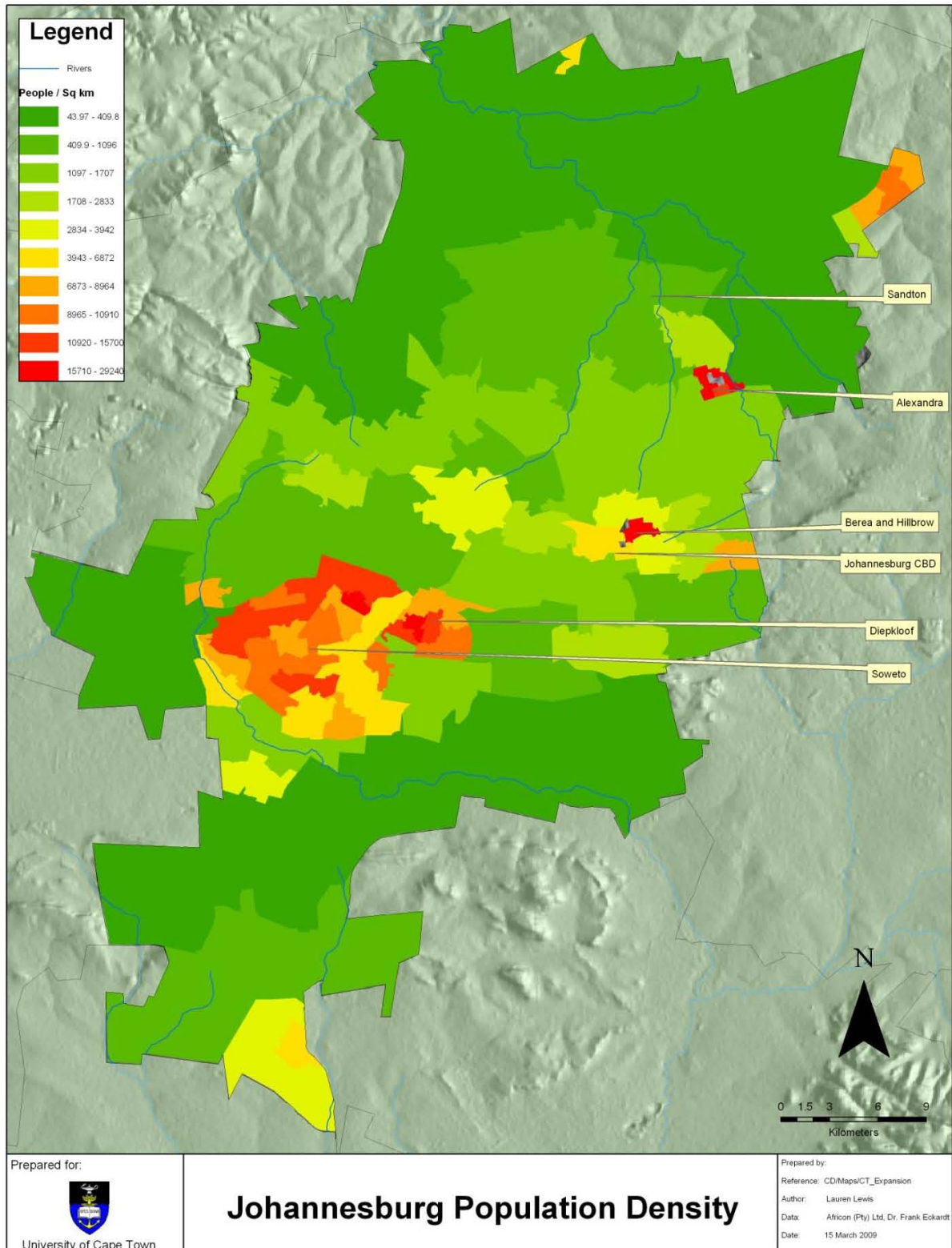


Figure 13: Population density of Johannesburg based on Census 2001 data

2.3.2 Study sites outside South Africa

2.3.2.1 Windhoek

The 18 October 1890 marked the day when Windhoek was founded by Von Francois when he laid down the foundation stone of the fort, which was known as the Alte Feste (Old Fortress). The development on the flat plain was slow, with the establishment of only the most important government and private buildings. After 1907, the rate of development accelerated as people migrated and emigrated from other areas of Namibia and other countries. A large proportion of the population influx came from Germany and South Africa (Njeru, 2008). The Germans were expelled in 1915 by South African forces (Simon, 1995, p. 139).

In 1893, the population of Windhoek was 600, increasing to 2700 in 1909 (Pendleton, 1994). The end of World War 1 also marked the end of the German colonial era when South African troops occupied Windhoek (Njeru, 2008). In 1919, Namibia was placed under South African mandate by the League of Nations (Friedman, 2000, p. 3). The city and nations development came to an abrupt halt during this period. After World War 2 development started to gain momentum again, due to the availability of more capital to improve the economic growth (Njeru, 2008). The economy was integrated closely with that of South Africa. By 1936, the population was roughly 10000, growing to 15000 in 1946 (Pendleton, 1994, p. 3). The spatial planning process included the implementation of apartheid town planning in 1948, when the National Party came to power in South Africa. The apartheid urban form was built on previous ideas of racial segregation which had been in place since the 1890s (Simon, 1995, p. 139; Friedman, 2000, p. 1) (Figure 14). In 1975, the total population reached 74500 (Simon, 1991, p. 3). During the period of South African occupation, the city was divided into three areas: Windhoek for whites, Khomasdal for coloureds and Katatura for blacks, which was the same as the apartheid town planning implemented in South Africa (Simon, 1995, p. 139; Njeru, 2008).



Figure 14: Windhoek, the Old Location and planned new townships in 1961

(Source: Friedman, 2000, p. 6)

Once Namibia gained independence from South Africa in 1990, changes in Windhoek led to dramatic accelerated growth and development (Njeru, 2008). The majority of settlement occurred around Katutura, an old black township. Windhoek's primate¹² city status as well as sophisticated infrastructure attracted secondary and tertiary activities, which also acted as driving factors surrounding the inward migration (Simon, 1995, p. 144). The majority of migrants were in the lower income category, and sought employment opportunities and a better quality of life in the urbanised region (The World Bank, 2002). Pendleton (1998) states that approximately 60% of Windhoek's population lives on approximately 20% of the city's total area, in Katutura. Between 1990 and 2000 more than two thirds of in-migration has been to the area (Frayne, 2007, p. 91). The influx also caused the establishment of informal settlements on vacant council-owned land as well as numerous service and sheltering problems for the Windhoek City Council (WCC) (The World Bank, 2002). Since independence in 1990, 67% of people in Katutura have moved to the township, 42% arriving between 1996 and 2000. The majority of migrants were born in rural northern Namibia, 79% of first generation migrants

¹² A **primate city** is defined as the leading city in its country or region, disproportionately larger than any other town or city in the urban hierarchy (Goodall, 1987).

coming from the central northern region (Oshiwambo-speaking area). This is more than double the percentage of non-migrants with the same mother tongue (Frayne, 2007). Figure 15 illustrates the main migration paths into Windhoek. Between 1991 and 1999 many formal low-income housing schemes were developed, however, in most cases the plots were still unaffordable for the majority of the poorer residents (The World Bank, 2002). The urban morphology has a direct impact on the access of the township residents to employment opportunities and amenities in the central business district (Friedman, 2000).

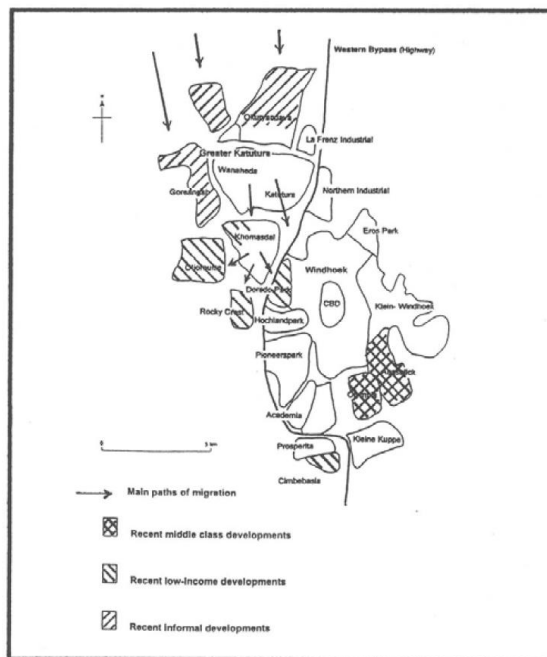


Figure 15: Windhoek's main migration paths
 (Source: Friedman, 2000, p. 16)

Frayne (2001) argues that prior to Namibia's independence in 1990, Windhoek's stabilised residents as well as the contract migrants faced enormous economic pressure (Frayne, 2007, p. 92). Previous studies show that the current situation for urban residents remains unimproved (Simon, 1991, p. 92; Pendleton, 1991, 1996, 1998, p. 92; Peyroux & Graefe, 1995, p. 92; Pomuti & Tvedten, 1998, p. 92; Frayne & Pendleton, 2001, p. 92). Employment opportunities have increased since 1990, however the volume of urban growth has a negative effect on the potential benefits for the poorer communities (Pendleton, 1998, p. 92; Hansohm, 2000, p. 92). The constraints on employment in the formal sector have resulted in an increase in the informal economy (Norval & Namoya, 1992, p. 92; Pendleton, 1996, p. 92). The competition for employment amongst the poorer residents is fierce, wages are also low and

many are forced to create their own opportunities in the urban informal sector. The sector in itself is largely underdevelopment, with a gross overemphasis on small commodity trading, resulting in oversaturation in some areas. This has contributed to increased urban poverty, which tends to be a growing phenomenon in Namibia (Freyne, 2007, p. 92).

In 2005, Windhoek's total population reached 293949 people. The main challenge facing the city is the creation of employment opportunities without encouraging more in-migration which would place unnecessary pressure on the land and water resources. There has been some evidence of efforts towards decentralisation by encouraging some industries to be located in Okahandja (Simon, 1995, p. 144). Another challenge facing Windhoek, like other Third World cities, there is a dramatic shortage of appropriately skilled labourers, especially in the technical and professional fields. This is complemented with a large number of unskilled, unemployed workers. During the 1980s the unemployment rate in Windhoek was between 30 and 45%, while in 1990 the national rate was approximately 30% (Simon, 1991; Frayne, 1992).

HIV/AIDS is also a major problem in Windhoek. An estimated 18.5% of the city's population is infected with the virus. On a global scale, Namibia has one of the highest HIV infection rates in the world (SIAPAC, 2002, p. ES1). Despite the high levels of HIV/AIDS, Windhoek's population will continue to grow, but at a much slower rate due to the high levels of in-migration from other areas (SIAPAC, 2002, p. ES3). In-migration will continually cause population growth, although the natural population growth rate will decrease due to HIV/AIDS (SIAPAC, 2002, p. 30). There will also be an increase in the death rate which will ultimately create a greater demand for burial space in the City, affecting the long term planning (SIAPAC, 2002, p. 55). City planning documents estimates that if the current in-migration growth trend persists, the Windhoek basin could be filled by 2012 (SIAPAC, 2002, p. 12).

2.3.2.2 Gaborone

Prior to 1910, investment and any administrative development were kept to a minimum in the Bechuanaland territory to the extent that it declined to be a mere adjacent member of South Africa. The purpose was to provide migrant labour and rail transportation route to Rhodesia (later Zimbabwe). During the 1930s there were short-lived disputes to improve administration and commence mining and agricultural activities (Parsons, 1999). The Tswana chiefs rejected this idea as it would enhance colonial control and white settlement. The territory remained

divided into the eight tribal reserves (which were largely self administering), five white settler farm blocks and the remainder was classified as state land (Parsons, 1999).

In South Africa's interest, the extent of Bechuanaland Protectorate's subordination was revealed in 1950. The British government banned Seretse Khama from the chieftainship of Ngwato and exiled him for six years due to a case that caused political controversy in Britain. It was revealed in secret documentation that this was in order to satisfy the South African government which objected to his marriage to a white woman when racial segregation was being reinforced in South Africa under apartheid (Parsons, 1999).

From the late 1950s it was clear that Bechuanaland (later called Botswana) needed to develop towards political and economic self sufficiency. After much resistance to constitutional advance before economic development could pay for it, the British began to set the movement towards political change in motion in 1964. The new administrative system was built at Gaborone (Parsons, 1999). Bechuanaland became self governing in 1965 and in 1966 the country became the Republic of Botswana with Seretse Khama as the first president.

When Gaborone was designated as the capital, it was the least populated urban area in the country. In 1962 the only existing infrastructure included a railway line and station, a hotel, a store and the Government Camp located approximately 3.5km east of the existing infrastructure (Mosha, 1996, p.120). In 1964, only 3855 people occupied the area, making it free from occupation by distinct indigenous ethnic groups that could claim ownership and also free from segregated working classes that could easily be politicised (Maudeni, 2003, p. 2; Sebege and Seane, 2008). When it was decided that the capital was to be relocated from Mafikeng, South Africa, preference was given to Gaborone village over Lobatse due to the fresh water source, railway line to Pretoria and lack of association with surrounding tribes (Njeru, 2009; Seth, 2008). Lobatse was home to Botswana's high court and national abattoir and was also equally as administratively competent as Gaborone District. The residents were highly politicised, having strong links with South African liberation politics (Maudeni, 2003, p. 2).

The new capital had to be politically, administratively, economically and culturally developed. Initially four main areas existed, namely Gaborone village, White City, Bontleng and the Mall

There was little room for expansion in the first three areas mentioned because they were already occupied. The Mall however was new and therefore designated as the political, cultural, economic and administrative centre area of the town (Maudeni, 2003, p. 4). The areas surrounding the mall were designated as different types of residential areas. The Northern area had the largest plots an average density of 2 to 4 homes per hectare. This was a high cost residential area. Between the Mall and Kaunda Road, the middle area was designated as a medium density zone with 5 to 12 houses per hectare. The south was a low cost area also reserved for residential development. The density exceeded 12 houses per hectare (Maudeni, 2003, p. 4). Segregation of income groups began in 1984, followed by the government instating a policy of non-centralisation to be adopted in the design of the development plan to prevent spatial polarisation within the city (Maudeni, 2003, p. 15).

Gaborone City includes a few tribal villages namely Tlokweng and Oodi in the east, and Mogoditshane, Metsemotlhabe and Gabane in the west. These villages that used to be situated on the periphery of the city were influenced by the growth of Gaborone and have reached the status of being called suburbs, even though their land tenure is still tribal. The northern area is bordered by the Bakgatla tribal land and the south is surrounded by freehold farms (Sebego and Seane, 2008). Despite the land tenure status, these areas are all included as part of Gaborone City, occurring within the demarcated administrative boundaries. The Ministry of Lands, Housing and Environment (2001) has stated that the implementation of the non-centralisation policy has resulted in a balance, well-integrated and socially healthy community (Maudeni, 2003, p. 15).

As a result of the intensive rural-urban migration, economic diversification, and the expansion of small traditional settlements into urban villages and small towns, urban agriculture has begun to occur on the rural-urban fringes (Mosha and Cavric, 2000, p. 1).

Gaborone's population has increased from approximately 3800 in 1963 to 18799 in 1971, 59657 in 1981, and more recently, 133500 in 1991 to 224000 in 2001 (Maudeni, 2003, p. 6; GoB, 2002, p. 18), indicating that the total population has almost doubled in ten years. This type of economic and population growth is unprecedented, posing challenges such as the need for land, housing and infrastructural services in the city. The demand for various resources is increasing, reducing the ability of the Gaborone City Council (GCC) to cope. The

service demands have also quadrupled in recent years, forcing the GCC to forge partnerships with the private sector in terms of service delivery (Mosha, 2004). The growth of the population has resulted in the physical expansion of the urban area to cover approximately 169 square kilometres, taking up most of the undeveloped land (Maudeni, 2003, p. 6). The Ministry of Local Government, Lands and Housing is in charge of town planning and land management and constantly working towards keeping up with the pace of rapid urbanisation. Several urban development policies have been developed over the years in order to guide the growth and development of urban areas (Mosha, 1996, p. 118).

University of Cape Town

2.4 Remote sensing in urban applications

2.4.1 Monitoring urban growth using remote sensing

On a global scale growing municipalities are in need of accurate information regarding the extent of urban growth for purposes such as urban planning, resource management and service delivery in order to assist in long term planning to assess future demands.

Conventional survey and mapping techniques for monitoring and the estimation of urban sprawl are both expensive and time consuming, particularly in developing countries where access to resources and information can sometimes be a challenge. As a result, there has been an increase in research interests directed towards both monitoring and mapping urban growth using GIS and remote sensing techniques (Epstein et al, 2002).

Remote sensing offers measures for a variety of dependant variables relating to human activity. The more prominent analyses highlight the particular environmental consequences of a variety of social, economic as well as demographic processes (Liverman et al, (ed) 1998).

Remote sensing is variably defined, but the following two definitions adequately capture the concept of remote sensing as to be used in this study. Remote sensing is ~~the~~ the gathering and recording of information from a distance, developed as a result of space technology (Elliot, 1992), and in more detail Jenson (1996) describes remote sensing as ~~the~~ the process of collecting data about objects or landscape features without coming into direct physical contact with them. Most remote sensing is performed from orbital or sub-orbital platforms using instruments which measure electromagnetic radiation reflected or emitted from the terrain (Jenson, 1996). For further details of the process, see Angel et al (2005a).

The availability and access to remotely sensed data can proved to be challenging and/or expensive depending on the data requirements, however, in this study these challenges as well as the temporal requirements were fully met. The Landsat images were obtained from the United States Geological Survey (USGS) and Global Land Cover Facility (GLCF), who freely distributes decadal Landsat images.

Classifying urban areas pose many difficulties, and this is equally true of a remote sensing approach. Urban change detection using remotely sensed satellite imagery requires precise

image classification results which are important for many socioeconomic and environmental applications (Lu and Weng, 2005). Producing satisfactory classification images using remotely sensed data is a challenging task, with many factors that need to be taken into account. The urban landscape itself is highly complex, being composed of features that are sometimes (or frequently) smaller than the sensor's spatial resolution, such as buildings, roads, grass, trees, bare soil and water bodies (Lu and Weng, 2005). However, using coarse resolution satellite imagery e.g. Landsat Multi-Spectral Scanner (MSS), features become distorted at larger scales, creating more generalisations of areas. Medium resolution imagery will have less generalisation as the pixels are smaller, thus covering a smaller area. The features will also be more distinguishable at larger scales, allowing mixed pixels to be identified easier. Mixed pixels (mixels) are individual pixels that contain more than one land cover type e.g. vegetation and infrastructure occurring in the same pixel, and is common in Landsat TM and ETM, both of which have a medium spatial resolution between 10m and 80m. This also accounts for the reduced accuracy in urban land classification. The mixed pixel issue is especially prevalent in residential areas where a combination of buildings, trees, lawns, concrete and asphalt can occur within a single pixel (Lu and Weng, 2005). In terms of the analysis, the spatial resolution requirement is thus partially fulfilled as the adequate spatial resolutions were available for the Landsat TM and ETM+ images, while the earlier images were only available in the coarser resolution Landsat MSS images, which were less appropriate for this type of study.

The complexity of the urban landscape and the variability between areas does not allow for a formal classification method. Every area that is being classified has its own urban characteristics e.g. different surfaces have different spectral signatures which can become complicated in being able to differentiate between surfaces that have very similar signatures. Consider bands where bare soil, sand and aged concrete have very similar percentage reflectance in many Landsat bands, this is also noted for asphalt and agricultural soil (Figure 16). Another problem to note is the shade/shadow caused by steep slopes in more rural and mountainous regions or tall building and other structures in urban areas. The shadows appear as black regions in the image, the same as water bodies. This is because water has quite a low reflectance in the visible spectrum (Angel et al, 2005, p. 31 - 48). In the study, the spectral requirements were fully met due to the sensors having all the required bands necessary for the analysis of the urban areas.

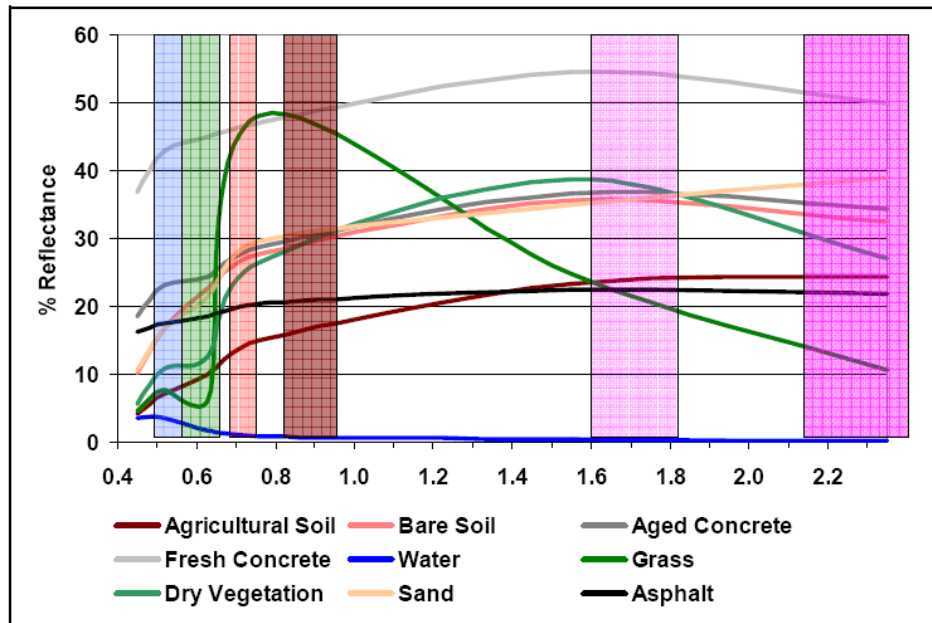


Figure 16: Spectral signatures of sample cover types and Landsat TM/ETM bands

(Source: Angel et al, 2005a, p. 36)

Specifically to urban areas, factors associated with image classification is the availability of remotely sensed data, the characteristics of the study area, understanding and properly using variables and classification algorithms, time constraints and lastly the knowledge and experience of the analyst.

Numerous studies have been conducted on a global scale in attempt to measure urban areas using satellite imagery. Although many of the studies are feasible, the methodologies used in localised studies are often not practical enough to be applied to other regions. An important attribute to note is that in the cases where Landsat satellite imagery is used, the authors focus on large study sites i.e. conducting their analyses at smaller scales e.g. city wide areas. This supports previous statements regarding the required spatial resolution of images needed for various size study sites.

A variety of techniques were used in various studies in order to determine urban growth over a time period. For the purpose of this study, the following methodologies were considered as potential processes to follow in order to calculate the urban expansion in the study sites. One of the selection criteria for the methodologies is that they can be applied to the coarse to moderate resolution of the Landsat TM, MSS and ETM+ imagery. From the literature,

supervised and unsupervised classification (specifically ISODATA and k-mean algorithm) appears to be the most frequently used technique in remote sensing analyses for the identification and classification of urban areas. The basic principle is that pixels with similar spectral reflective characteristics are grouped into distinct clusters.

2.4.2 Image classification techniques

The objective of an unsupervised classification is to group multiband spectral responses into statistically separable clusters, as illustrated in Figure 17 (e.g. forest will be grouped together, bare soil will be grouped together) (Nicholas, 2007). The more classes that are assigned to the unsupervised classification, the more variability between spectral signatures will be determined by the software. For example, if 5 classes are assigned, 5 clusters will be determined with each pixel falling into one of the five classes depending on its spectral signature, similarly, if 50 classes are assigned, 50 clusters will be created (Angel et al, 2005). The grouping of the pixels into the defined amount of classes will result in some confusion between pixels e.g. one pixel may be made up of 20% grass and 80% urban area. In these cases the pixels will be generalised and be classified according to the feature that occupies the largest proportion of the pixel i.e. if 20% of the pixel depicts grass, and 80% urban, the pixel will be considered to be an urban pixel.

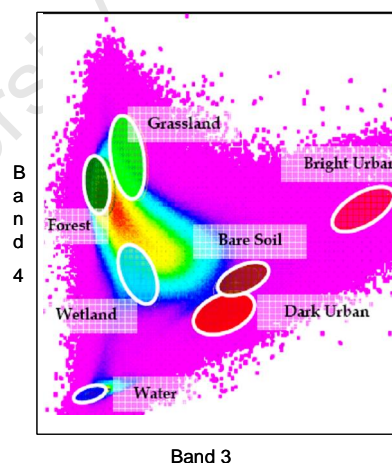


Figure 17: ETM pixel brightness values for bands 3 and 4¹³.
 (Source: Angel et al, 2005 (corrected by author, 2008))

The supervised classification method differs from unsupervised in that the user knows beforehand which classes are present in the scene. These areas are identified and marked as training sites and the statistical analysis is performed on the multiband data for each class.

¹³ Each ellipse shows the mean vector and standard deviation for different cover types.

This results in class groupings instead of clusters, where each class group has an appropriate discriminating function that distinguishes the different groups. The pixels outside the training sites are compared with the class discriminants (obtained from the training sites), and each one then being assigned to the class it is closest to, creating a map of established classes. In most circumstances there will be a few undefined pixels (Nicholas, 2007). A diagram illustrating the differences between supervised and unsupervised classification methods are displayed below (Figure 18):

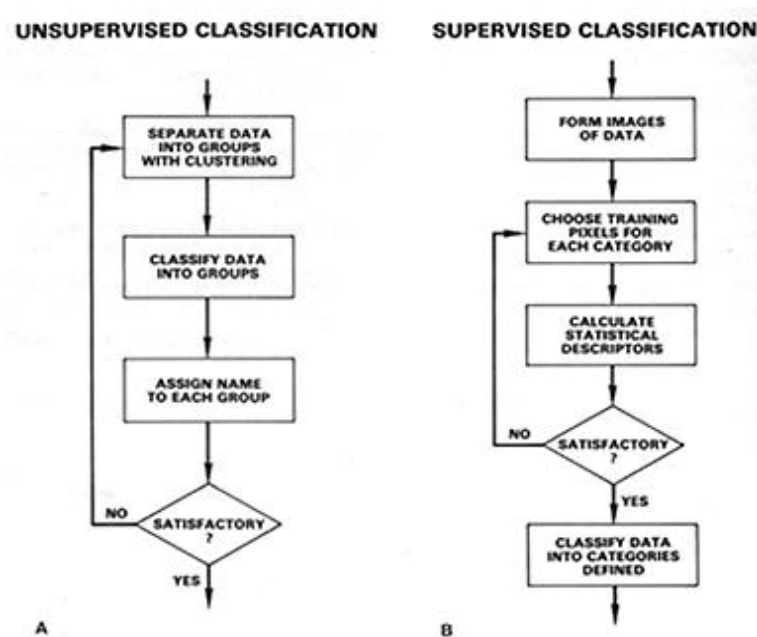


Figure 18: Unsupervised and Supervised classification

(Source: Nicholas, 2007)

2.4.2.1 Studies using Unsupervised Classification Techniques

The most simplistic approach is that used by Schneider (2007) who used a multi-date k-means clustering of the stable and change land cover classes. The premise of the technique is that the new change classes should have distinct combinations of change classes and therefore be separable from the other spectral signatures. A segmentation algorithm was used to exploit the correlation between the neighboring pixels and aggregate them into polygons (Schneider, 2007). The resulting polygons were combined with the class maps and labeled according to the classes occurring inside each polygon using a majority rule method i.e. if the majority of the classes inside a polygon are classified as urban then the polygon would be classified as urban (Schneider, 2007).

Another popular technique is the use of unsupervised multi-temporal classification using the ISODATA algorithm (Menz and Bethke, 2000). The basic idea behind the ISODATA algorithm is a procedure involving the splitting and merging of clusters (Mather, 1989) (Figure 19). The user supplies an elongation criterion which is used to decide if the standard deviations of the clusters are \geq a certain value. If a cluster has a \geq standard deviation, it will be split in half along a line which is perpendicular to the feature axis. This results in new cluster centre positions. The pixels are then relabeled with respect to the new centroids. The process repeats itself until no more clusters can be split or merged. At each cycle, cluster centers with less than a specified number of pixels are eliminated. These pixels are either placed back into the pool to be potentially relabeled in the following iteration or are ignored as unclassifiable (Mather, 1989). In the study, 13 land cover classes were obtained, two of which were for water (which were subsequently merged to obtain one water class). Clusters that were identified to have similar seasonal NDVI were merged (the minimum and maximum NDVIs were taken into account), resulting in 10 cover classes (Menz and Bethke, 2000). The resulting clusters were transformed into thematic classes based on the statistical characteristics, spatial distribution as well as on previous knowledge of the study site (Menz and Bethke, 2000).

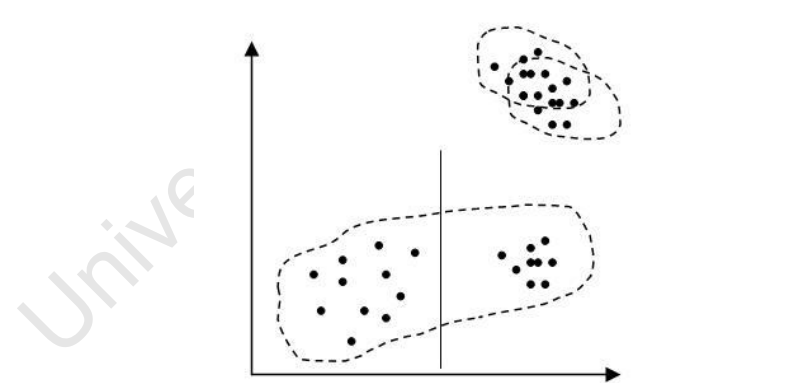


Figure 19: Unsupervised Classification
 (Source: Mather, 1989)

Angel et al, (2005) uses an initial similar approach as Menz and Bethke (2000). An unsupervised classification and ISODATA clustering was used to create 50 spectrally separable classes (clusters). Each cluster was placed into one of seven pre-defined cover classes. Some pixels were classed as \pm undetermined \pm and were subsequently re-clustered. These pixels were mainly defined as mixels where mixture of land classes (e.g. urban and barren land) occurring in the same pixel (Angel et al, 2005). Apparent errors were rectified by

on screen editing (heads up digitizing). The final output involved extracting the urban pixels as one class and all the other classes grouped together as a single non-urban class. The binary data set made it easy to calculate the amount of urban expansion that had occurred, simply by subtracting the earlier image from the later one (Angel et al, 2005). The results of the urban extraction using Landsat images were compared to EarthSat's Geosat Land Cover product (Figure 20) as well as to Socioeconomic Data and Applications Center (SEDAC) nightlight classification (Figure 21). Although, since the two results displayed in Figure 21 illustrated for comparative purposes where not represented at the same scale, an accurate comparison cannot be made. The study was aimed at developing a detailed classification of developed or built up land (Angel et al, 2005).

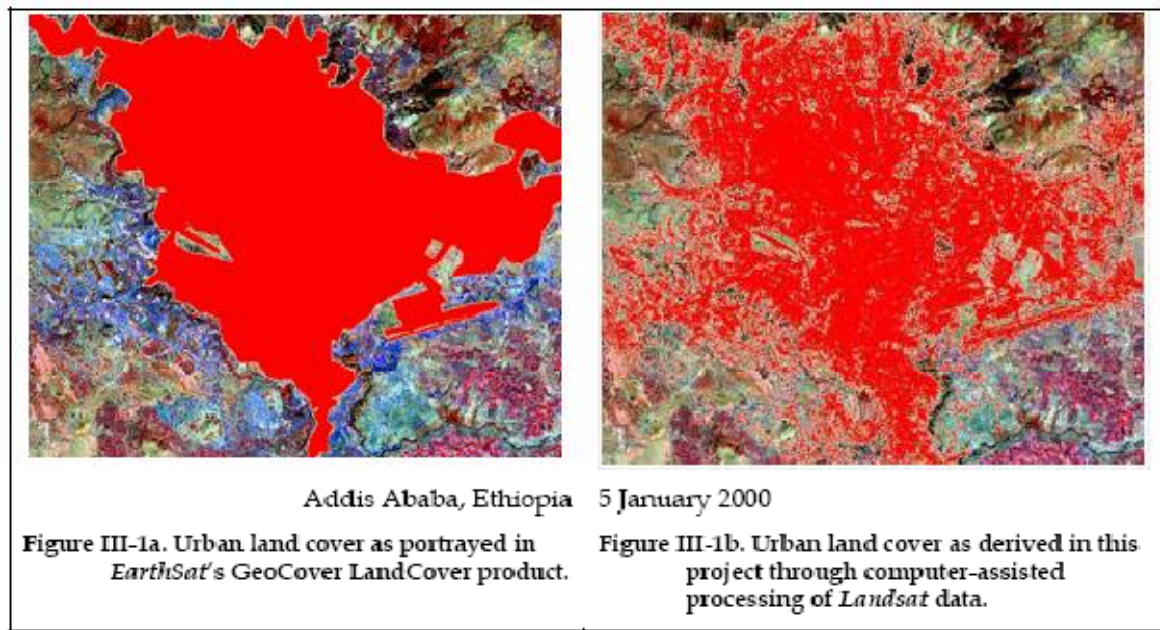


Figure 20: Comparison between EarthSat's Geocover and the derived developed area from Landsat data
 (Source: Angel et al, 2005)

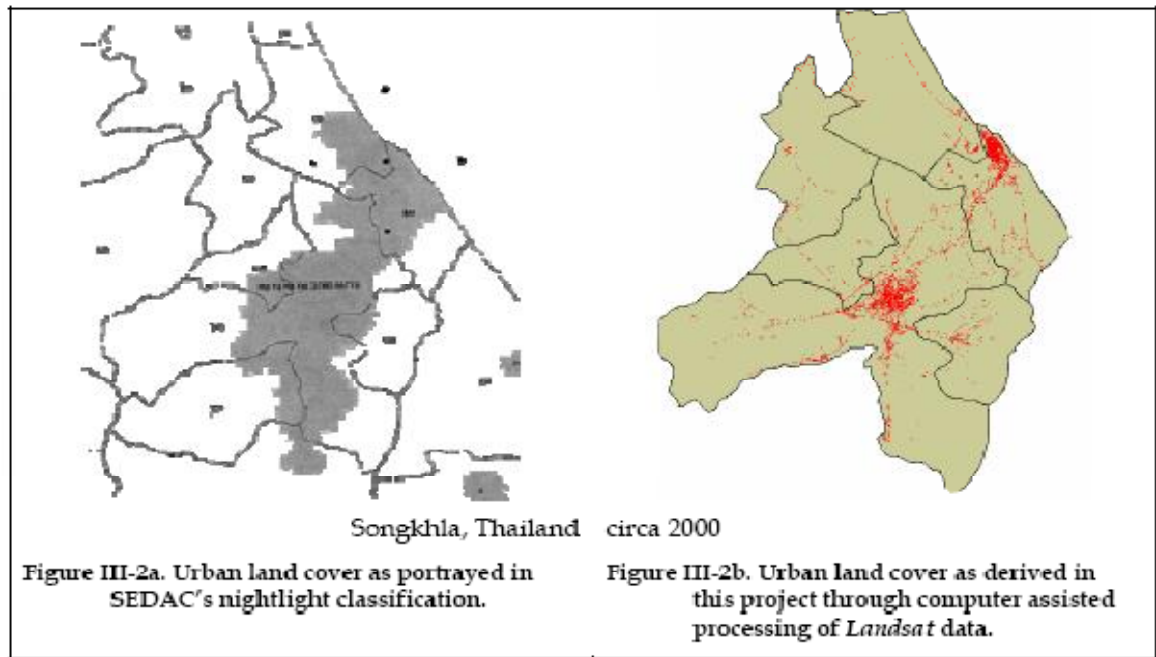


Figure 21: SEDAC's nightlight classification and derived developed areas from Landsat data
(Source: Angel et al, 2005)

2.4.2.2 Studies using Supervised Classification Techniques and Decision Trees

Schneider et al (2003) made use of image processing and change detection using supervised methods. The study used eight Landsat TM images dating between 1978 and 2002 (WRS path 129, row 39). Each tile covered the entire study site. The focus was to determine the amount of land that change to urban use, therefore the primary stable classes were urban, natural vegetation, agriculture and water. During the image processing, bands 4, 3 and 2 were set to red, green and blue respectively, where vegetation appears red, and the city areas appear blue (Schneider et al, 2003). The supervised multi-date change method was then used to map the stable and change land cover classes using a supervised decision tree classification algorithm. The decision trees are becoming increasingly popular in remote sensing change detection problems because of their ability to cope with missing or noisy data. They also do not rely on apriori assumptions regarding the input data and are able to handle complex, nonlinear relations between the features and the classes (Schneider et al, 2003).

In another study conducted by Schneider et al, (2003), night time lights data was combined with grid population density data in a logistic regression model, producing a probability surface for urban areas. A decision tree algorithm was trained on a global set of training sites for 17 land classes (including an urban land class) which was defined by the International

Geosphere-Biosphere Program (IGBP). The trained tree was applied to MODIS data. The output provided the per-pixel probabilities for each of the 17 classes (Schneider et al, 2003). The final stage involved applying Bayes rule to every pixel. The Bayes rule is described by Howson and Urbach (1993) as showing how one conditional probability e.g. the likelihood of an observed hypothesis given observed evidence, is dependent upon on its inverse e.g. prior to the likelihood of the evidence, given the hypothesis. In order to accomplish this, the probabilities of urban areas that were previously derived from the logistic regression, were used as the known probabilities. The final output was the fusing of all the data sources to create a final map of urban areas (Schneider et al, 2003).

Thapa and Murayama (2006) used ERDAS Imagine 9 software to apply the supervised classification techniques to the Landsat imagery covering the Kathmandu Metropolitan, Nepal (1989, 1999 and 2005), using maximum likelihood classifier. Five land use classes were identified namely urban built up area, cultivated land, orchard, water and natural vegetation (Figure 22). The quantitative results were illustrated graphically to show how each class fluctuated over the time series (Figure 22, far right).

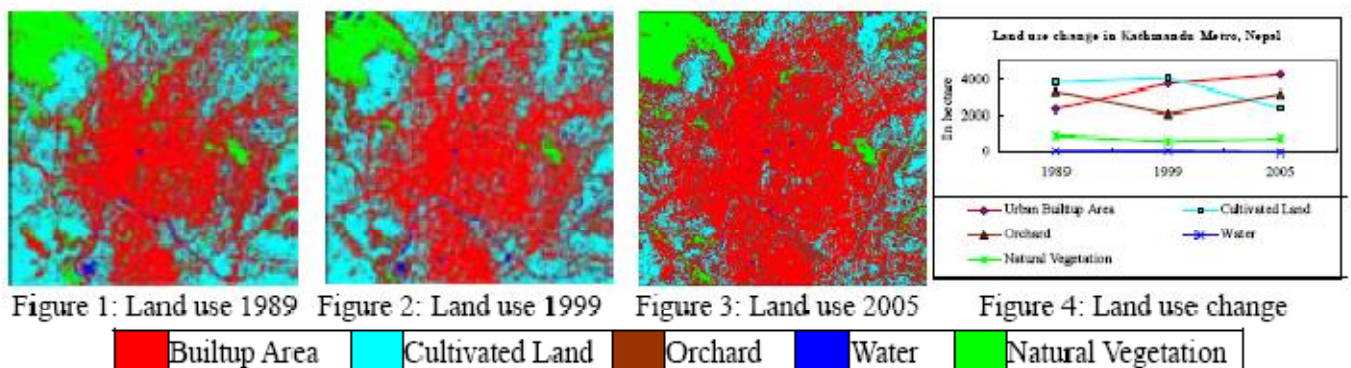


Figure 22: Results obtained from the study

(Source: Thapa and Murayama, 2005)

Elnazir, Xue-zhi and Zheng (2004) selected Shaoxing City (China) as the study site to determine urban growth using remote sensing. ERDAS Imagine 8.4 software was used to classify Landsat TM images for 1984 and 1997, and ETM for 2000, with a spatial resolution of 30m and 33m respectively. In addition, IRS 1C LISS 111 panchromatic image (6m spatial resolution) was acquired for 1996 and a topographic map (scale 1:50000) for 1974. The panchromatic image was to be used as a reference in the classification. One of the primary

goals of this analysis was to produce a land-use map showing Shaoxing City and its surroundings. This was achieved by implementing a two-step approach. A maximum likelihood supervised classification was used based on training areas chosen according to extensive field knowledge. The initial results were verified by visual interpretation of the environment, recoding incorrect polygons. Identified land cover classes included fallow land, farming, forest, settlement and water. The accuracy of the classification was confirmed by field inspections and comparison with existing land use maps. A confusion matrix was then used for the 2000 image, which showed an overall accuracy of 92%. This was repeated for the 1974 and 1997 land use classification, obtaining accuracies of 81% and 87% respectively. The settlements were finally extracted from images and overlaid on each other to produce the urban expansion map/image (Elnazir, Xue-zhi and Zheng, 2004).

More recently Ma and Xu (2010) used supervised classification techniques to monitor and analyse the driving forces of urban expansion in Guangzhou City, China. Landsat imagery was acquired for four different temporal phases, namely 1979, 1988, 1995 and 2002. Control points were selected based on locations with fixed positions and notable features in order to perform the calibration of coordinates for the satellite images. The pixels were resampled at a resolution of 30m.

Although there are many different remote sensing classification techniques, Ma and Xu (2010) employed the maximum likelihood algorithm for the supervised classification. Based on the land resources, use attributes and the spectral signatures of objects on the ground, 5 classes were devised, namely water bodies, vegetation zones, dry land, exposed land and construction land (town including commercial centers, plants, mines, public utilities, buildings, residential blocks and traffic facilities). The supervised classification was performed on each temporal phase, producing the results observed in Figure 23.

The built up urban area is representative of the city's development at different periods. Water bodies, farmlands, hilly areas, waste land and forest lands can therefore be integrated into a single class of ground object i.e. binary processing can be carried out on the classified image resulting in two classes namely urban and non-urban land (Figure 26), also allowing for the urban boundary to be easily digitized (Ma and Xu, 2010).

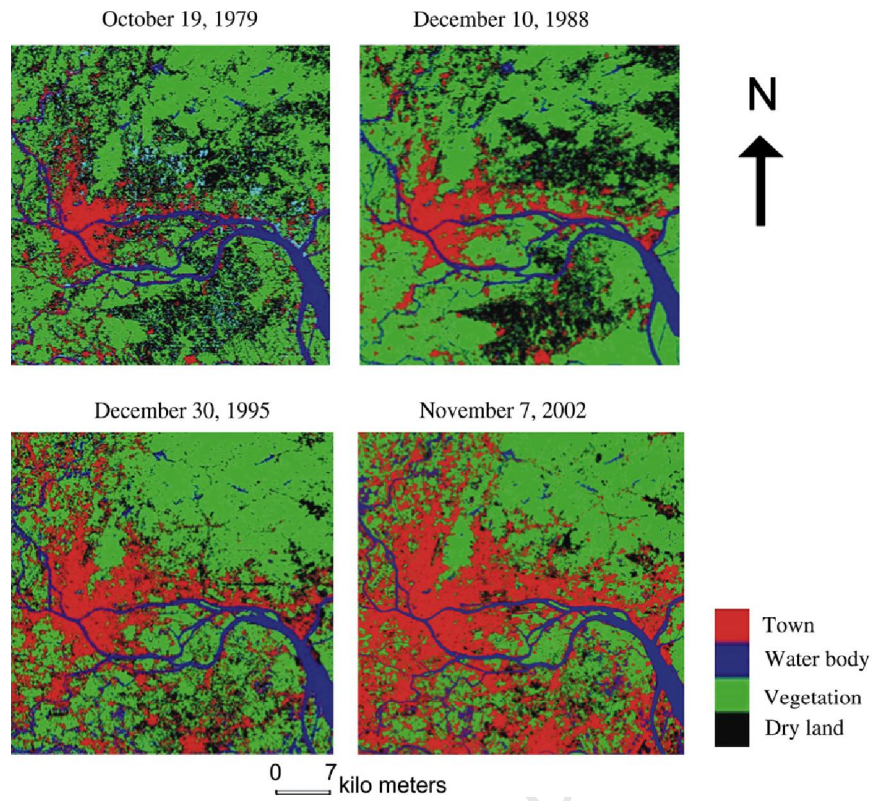


Figure 23: Supervised classification results for Guanzhou City, China
 (Source: Ma and Xu, 2010)

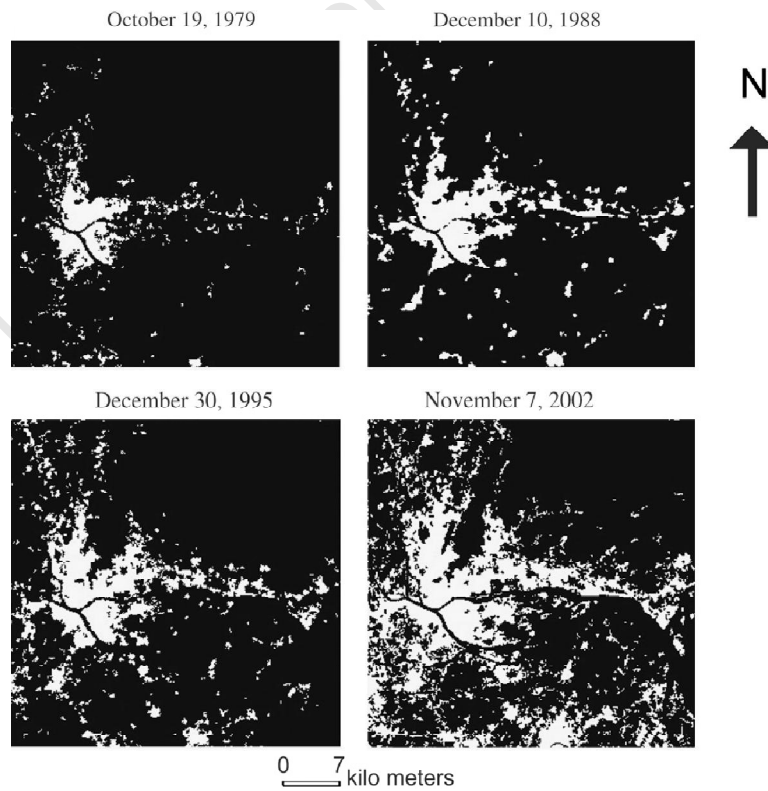


Figure 24: Binary image showing urban and non-urban areas
 (Source: Ma and Xu, 2010)

The urban areas identified in the study were superimposed with one another in order to perform a detailed analysis providing both a qualitative and quantitative analysis of urban expansion as depicted below (Figure 25).

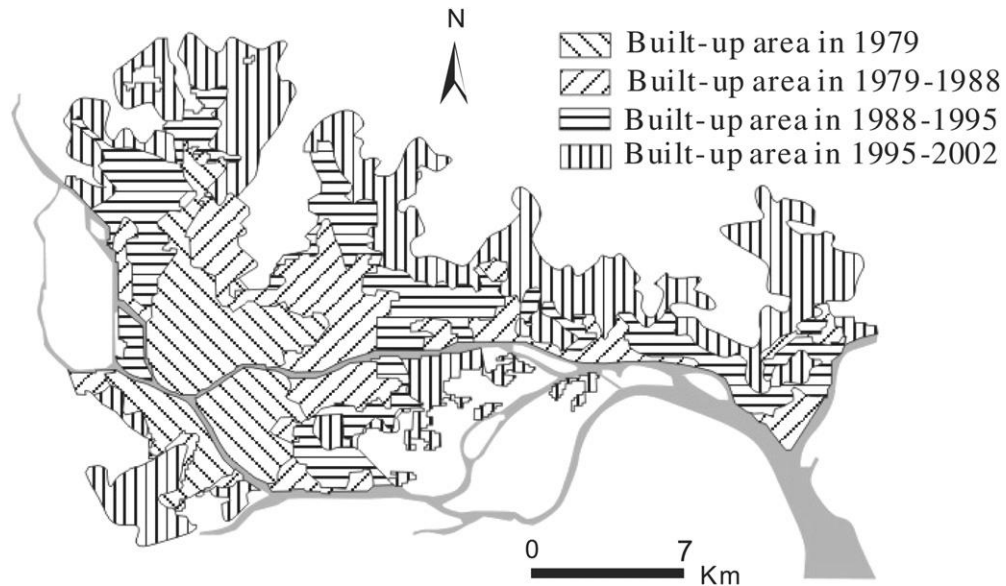


Figure 25: Urban expansion in Guanzhou City, China

(Source: Ma and Xu, 2010)

The results of the study over a period of 23 years indicates that urban expansion was relatively slow prior to 1988, accelerating in the 7 year period between 1988 and 1995, and even faster between 1995 and 2002, which is characterized by the fast economic development of the city. The driving forces of urban expansion have been identified as topographic elements, economic growth elements, population growth elements, resident income elements, city infrastructure construction elements and city planning and policy elements (all of which are discussed in detail in Ma and Xu, 2010).

2.4.2.3 Accuracy Assessments in Image Classifications

Accuracy assessments are important in classification exercises to determine the degree of error in the end product (Mather, 1989). The most common means of representing the degree of accuracy of a classification is by producing a confusion (error) matrix. The confusion matrix is a square array of numbers that expresses the number of pixels assigned to a particular category relative to the actual category as verified on the ground (Story and Congalton, 1986). The reference (ground truth data) is represented in the columns, while the rows indicate the

classification produced from the remotely sensed data. This method is deemed an effective way of displaying the accuracy, as the accuracies of each category are described, including both errors of inclusion (commission errors) and errors of exclusion (omission errors) (Lunetta et al, 1991).

The overall accuracy is considered to be the simplest descriptive statistic which is calculated by the total correct pixels (i.e. the sum of the major diagonal) by the total number of pixels in the matrix. A similar method can be used to determine the accuracies of individual classes whereby the user would be required to choose whether to divide the amount of correct pixels by the total number of pixels in the corresponding row or column. Conventionally the number of correct pixels is divided by the total pixels in the column total (i.e. the total number of pixels in the reference data). This indicates the probability of a reference pixel being correctly classified and is ultimately a measure of omission error, and is referred to as producer's accuracy as the producer of the classification is interested in how well a certain area can be classified. Alternatively, if the number of correct pixels is divided by the number of pixels in the corresponding row, then the result is a measure of commission error and is referred to as user's accuracy. This measure is indicative of the probability that a pixel classified on the map actually represents that image on the ground (Lunetta et al, 1991).

GIS and remote sensing have different methods in order to assess the data accuracy. These differing methods are also incompatible with each other. GIS operators tend to use error models which provide more local accuracy information while remote sensing uses an error matrix which provides global information. As of yet, there has not been an effective approach to facilitate the flow of accuracy information between GIS and remote sensing (Wang, 1991)

Lu and Weng (2005) investigated the potential roles of high spatial resolution panchromatic band and lower resolution thermal infrared band for improving urban classification accuracy as well as attempting to identify suitable remote sensing procedures for urban classification through a comparative study of different image processing techniques. The methodologies included:

Image processing: The data was radiometrically converted to at-sensor reflectance by using an image based correction method. The image was ortho-rectified to a common coordinate

system, namely Universal Transverse Mercator. The raster image was then resampled to a 30m*30m pixel size using the nearest neighbour resampling algorithm. During the rectification a root mean square error of less than 0.5 pixels was achieved.

Nine colour orthophotographs with a spatial resolution of 0.14m were used as ground truth reference data for the collection of training and test sample plots. These were resampled to 5m pixels for reduced computational time, as well as quicker display and decreased computational time. The orthophotographs were then mosaicked into a single image of the study area.

Texture analysis: Many texture methods have been developed and used for land cover classification (Marceau et al., 1990; Augusteijn et al., 1995; Groom et al., 1996; Podest and Saatchi, 2002; Chen et al., 2004). A comparison between grey level co-occurrence matrix (GLCM), simple statistical transformations (SST) and texture spectrum (TS) using SPOT HRV data was conducted by Gong et al (1992) whereby the results illustrated that certain textures derived from GLCM and SST could improve the accuracy of urban classifications. Shaban and Dikshit (2001) considered GLCM, grey level difference histogram (GLDH) and sum and difference histogram (SADH) textures from SPOT spectral data for urban areas in India. The results showed that a combination of textures and spectral features improved the classification performance considerably. Comparing the results using pure spectral features, approximately 9% and 17% improvement were achieved for an addition of one and two textures respectively. In addition, they found that contrast, entropy, variance and inverse difference moment provided higher accuracy than other tested texture measures, with the most appropriate sizes of moving window being 7x7 and 9x9.

The incorporation of texture and spectral information has been proven to be effective in improving the accuracy of classifications (Butusov, 2003; Shaban and Dikshit, 2001). Based on the research conducted by Shaban and Dikshit (2001), variance associated with a window size of 9 x 9 was chosen as the texture measure in the study. In order to observe the significance of textures in improving classification performance, the variance in textures were calculated for the multispectral bands 3, 4 and 5 with a 30m spatial resolution and for the panchromatic band with a 15m spatial resolution. The variance is mathematically expressed¹⁴ as:

14 Where X_{ij} is the reflectance value of pixel (i, j), and n is the number of pixels in a window.

$$Var = \frac{\sum_{i,j=0}^{n-1} (X_{ij} - \frac{1}{n} \sum_{i,j=0}^{n-1} X_{ij})^2}{n - 1}$$

Equation 1: Mathematical expression for variance

The textures resulting from the multispectral bands (3, 4 and 5) lost much of its detail and appeared to be over-smoothed, whereas the textures from the panchromatic band provided for a better visual interpretation effect than those from lower spatial resolution multispectral bands.

The use of multiple or multi-scale images should be in conjunction with spectral information to improve the results of the classification (Kurosu et al., 2001; Shaban and Dikshit, 2001; Butusov, 2003). However, it is important to note that for specific studies there are no obvious ways for identifying suitable texture measures as texture varies with the characteristics of the identified landscapes and image data used. The identification of suitable textures involves the determination of texture measures, image band and size of the moving window (Franklin et al., 1996; Chen et al., 2004).

Surface temperature computation: The study used the thermal infrared band which was converted to a surface temperature map in order to reveal the probable urban areas based on the idea that urban areas have a higher surface temperature than their surrounding areas. The procedure used to convert the thermal infrared map to a surface temperature map involved the conversion of the digital number of Landsat ETM thermal infrared band into spectral radiance using the equation:

$$L_{\lambda} = 0.0370588 \times DN + 3.2,$$

Equation 2: Mathematical expression for spectral radiance

Thereafter it was converted to a satellite brightness temperature under the assumption of uniform emissivity using the equation¹⁵:

$$T_B = \frac{K_2}{\ln\left(\frac{K_1}{L_{\lambda}} + 1\right)}$$

Equation 3: Mathematical expression for at-satellite temperature

¹⁵ Where T_B is effective at-satellite temperature in Kelvin, L is spectral radiance in watts/(meters squared * ster * μm); and K_2 and K_1 are pre-launch calibration constants. For Landsat-7 ETM+, $K_2 = 1282.71$ K and $K_1 = 666.09 \text{ mWcm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ were used.

Based on research by Artis and Carnhan (1982), the emissivity corrected land surface temperatures (T_s) were calculated as follows¹⁶:

$$T_s = \frac{T_B}{1 + (\lambda \times T_B / \rho) \ln \varepsilon}$$

Equation 4: Mathematical expression for land surface temperatures

Principal components analysis (PCA): PCA was used to reduce data dimensions and implement data fusion. There was a high amount of redundant data due to the high correlation between bands e.g. the correlation coefficient between band 1 and 2 was 0.985, and between band 2 and 3 it was 0.970. The PCA reprojected the original dataset into a new coordinate set where no correlation existed between images. The first principal component (PC1) was the sum of all the bands; therefore it gave the total brightness. It also contained the largest percentage of the data variance. PC2 (containing the second largest amount of variance) enhanced vegetation information by taking the difference between the sum of bands 4 and 5 and the sum of visible bands and band 7 (Lu and Weng, 2005). PC3 showed the difference between short-wave and infrared bands (TM5 and TM7) and the sum of visible bands and near infrared band. The higher principal components contained very little variance, making them appear noisy, which was a result of the noise in the original spectral data.

Data fusion was based on the PCA approach, involving the integration of the ETM+ multispectral and panchromatic images by¹⁷: (a) transforming the multispectral bands into six PCs (b) re-mapping the panchromatic image into the data range of Pc1 (c) substituting PC1 with the panchromatic image, and (d) applying an inverse PCA to the data. An important step making use of this approach is to match the histograms of a panchromatic image and that of the PC1.

This study resulted in PC1 showing impervious surfaces, while the panchromatic image with its higher spatial resolution, had more detail. When the original ETM+ band 5 was compared to the result of the data fusion, the new image showed a definite enhancement of the spatial detail, especially noting the linear features (Lu and Weng, 2005).

¹⁶ Where, λ is the wavelength of emitted radiance [for which the peak response and the average of the limiting wavelengths ($\lambda = 11.5 \mu\text{m}$) (Markham and Barker, 1985) were used], $\rho = h \cdot c / (1.438 \cdot 10^{-2} \text{ mK})$, $\sigma = \text{Stefan Boltzmann's constant } (5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} = 1.38 \cdot 10^{-23} \text{ J/K})$, $h = \text{Planck's constant } (6.626 \cdot 10^{-34} \text{ J sec})$, $c = \text{velocity of light } (2.998 \cdot 10^8 \text{ m/sec})$, and ε is spectral emissivity.

¹⁷ The following steps were taken directly from the paper by Lu and Weng (2005).

Image Classification

Lu and Weng (2005) designed different image processing routines to identify the most suitable method(s) for improving urban classification, as described below:

Table 3: Image Classification Methods Investigated¹⁸

(Source: Lu & Weng, 2005)

No.	Code	Method
1*	ETM	ETM+ multispectral image (excluding thermal and panchromatic bands)
2*	PCA	The first three components derived from PCA of ETM+ multispectral image
3*	B ₃₄₅ Text	Combination of spectral bands (ETM+ multispectral bands) and textural data (three textures based on variance associated with 9*9 window size and ETM+ bands 3,4 and 5).
4	Pantext	Combination of spectral bands (ETM+ multispectral bands) and textural data (variance associated with 9*9 window size and panchromatic image).
5*	Temp	Combination of spectral bands (ETM+ multispectral bands) and temperature (derived from TIR band)
6	Pantext-Temp	Combination of spectral bands (ETM+ multispectral bands) and textural data (variance associated with 9*9 window size and panchromatic image), and temperature (derived from TIR band).
7	Pan-Fusion	Data fusion using PCA method based on ETM+ multispectral bands and one panchromatic band.
8	Fusion-Pantext	Combination of data fusion image (using PCA method) and texture (derived from panchromatic image using variance associated with 9*9 window size).

The following research questions were posed¹⁹:

- Would the use of the first three PCs from PCA of the ETM+ multispectral bands increase or decrease classification accuracy?
- Would incorporation of textures from 30 m multispectral bands improve classification accuracy?
- Would incorporation of a texture from 15 m panchromatic band improve classification accuracy?
- Would incorporation of surface temperature improve classification accuracy?
- Would incorporation of both texture and surface temperature improve classification accuracy?
- Would a data fusion of panchromatic and multispectral images improve classification accuracy?
- Would incorporation of data fusion and texture images improve classification accuracy?

Prior to implementing the image classification, a suitable classification scheme had to be selected. The ETM+ colour composite was visually analysed and compared with

¹⁸ Note: *1, 2, 3 and 5 approaches used 30m spatial resolution images, others used 15m spatial resolution images because they used panchromatic bands with 15m spatial resolution

¹⁹ The following was taken directly from Lu and Weng (2005), unless otherwise stated.

orthophotography images. Following the initial image interpretation, two classification schemes with six and eleven classes respectively were identified (Table 4)

Table 4: Land-use and land-cover classes

(Source: Lu & Weng, 2005)

Classification Scheme 1	Code 1	Classification Scheme 2	Code 2	Definition
Commercial / industrial / transportation lands	CIT	Commercial / industrial / transportation lands	CIT	Highly developed areas, mainly for commercial or industrial use, including transportation.
Residential	RES	High density residential	HDR	Highly developed areas where people reside in high numbers.
		Low density residential	LDR	A mixture of constructed materials and vegetation, population density is lower than in high density residential areas.
Forest	FOR	Upland forest	UPF	Areas dominated by dense vegetation.
		Wetland forest	WLF	Areas covered by forest but the soil is periodically saturated with water.
Agricultural lands	AGR	Crops	CRP	Different crops in agricultural lands.
		Fallow	FAL	Areas used for the production of crops that are temporarily barren or with sparse vegetation.
		Non-vegetated wetland	NVW	Areas where the soil is periodically saturated with water.
		Pastures	PAS	Areas of grasses used for livestock grazing or the production of hay crops.
Grass	GRA	Grass	GRA	Vegetation planted in developed settings for recreation.
Water	WAT	Water	WAT	All areas of open water.

In the classification scheme with six classes, cropland, fallow and pastures were grouped as agricultural land and upland forest and wetland forest were combined into a single forest class. In addition, high density residential and low density residential areas were grouped to form one residential class. The classification with eleven classes, two building types and three transportation types were combined into the commercial/industrial/transportation class, as well as three crops being combined into a single crop class.

Training sample plots were selected from the 2002 color orthophotography, whereby each class had a total of fifteen to twenty selected sample plots. The spectral response curves of the selected sample plots for each class were analyzed to ensure they had similar reflectance characteristics within the class, and that a distinct response pattern exists between classes. The transformed divergence index was calculated in order to analyze the separability of the selected classes. After refining the training sample data, the maximum likelihood classification (MLC) algorithm was applied to classify the images. The resulting thematic images were then merged into eleven and six classes, respectively, and a majority filter with 3 × 3 window size was applied to eliminate noise in the classified images.

An **Accuracy Assessment** is considered important in evaluating different image processing classifications (Foody, 2002). An error matrix was produced to assess the results of each classification described above, with which relevant accuracy assessment parameters can be derived. 350 test samples were selected at random and examined using colour orthophotography, after which the overall accuracy, producer's accuracy, user's accuracy and kappa coefficient were calculated for each of the classified images, the results of which are described below (Lu and Weng, 2005):

Method 1: The classification achieved 70.6% accuracy. Commercial/industrial/transport, low density residential areas, pastures and water have higher accuracies than other classes (more than 79% of producer's accuracy and 72% of user's accuracy). The primary confusion resulted from the following classes:

- Commercial/industrial/transportation and high density residential;
- Crops, pastures and grass;
- Upland forest and wetland forest; and
- Upland forest and low density residential.

Lu and Weng (2005) compared other processing methods with Method 1 in order to determine whether an image processing method will improve the accuracy of the classification.

Method 2 obtained an accuracy of 68.3%. Compared to Method 1, there was a decrease in the accuracies of low density residential, crops and fallow land, and an improvement in the wetland forest and pasture classes. The same level of accuracy obtained in Method 1 was obtained using Method 2 for commercial/industrial/transportation, high density residential and grass. The classification performance was very similar to the results obtained using Method 1, whereby the primary confusion occurred between:

- Crops and grass;
- Upland forest and low density residential; and
- Upland forest and wetland forest.

The results concluded that Method 2 would be useful for classifying images over a large area as it could dramatically reduce image storage and classification time.

Compared to Method 1, the results obtained using **Method 3** was poor. The classification resulted in an overall accuracy of 62.3%, with a marginal reduction in the accuracies of almost all classes. These results imply that selected textures smoothed the differences among the classes, most notably between:

- High density residential;
- Upland forest and wetland forest; and
- Crops and grass

Method 4 achieved an accuracy of 74%, outperforming method 1 by 3.4%. The accuracies of most classes improved due to the combination of multispectral data with a texture image derived from the panchromatic band. The confusion between crops and grass as well as between upland forest and wetland forest was dramatically reduced.

The technique of including a temperature image did not improve the classification results of **Method 5**, which obtained an accuracy of 69.1%. There was a notable decrease in accuracy of commercial/industrial/transportation, high density residential, low density residential and upland forest classes, although there was an increase in accuracy for other classes such as the wetland forests. The minor variation of thermal response patterns among low density residential and upland forest classes did not aid in separating them. In addition, Landsat ETM+ thermal infrared bands low spatial resolution²⁰ may have contributed to smoothing the inherent differences between certain classes.

Method 6 was similar to Method 5, only including a texture image derived from the panchromatic band for classification. 73.4% accuracy was achieved, attributed to the texture image, not the temperature image. The distinction between upland forest and wetland forest showed the most significant improvement.

The data fusion technique was used for both Method 7 and 8. **Method 7** merged the ETM+ multispectral and panchromatic bands using the PCA fusion method, while **Method 8** combined the data fusion image obtained from Method 7 with a texture image derived from the panchromatic band. Although **Method 7** did not result in an overall improvement in accuracy, the classification accuracy for upland forest, wetland forest, fallow land and grass improved.

²⁰ 60m as compared with 30m for the multispectral bands

Notably, there was a slight decline in the accuracy of low density residential areas. Confusion continued to exist between low density residential and upland forest, despite the increase in spatial resolution. This suggests that although data fusion with different spatial resolution images is becoming a popular approach to image classification, the increased spectral variation within a class may degrade the distinction among certain classes, and therefore the overall accuracy of the classification. In particular, this seems to be true for low density residential classes due to the complex composition of the materials and increased spectral variation within the class.

Method 8 achieved the best performance out of all the tested methods. Almost all classes showed an increase in their classification accuracies. There was a notable reduction in confusion between commercial/industrial/transportation and high density residential as well as between low density residential and upland forest.

The results concluded that a combination of data fusion and texture is an effective means of improving the accuracy of classifications. The data fusion of panchromatic and multispectral bands controlled the mixed pixel problem, while the issue of spectral variation within a class was moderated by the texture image from the panchromatic band (Lu and Weng, 2005).

2.4.2.4 Additional Studies Using Remote Sensing

The aim of the research conducted by Sutton et al, (2001) was to estimate the global urban population using night-time lights. A dataset of 2000 known cities with known populations was used and a global night-time image product was registered to it. The city population data was obtained from the United Nations Statistical Yearbook (1992) and the National Geographic Atlas of the World (1995), also included was census data varying from the 1970s to the 1990s. The population data was updated to an estimated value for 1997 using the national and annual specific urban population growth rates (Sutton et al, 2001)

The digital imagery of the Defence Meteorological Satellite Program's Operational Linescan System (DMSP OLS) (available from 1992) has been used in mapping human settlements on a global scale. The system used a thermal band and a panchromatic visible and near-infrared (VNIR) band. The technical specifications of DMSP are available in Dickinson et al, (1974). The pixel values recorded the percentage of VNIR at the various locations, and were not a

measurement of the light intensity. The purpose of the thermal band was for screening data affected by cloud cover. By counting the number of neighbouring illuminated pixels for all isolated urban areas, the aerial extent of the cities could be measured (see Sutton et al, (2001) for further details of the study).

The weaknesses identified is that it assumes all global urban areas have sufficient lighting sources, including rural areas and informal settlements, however it is likely that these areas have been omitted and therefore this type of census cannot be applied to these populations. The census data and method used to estimate the populations of the cities may not have been the most appropriate way of determining the city populations as Cohen (2004) states that according to the World Urbanization Prospects: the 1999 revision (United Nations, 2001), some countries have not produced updated censuses since the 1980s and some even the 1970s. 38% of the data used was older than 8 years. The larger metropolitan population was used in the case of city census data, however, they do not mention if administrative boundaries were considered in megalopolis areas.

A study conducted by Yankson et al, 2004 involved the use of Landsat TM data to monitor urbanization on the fringe areas of Accra in Ghana. A texture based classification method was applied to the images. Principal Component analysis was generated using all the bands that had 30m pixel resolution. Co-occurrence matrices as well as second order texture measures were computed from the first Principle Component. The training sites were based on GPS coordinates (recorded on the ground) and defined in the images (Yankson et al, 2004). One of the criteria for selecting the training points is that they were taken in areas with a large proportion of nearly completed houses (termed the urban area) and also in areas with scattered houses that were still in their initial construction phases (termed the transition area). The aim of using this method was to be able to delineate a fringe area transition zone that will ultimately be defines as urban (Yankson et al, 2004).

2.4.2.5 The utilization of GIS software in raster classification

The accelerated economic growth experienced in the Zhuiiang Delta of South China resulted in rapid urban expansion over the past two decades. GIS and remote sensing has been utilized in a study conducted by Weng (2001) to detect the urban growth and the impact on the surface area temperatures in the region. The GIS application was used in analyzing urban growth

patterns based on various models, and the remote sensing process utilized Landsat TM data to detect land use/cover change and then expanded the study to examine the influence the urban growth had on the surface temperatures. The Landsat TM thermal infrared data can be used to differentiate between urban and rural areas as the temperature usually differs by at least one degree Celsius, but can reach differences of several degrees if the Urban Heat Island (UHI) is allowed to develop (usually under the influence of meteorological and topographical conditions). Weng (2001) GIS results revealed a notable and uneven urban growth pattern that was also responsible for raising the surface radiant temperature by 13.01K (Kelvin²¹) in the urbanized area. The integration of remote sensing and GIS proved to be of great value in the study (Weng, 2001).

A contrasting method was used in the study conducted by Angel et al (2005), whereby Landsat images that were previously classified into three classes, namely urban²², non-urban²³ and water²⁴ were used. Administrative boundaries (district boundaries) were used to define the spatial extent of the study areas. Urban pixels were extracted from the Landsat images and reclassified into a grid file. A smoothing algorithm²⁵ was applied to the urban grid. The smoothed grid was then subjected to a grouping algorithm²⁶ that grouped neighbouring pixels together to form clusters. Clusters exceeding 1km² (1231 pixels) were identified and converted to shapefiles²⁷, with the larger polygons identified as the main urban centers of the study sites. The *select-by-location* tool was used to identify administrative boundaries intersecting a 1km buffer around the urban polygons, thereby eliminating the districts that do not contain urban areas. These steps are illustrated in Figure 26 below:

²¹ 0°C = 273K. The size of 1 Kelvin equals 1 Degree Celcius, so 1°C = 274K (Silberberg, 2003). The temperature thus increased by 13.01°C in the study

²² Refer to definitions

²³ Areas excluded in the definition of urban including rural landscapes, open spaces and conservation areas

²⁴ Including all water bodies occurring in the study area i.e. rivers, lakes and recreational water bodies

²⁵ In ESRI's ArcMap, the Boundary Clean algorithm (one of the Generalization features within Spatial Analysis Tools) was used. The Boundary Clean tool is primarily used for cleaning "ragged" edges between zones. The algorithm uses an expansion and shrinking method that cleans boundaries (Angel et al, 2005).

²⁶ Region Grouping is a spatial operator that identifies contiguous patches of like-valued pixels and assigns those patches (groups or regions) a unique identifier. Essentially, this is analogous to enumerating all unique polygons (in a vector-based GIS).

²⁷ ESRI GIS data format

Figure IV-1. Illustration of the progression of steps involved in creating a district shapefile for the city Accra

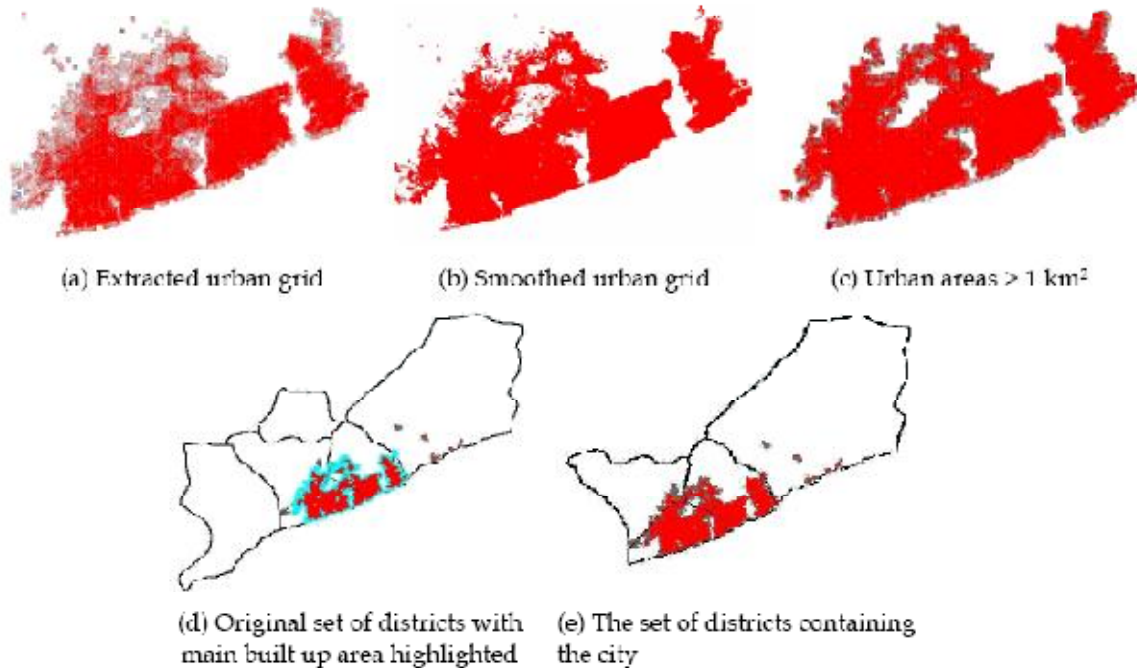


Figure 26: Representation of the steps taken to create an urban shapefile for Accra (Ghana)

Source: Angel et al (2005)

The remaining districts contained urban areas that overlapped administrative boundaries, therefore in order to calculate the urban areas in each district, the urban grid would need to be clipped using the administrative boundaries. The urban grid was clipped using the Raster Calculation tool with the city district shapefile set as the analysis mask. The Zonal Statistics tool was then used to count the amount of urban pixels in each city district and the results were organized into a table. The final step involved the simple calculation of the total urban area by multiplying the number of urban pixels by the area of each pixel, after which the total urban area was calculated by adding the urban areas for each district (Angel et al, 2005).

2.4.2.6 Combining Remote Sensing and GIS techniques for Land Use Classification

Rozenstein and Karnieli (2010) used remote sensing classifications (unsupervised and supervised) to determine if combining the techniques as well as using GIS will improve the overall accuracy of a land use classification in Negev, Israel. Visual interpretation was identified as a method of extracting land use information from remote sensing data, however the technique is limited to a single band or a three-band (RGB) composite. Manual digitizing is tedious and subjective (Bolstad, Gessler and Lillesand, 1990), therefore particularly in large

areas, automatic remote sensing classification would be a more appropriate approach. This introduces new challenges as although visual interpretation may be obvious to the researcher, the software does not possess the superior pattern recognition capabilities of the human brain (Hudak and Brockett, 2004). Achieving an accurate classification of complex landscapes from remotely sensed imagery is therefore challenging (Manandhar et al, 2009). Rozenstein and Karnieli (2010) aimed to compare supervised and unsupervised land use classification techniques, examine whether combining the signatures would provide significantly more accurate results than each separate approach and finally to determine whether using a decision support system for updating the map based on expert knowledge and ancillary GIS data significantly improves the classification accuracy.

Landsat TM images with a spatial resolution of 30m were used for the analysis. Previous studies have determined that satellite image classification results have not improved over a period of 15 years despite efforts to establish new classification algorithms (Wilkinson, 2005) and was therefore concluded that there is little value in continued research efforts to improve classification algorithms in remote sensing (Manandhar et al, 2009). In the image pre-processing phase radiometric and atmospheric correction was applied using the dark-object subtraction method. The corrected image was then geo-registered to an updated orthophoto. The successful geo-registration allowed for comparison to the orthophoto and additional maps (Rozenstein and Karnieli, 2010).

The ISODATA unsupervised classification involved classifying the pre-processed image into 80 classes. Each class was then assigned into one of six identified land use classes, namely urban/built up, agricultural fields, rangeland, forest, water bodies and barren land, by masking each class and projecting it onto the orthophoto for visual interpretation. Finally the image was recoded to the six classes (Rozenstein and Karnieli, 2010).

The image was classified using signatures from the training sites to include the six identified land cover classes. In total 120 signatures were collected by digitizing polygons on the orthophoto and then projecting them onto the image to collect the training samples. Digitizing from the orthophoto allowed for greater accuracy than what would have been achieved by digitizing from the Landsat image. Once the collection of training sites was complete, the Euclidian distance between the spectral signatures served as a measure to separate the

signatures collected from each land use class. Spectrally similar signatures of the same class were combined. The maximum likelihood classification was run with a feature space non-parametric rule. Classes of the resulting image were recoded into the six land use classes (Rozenstein and Karnieli, 2010).

For the hybrid classification an iterative classification approach was used. The spectral signatures for specific land-use and land-cover classes were created using unsupervised training followed by supervised training (Bakr et al, 2010). After evaluating the classification product accuracies, signatures that contributed to the most accurate class assignments from both supervised and unsupervised training were joined together. The maximum likelihood classifier was applied again with the improved signature set (Rozenstein and Karnieli, 2010).

During the post-classification processing, the land-use polygons were clipped according to the research area boundary and converted to raster data. The data was resampled to 30m resolution to match the Landsat TM image. Each of the LULC classes of the original maps was recoded into the appropriate six identified classes. A decision support system was designed for improving the accuracy by filtering noise and incorporating the ancillary data (Rozenstein and Karnieli, 2010).

The results of the accuracy assessment revealed that the unsupervised training products are more accurate than the supervised training. However, using a combination of supervised and unsupervised classifications produced a more accurate result than using them separately. It was also shown that the use of GIS improved the accuracy of all classification products by up to 10%. The study also illustrated that in many (but not all) cases, in order to properly train the maximum likelihood classifier, the researcher may be required to be quite familiar with the research area (Rozenstein and Karnieli, 2010).

Hadeel et al (2009) used both GIS and remote sensing in analyzing land use/ land cover change and urban expansion in the Basrah Province in Southern Iraq. Over the past 20 years urbanization has increased rapidly due to the former government implementing a strategy of fast development in the urban economy, transportation and large expansion of military camps. This resulted in the loss of urban peripheral farmland and peripheral ecological environments. Various forms of urban analyses were considered during this study including:

- LULC maps for the urban area of Boston which were produced at level III of the Anderson scheme (Anderson et al, 1976) which used large format camera shuttle photographs and national high altitude photographs, resulting in accuracies of 65% and 70% respectively (Lo and Noble, 1990);
- SPOT XS images were tested for automatically outlining agricultural near-urban interfaces for an area around Yogyakarta, Central Java, resulting in satisfactory results which were visually compared to 1:100 000 near infrared aerial photographs (Gastellu-Etchegorry, 1990);
- Eight land covers were mapped using Landsat MSS data at the level of the Anderson scheme on the urban fringe in England (Curan and Pedley, 1990);
- 10m resolution SPOT panchromatic band was used by registering it with the multi-spectral ones to obtain a classification of land covers at the urban rural fringe of Toronto, Canada. This produced an accuracy of 78% (Treitz et al, 1992);
- Three Landsat MSS images were used to monitor urban expansion in Montreal, Canada (Charbonneau et al, 1993);
- A five-category classification was obtained in the small area of beaver Dam, Wisconsin (Harris and Ventura, 1995);
- SPOT XS data was used to produce detailed land cover maps at the urban-rural periphery in Southern Auckland which reflected the influence on land use at the urban fringe (Gao and Skillcom, 1998); and
- The urban land use map of Wuxi City was achieved from TM and ETM+ imagery using normalized difference built-up index (Sidjak and Wheate, 1999).

The study conducted by Hadeel et al (2009) aimed to analyse urban expansion impacts on LULC in the Basrah Province between 1990 and 2003 using the following objectives:

1. To retrieve the two phases of the urban boundary of the Basrah Province in 1990 and 2003 using the supervised classification and normalized different built-up index (NDBI) respectively followed by comparison of the results derived from these two different methods;
2. To map urban LULC of Basrah Province in 1990 and 2003, to find the factors causing LULC change s during the past 13 years; and
3. To propose some suggestions for the city's development, while protecting limited farmland resources and ecological environment.

The supervised classification method was used to extract two land cover classes, namely urban and non-urban areas. This was required to separate the urban class. The maximum likelihood classification was then used to map LULC, resulting in accuracies of 97.89% and 95.93% respectively. In order to convert the raster data into vector data, the classified result was filtered by a 5x5 window, and then the aggregation was carried out. This involved the non-urban part within the city being merged in to the urban area and the urban area outside of the city being aggregated into non-urban area. In turn, urban profiles were obtained. Based on these results, urban boundaries were extracted for 1990 and 2003 were extracted by converting raster to vector (Hadeel et al, 2009).

The NDBI method takes advantage of the unique spectral response of built up areas. Effectively, built-up areas are mapped through arithmetic manipulation of the normalized different vegetation index (NDVI). Band 4 (0.76~0.90 μ m) of the TM and ETM+ images is the near infrared waveband that reflects vegetation information, therefore resulting in a low reflectance of residential areas. The shortest infrared waveband (1.55~1.75 μ m) can reflect information regarding moisture content in different land use types e.g. in band 5 the reflectance of forest and farmland with high moisture content is low, but residential areas with a high moisture content will result in a high reflectance. Based on work by other researchers, Landsat TM and ETM+ images, except for urban and barren areas, the digital numbers of other landscapes in band 4 are lower than in band 5. NDBI is the result of the following calculation (Hadeel et al, 2009):

$$\text{(band 5 - band 4) / (band 5 + band 4)}$$

Equation 5: Equation expressing NDBI

In the Basrah province, the NDBI ranges between -0.49 to 0.20. The mask processing was then done to the binary image, thereby converting raster to vector (Hadeel et al, 2009).

The results of the study show that the average accuracy of the supervised classification is 89% and NDBI 81%, concluding that the supervised classification is the ideal method of retrieving the urban boundaries for 1990 and 2003. The study showed the urban area to have increased by 476.7km² during the time series. The urban periphery illustrated the most LULC change. Large amounts of farmland had been converted to urban construction areas. Human activity

appeared to be the main driver behind LULC change, including rapid economic development and fast urbanization (Hadeel et al, 2009).

Manonmani and Suganya (2010) applied remote sensing and GIS to a change detection study in an urban zone in the Villivakkam block (study area) of Thiruvallur district (Chennai, India) using 1:50 000 topographic maps, Landsat TM and IRS-P6 LISS III satellite data. The methodology employed used topographic maps dated 1976 and comparing it to satellite imagery. The region had been subjected to increased construction activities which were dependent on the population growth, as well as the establishment of industry, transport and educational infrastructure.

The pre-processing of the data included scanning, digitizing and georeferencing the topographic maps to serve as the base map. The initial Landsat image (1990) and final IRS- IC LISS III (2005) were classified based on visual interpretation to produce five LULC classes, namely agriculture, fallow land, scrub land, industry and built-up. The accuracy obtained for the Landsat and IRS- IC LISS III images was 82.14% and 86.46% respectively. The results indicated that the built-up area had increased from 36.99% in 1990 to 52.82% in 2005 which resulted in a decrease in the amount of agriculture, fallow land and scrub land through the time series (Manonmani and Suganya, 2010).

Thapa and Murayama (2009) considered four approaches to urban mapping, namely unsupervised classification, supervised classification, fuzzy supervised classification and GIS post-processing using Advanced Land Observation Satellite (ALOS) images to predict urban LULC in Tsukuba City, Japan. Intensive field work was conducted in order to collect ground truth data. The study site consisted of homogenous (e.g. water bodies and paddy fields) and heterogeneous (e.g. residential areas and parks) areas, including both dense and sparse developments.

The images were georeferenced using 30 ground control points and a road network map. Ground reference data played an important role in determining information classes, interpret decisions and assess the accuracy of the results. To improve the visual interpretability of the image, image enhancement, contrast stretching, and false colour composites were calculated

resulting in an increase in the apparent distinction between the features. After thorough inspection, seven LULC classes were identified namely:

Table 5: Classes used in the classification process

(Source: Thapa and Murayama, 2009)

No	Classes	Description
1	Urban forest	Natural vegetation and planted trees
2	Lawn/grass	Lawn, grass and bush
3	Paddy field	Paddy field
4	Dry farm/exposed field	Non irrigated land, vegetables and fruits area
5	Facility/industry	Land space house
6	Residence/parking/road	Small houses, back/front yards, parking areas, roads
7	Water	Lake, river and wetlands

The unsupervised classification approach used the ISODATA technique to cluster the image pixels into groups. Thirty clusters were used as the exact number of spectral classes in the dataset was unknown. The ground truthed data was used to verify these clusters and merge them into the appropriate classes (Thapa and Murayama, 2009).

The supervised classification used five to ten areas of interest which were prepared as the signatures of training samples for each LULC class. After obtaining satisfactory discrimination between the classes during the spectral signature evaluation, supervised classification with the Maximum likelihood Classifier (MLC) was run using all four bands of the image (Thapa and Murayama, 2009).

The fuzzy supervised classification approach involved preparing five to ten training areas for each land training site. Mixtures of the various features defined the fuzzy training class weight. A classified pixel was then assigned a membership grade with respect to its membership in each information class. Two maps namely a multi-layer class map and distance map was generated. Fuzzy convolution was then performed to create a single classification layer by calculating the total weighted inverse distance of all the classes in a 3x3 window of pixels. This operation assigns the centre pixel in the class with the largest total inverse distance summed over the entire set of fuzzy classification layers (Leica Geosystems, 2005). Classes with very small distance values remained unchanged and classes with high distance values may change to a neighbouring value provided that there are sufficient neighbouring pixels with class values and small corresponding distance values (Thapa and Murayama, 2009).

The GIS post processing approach combines the advantages of all previous approaches (i.e. supervised, unsupervised and fuzzy supervised classifications) thereby producing an improved LULC map. The maps produced by the supervised and unsupervised approaches were combined using the GIS overlay function. Common land use pixels (i.e. land use clusters identified by both approaches) were extracted from the maps and considered as the best results. The resulting map revealed that the most likely homogeneous features were represented by common pixels, but the more heterogeneous landscapes were better identified by the fuzzy approach. The remaining empty pixels were filled by the land use and land cover pixels derived from the fuzzy supervised approach. Finally post-classification smoothing was applied by a 3x3 grid cell majority filter in the maps generated from supervised, unsupervised and GIS post-processing approaches before the accuracy assessment (Thapa and Murayama, 2009). The results are displayed in Figure 27.

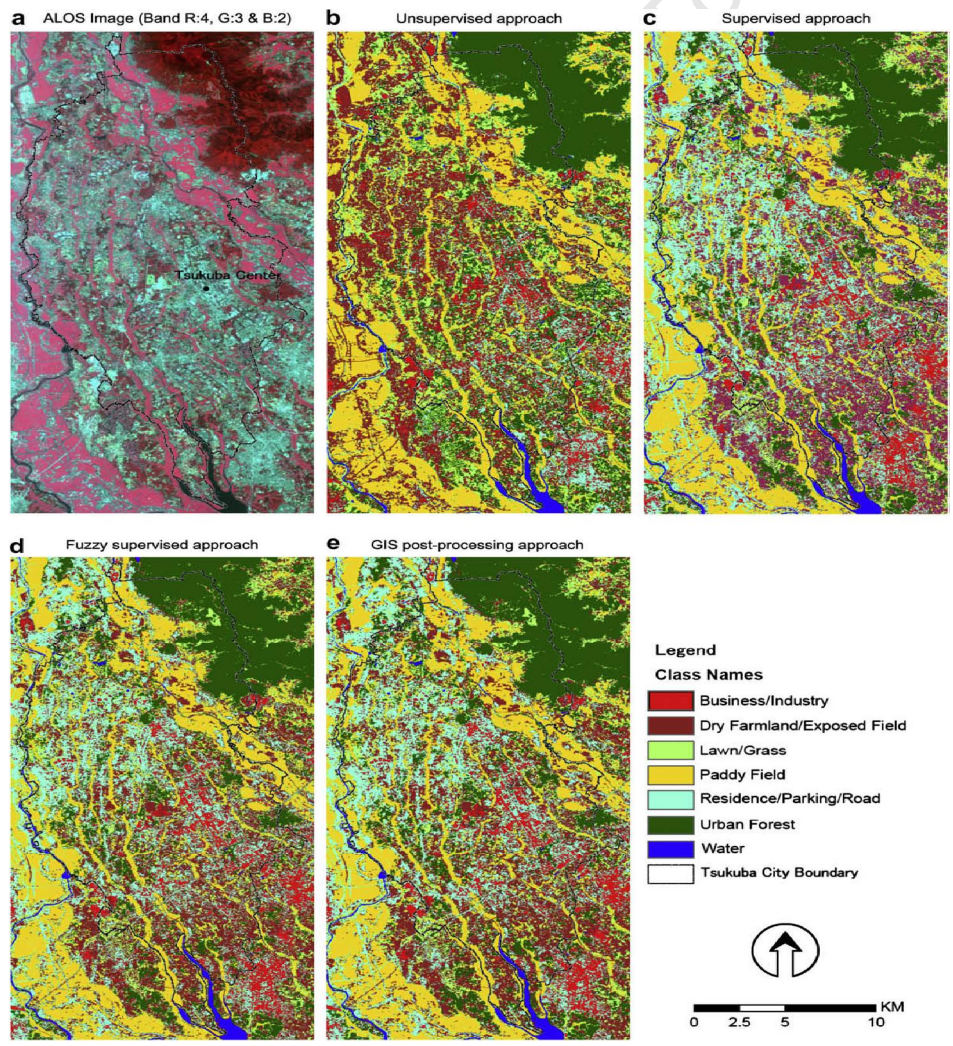


Figure 27: Results produced by the respective classifications
(Source: Thapa and Murayama, 2009)

An error matrix was prepared for each resulting thematic map, producing the results illustrated in Table 6.

Table 6: Overall results of the accuracy assessments
(Source: Thapa and Murayama, 2009)

	Unsupervised classification	Supervised classification	Fuzzy supervised classification	GIS post-processing
Overall classification accuracy	75.33%	83.67%	87.67%	89.33%
Overall Kappa ²⁸ statistics	0.71	0.80	0.85	0.87

The combination of fieldwork, satellite image data and analysis techniques improved the accuracy of the mapping. The GIS post-processing approach provided the most accurate results in predicting LULC of the complex urban environment. The fuzzy supervised method produced more accurate results than the traditional supervised classification and also showed great potential in dealing with heterogeneous surface features in urban residential areas, showing low very low difference in the errors of omission and commission. The supervised approach showed a lower difference between the user and producer's accuracies for the vegetation, paddy fields and water classes compared to the other methods. Overall, the unsupervised technique provided great insight into in helping understand the land cover structure and identify homogeneous clusters in the imagery (Thapa and Murayama, 2009).

²⁸ The Kappa coefficient expresses the proportionate reduction in error generated by a classification process (Thapa and Murayama, 2009)

3 Description of Data Sources

3.1 Satellite Imagery

3.1.1 Landsat Characteristics

Over the last quarter century scientists have expressed increasing interest in understanding the Earth's environmental systems (Bretherton, 1988). Initial attempts to estimate possible changes in the Earth over the next century have revealed that the current understanding of the Earth's processes is incomplete (National Research Council, 1993). Landsat imagery has been widely used in various types of analyses, specifically in studies analysing land cover change as data is cost efficient, has a longer history and higher frequency of archives compared to other remote sensing data sources (Rozenstein and Karnieli, 2010). Recently, human activity has been identified as a major driver in land use and land cover change, creating the need to develop an integrated understanding of the various elements in the Earth system (e.g. climate, hydrology, environmental processes and human activities) (Williams et al, 2006). In the mid-1980s, after a decade of Landsat research, it was evident that satellite remote sensing had the ability to provide the globally consistent, spatially disaggregated, and temporally repetitive measurements of land conditions that were needed in order to describe the Earth's terrestrial systems (National Research Council, 1993). Early research uses Landsat to demonstrate the significance of measuring spectral vegetation indices in order to record vegetation conditions (Jackson, 1983; National Research Council, 1986; Tucker, 1979).

All Landsat satellites have flown in a sun-synchronous orbit which allows the satellite to maintain a constant orientation between the Earth and the Sun. This resulted in the mean Sun time at each point in the orbit to remain relatively fixed. For example, the equatorial crossing time range from 8:30 a.m. Landsat 1, to 9 a.m. for Landsat 2, and to approximately 10:00 a.m. for Landsats 5 and 7 (USGS, 2006). The Landsat satellites are briefly described below and their characteristics are summarised in Table 7.

Landsats 1, 2 and 3 orbited at an altitude of 920km above the earth's surface, following a near-polar orbit. They circled the Earth every 103 minutes and completed 14 orbits each day. In order to produce a nearly complete coverage of the Earth's surface with 185km images swaths, the satellites took 18 days and 251 overlapping orbits. The main sensor onboard these

satellites was the Multispectral Scanner (MSS), with a resolution of approximately 80m, with radiometric coverage in four spectral bands from visible green to the near infrared (IR) wavelengths. On Landsat 3, the MSS sensor had a fifth band in the thermal infrared wavelength (USGS, 2006).

Besides MSS, Landsats 4 and 5 carried an improved thematic mapper sensor (TM). The MSS sensor was identical to the one onboard Landsat 3. The MSS and TM sensors detected reflected or emitted energy from the Earth's surface in the visible and IR wavelengths. The reflected energy is collected by TM bands 1, 5 and 7, while band 6 collects emitted energy. The sensor has a 120m resolution for the thermal IR band and 30m for the remaining 6 reflective bands. Data collection was halted by Landsat 4 in 1994 when onboard electronics failed. It remained in orbit as a test bed until it was decommissioned in June 2001 (USGS, 2006).

Landsat 6 was launched on 5 October 1993, but failed to reach orbit. Landsat 7 was launched on 15 April 1999 and carries the Enhanced Thematic Mapper plus (ETM+). The spatial resolution is 30m in the visible and IR bands, 60m in the thermal band and 15m in the panchromatic band (USGS, 2006).

Landsat 5 and 7 are the two remaining operational satellites, orbiting the earth at an altitude of 705km collecting data at 185km swaths. Each provides a 16 day, 233 orbit cycle. The two satellites are offset which allows for an 8 day repeat coverage (USGS, 2006).

Table 7: Summary of Landsat Characteristics

(Source: The Satellite Encyclopaedia, 2009)

Satellite	Launch Date	End of Life	Scanner	Resolution (m)	Swath width (km)
Landsat 1	23 July 1972	1978	MSS	80 m	185
Landsat 2	22 Jan 1975	1982	MSS	80 m	185
Landsat 3	5 March 1978	1983	MSS	80 m	185
Landsat 4	16 July 1982	1994	MSS & TM	80 m	185
Landsat 5	1 March 1984		MSS & TM	30 m (visible, near & middle IR); 120 m (thermal IR)	185
Landsat 6	5 Oct 1993			Failed to reach orbit	
Landsat 7	15-Apr-99		ETM+	15 m (panchromatic), 30 m (visible, near & middle IR)	185

3.1.2 Data Selection criteria for Landsat images

There are many factors that could result in poor data quality of the Landsat images. The characteristics of each image are weighed against the season as well as the year that it has been acquired. Reference for scene selection is based on the following:

The year of acquisition:

Landsat 4 and 5 MSS scenes were collected between 1972 and 1980. The data was very limited and much was lost through the degradation of the magnetic media. From 1985 to 1999, the Landsat program was commercialised which also led to a limited amount of data acquisition and archiving. Much of the Landsat TM 4 and 5 data were also not used due to extensive cloud cover, bad data quality and changing surface conditions. Preference was always given to the best scene (Tucker, 2004).

Cloud cover:

At any given time, approximately 60% of the earth's surface is covered by clouds. Although it would be better to use cloud free images, certain areas experience consistent cloud cover e.g. the Inter-Tropical Convergence Zone over the Equatorial regions. Priority is given to images with the least amount of cloud cover. In cases where similar cloud cover is observed in all of the images, the location of the clouds is taken into account as well as the vegetation phenology (Tucker, 2004).

Data quality:

The very nature of remote sensing makes the process prone to many types of errors. The Landsat data could be missing scan lines, pixel dropouts, saturation/missing bands etc. These are all common problems that could be related to the malfunction of instruments either on the satellite or at the ground receiving stations. Sometimes these errors are noted in the metadata. Priority was given only to the reflective channels. Issues regarding the quality of the thermal-band for TM and ETM+ data did not prevent the release of images from those periods. The final judgement with regard to data quality was based upon visual and radiometric inspections for every image used (Tucker, 2004).

Phenology:

In the case of TM and ETM images, the spectral bands are optimised for vegetation studies and therefore images taken during the growing season are favoured. The Landsat 7 data acquisition period was selected when the NDVI data was at its peak. Humid areas posed a problem as their peak greenness period was accompanied by high amounts of cloud cover. If clear scenes were unavailable, the image selection criteria were based on the amount of cloud cover. In the high latitude areas and also areas of high altitude the scenes were selected based on the amount of greenness and also the absence of snow and ice (Tucker, 2004). The wavebands of MSS, TM and ETM+ are summarised below in Table 8.

Table 8: Summary of wavebands

(Source: The Satellite Encyclopaedia, 2009)

Multi Spectral Scanner	Thematic Mapper	Enhanced Thematic Mapper Plus
0.5-0.6 μm (green): mapping coastal features in sediment-laden water	0.45-0.52 μm (visible): soil/vegetation differentiation & coastal water mapping	0.45-0.52 μm (visible)
0.6-0.7 μm (red): mapping roads and urban areas	0.52-0.60 μm (visible): vegetation mapping	0.52-0.60 μm (visible)
0.7-0.8 μm (red to near IR): as below	0.63-0.69 μm (visible): plant species differentiation	0.63-0.69 μm (visible)
0.8-1.1 μm (near IR): vegetation studies and mapping land/water boundaries	0.76-0.90 μm (near IR): biomass survey	0.76-0.90 μm (near IR)
	1.55-1.75 μm (IR): snow/cloud differentiation	1.55-1.75 μm (IR)
	10.4-12.5 μm (thermal IR): thermal mapping	10.4-12.5 μm (thermal IR)
	2.08-1.35 μm (IR): geological mapping	2.08-2.35 μm (IR)
		0.5-0.9 μm (panchromatic)

Single data runs:

Data obtained on the same day and on the same path makes it easier to derive information from the scenes. This is because the atmospheric data and solar zenith angle variation will gradually change for the data in question. This however would not apply to images taken on different day as the variation between images would be much greater in a constructed mosaic (Tucker, 2004).

3.2 National Land Cover (NLC) Dataset

Prior to the publication of the South African national land cover database, there was no standardised classification scheme for remote sensing applications as most have been developed for user specific applications thereby not being directly comparable. There was therefore an urgent need for a standardised database that will provide standard baseline

specifications thereby ensuring consistency and conformity in spatial data produced by different organisations for purposes such as environmental management and planning (Thompson, 1996). The CSIR and Agricultural Research Council (ARC) jointly established a project to produce a standardised digital land cover database for South Africa, Swaziland and Lesotho. The project aimed to provide a land cover data at a 1:250000 scale, derived from Landsat TM imagery.

In 1996 the National Land Cover mapping was successfully completed, providing for the first time a standardised 1:250000 baseline dataset on land cover for the whole of South Africa, Lesotho and Swaziland containing enhanced spatial detail and content. This vector dataset was updated in 2001 and is suitable for 1:50000 scale GIS-based mapping and modelling applications. The database is derived from Landsat 7 ETM+ imagery acquired during 2000 . 2002 and in conjunction with ancillary data (CSIR, 2002).

3.3 Census Data

The United Nations Department of Economic and Social Affairs defines a population census as % the total process of collecting, compiling, evaluating, analysing and publishing or otherwise disseminating demographic, economic and social data pertaining, at a specified time, to all persons in a country or in a well-delimited part of a country+ (StatsSA, 2001, p. 8).

The United Nations Statistics Division (UNSD) is a division under the United Nations Department of Economic and Social Affairs (DESA) and serves as the central mechanism within the Secretariat of the United Nations. Their function is to supply the statistical needs and coordinate activities of the global statistical system (United Nations, 2009). The United Nations Statistical Commission was established in 1947 and is responsible for overseeing the Division, it is also the highest decision making body for the coordination of international statistical activities and the head entity of the global statistical system (United Nations, 2009).

The UNSD is responsible for issuing standards and methods approved by the Statistical Commission to assist national statistical authorities as well as other producers of official statistics in planning and conducting successful population and housing censuses (United Nations, 2009).

Censuses are carried out at regular intervals, in most countries it is usually every five to ten years. Government uses the data for planning, policy making and administrative purposes e.g. distributing financial resources, as well as for social research. Other applications of the data include informing the public, businesses and industry. In most applications the data is used in basic analyses, often as an isolated dataset, however more recently the integration of census and spatial data has increased in the study of social sciences. Codjoe (2007) illustrates three examples where remote sensing and GIS has been used as analysis tools in population studies. Jensen and Cowen (1999) identified three remote sensing methods which could be used to attain population estimates namely:

- Individual dwelling unit counts
- Measuring urban extent
- Land use/ land cover classifications

Leddy and Mathur (2002) and Sutton et al (2001) used remote sensing to determine population estimates using night-time lights, although the weaknesses of this type of study is discussed in section 2.4.1. Finally, remote sensing and GIS can be used as census planning tools by identifying newly developed areas and providing regular updates of housing counts for planners (Codjoe, 2007).

3.3.1 A short history of census taking

South Africa's historical censuses are considered fragmented as only parts of the country and sections of the population were sampled. The first census was conducted in 1798. The first statistical manuscript, known as 'The Annual Blue Book in the Cape of Good Hope' was released in 1823. The manuscript continued till 1837, but was never published (StatsSA, 2001, p. 18).

Censuses that included all races were taken in the Cape in 1865 and 1875, Free State in 1880 and in Natal in 1891. In 1890 in the first Transvaal census, only the white population took part. The 1904 census was conducted in the Cape, Natal, Free State and Transvaal, and although they were separately conducted, they covered the whole country within the same year (StatsSA, 2001, p. 18). The Union of South Africa was formed in 1910, and government ruled in terms of the South Africa Act of 1909 that a population census for all races be conducted in that same year, and thereafter whenever the government indicated the requirement (StatsSA,

2001, p. 18). The censuses taken after 1960 were more reflective of the realistic situations of the populations i.e. the respondent reported on all individuals, regardless of being a usual resident or not, who spent the night at a particular dwelling.

Botswana's census taking started in 1904, on a de-jure basis until 1964, under British rule. After attaining independence in 1966, the United Nations advised that censuses were to be conducted in years ending with 0 or 1, resulting in the next census being conducted in 1971. The 1971 census was the first to be conducted on a de facto basis (Botswana Central Statistics Office, 2007).

Prior to independence, there were no statistical organizations in Namibia. A local section of the South African Statistical Services (SASS) was responsible for obtaining statistical information as required by the Office in Pretoria (Namibia Central Bureau of Statistics, 2003). The Central Statistics Office (CSO), which was later renamed to the Central Statistics Bureau, was established after independence in the National Planning Commission.

The census year and topics covered in each census are important as they provide common fields of reliable data which can be used in comparability studies. The South African Development Community (SADC) 2000 census initiative was aimed at achieving uniformity in terms of covering similar topics for better data comparability in the SADC (Botswana Central Statistics Office, 2007).

3.3.2 Challenges of population censuses

One of the most prominent issues regarding census data is the possibility of over or under estimation of the sizes of populations. In most cases undercounting tends to be more prevalent. The undercount rate is defined as the difference between the final estimate and the raw census count, and is expressed as a percentage of the final count (StatsSA, 1996).

South Africa's 1996 census was the first to be conducted across the whole country, which resulted in many people or dwellings not being reached. StatsSA (1996) states that there is a range of reasons that people could have been unintentionally excluded, which could include: They moved around during the period of the census and were difficult to contact.

a) They mistakenly thought that they were included by the informant in another household.

- b) They were not included by the householder completing the questionnaire who may have thought that, for example, young babies need not be included in the census.
- c) They were concerned about the confidentiality of their data and declined to be interviewed or to fill in the questionnaire.
- d) They were concerned about security and denied access to enumerators (particularly in some more affluent urban areas).
- e) They were on a farm where the enumerator encountered difficulty gaining access, particularly in remote areas or where farmers were not co-operative.
- f) Their dwelling was missed by the enumerator.
- g) The area they lived in was not demarcated.

The 1996 census revealed a 10.7% undercount in South Africa, increasing to 17% in 2001 (Schmidt, 2005).

In addition, the United Nations has identified further challenges posed by groups that are considered difficult to enumerate. The challenges are listed below (further discussion is provided in United Nations (2008)):

- a) *Nomads and persons living in areas to which access is difficult.*
- b) *Civilian residents temporarily absent from the country.*
- c) *Civilian foreigners who do not cross a frontier daily and are in the country temporarily, including undocumented persons or transients on ships in harbour at the time of the census.*
- d) *Refugees.*
- e) *Military, naval and diplomatic personnel and their families located outside the country and foreign military, naval and diplomatic personnel and their families located in the country.*
- f) *Civilian foreigners who cross a frontier daily to work in the country.*
- g) *Civilian residents who cross a frontier daily to work in another country.*
- h) *Merchant seamen and fishermen resident in the country but at sea at the time of the census (including those who have no place of residence other than their quarters aboard ship).*

4 Methodology Technique

The methodology utilized in this study follows approaches taken by researchers, as previously discussed, in attempt to monitor urban expansion. The main aspects of the methodology are summarized in Table 9 below:

Table 9: Methodology approach and references

Technique	Steps implemented	Reference work
Data Selection	Use of Landsat MSS, TM and ETM imagery in time series analysis	<ul style="list-style-type: none"> · Lu and Weng (2005) · Angel et al (2005)
Pre-processing	Scanning and georeferencing topographic maps to use as reference data	<ul style="list-style-type: none"> · Elnazir, Xue-zhi and Zheng (2004) · Manonmani and Suganya (2010)
	Digitising and extracting land classes to be used as reference data	<ul style="list-style-type: none"> · Rosenstein and Karnieli (2010)
	Subset to required areas and eliminates irrelevant areas	<ul style="list-style-type: none"> · Angel et al (2005)
Unsupervised Classification	The technique was selected as no field work had been conducted and no knowledge of classes present in each site existed	<ul style="list-style-type: none"> · Menz and Bethke (2000) · Angel et al (2005) · Schneider (2007) · Thapa and Murayama (2009) · Rozenstein and Karnieli (2010)
	The use of varying amount of clusters in the classification due to the difference in imagery	<ul style="list-style-type: none"> · Menz and Bethke (2000) · Angel et al (2005) · Thapa and Murayama (2009)
	Comparison of classification results to aerial photos, Google Earth imagery and topographic maps to verify urban areas and eliminate any identified errors	<ul style="list-style-type: none"> · Elnazir, Xue-zhi and Zheng (2004) · Manonmani and Suganya (2010)
GIS Integration	Dataset conversion	<ul style="list-style-type: none"> · Rozenstein and Karnieli (2010)
	Producing binary dataset from results	<ul style="list-style-type: none"> · Rozenstein and Karnieli (2010) · Angel et al (2005) · Ma and Xu (2010)
	Use administrative boundaries to clearly define the study areas and maintain uniform areas throughout the time series	<ul style="list-style-type: none"> · Angel et al (2005) · Rozenstein and Karnieli (2010)
	Use of topographic maps in the absence of electronic spatial data	<ul style="list-style-type: none"> · Angel et al (2005) · Elnazir, Xue-zhi and Zheng (2004) · Rozenstein and Karnieli (2010) · Manonmani and Suganya (2010)
	Super impose time series data for each study site	<ul style="list-style-type: none"> · Ma and Xu (2010) · Thapa and Murayama (2005)

Process flow diagrams of the methodology employed are indicated in Figure 30 and Figure 31, after which they are comprehensively explained. The flow diagrams utilise various objects to indicate the types of steps used in the analysis process. The figures below serves as a key in order to create a clearer understanding of the process:

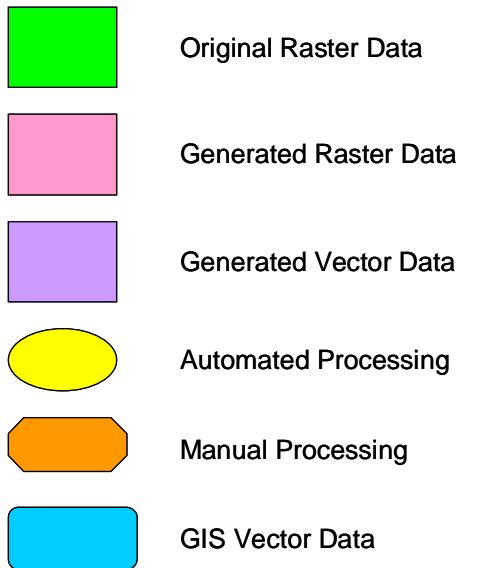


Figure 28: Key for Figure 30

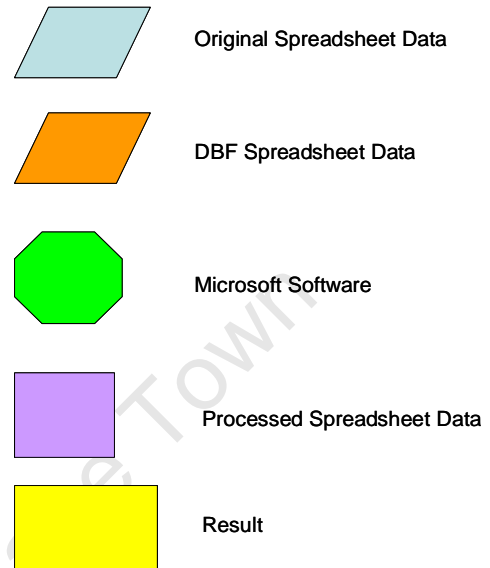


Figure 29: Key for Figure 31

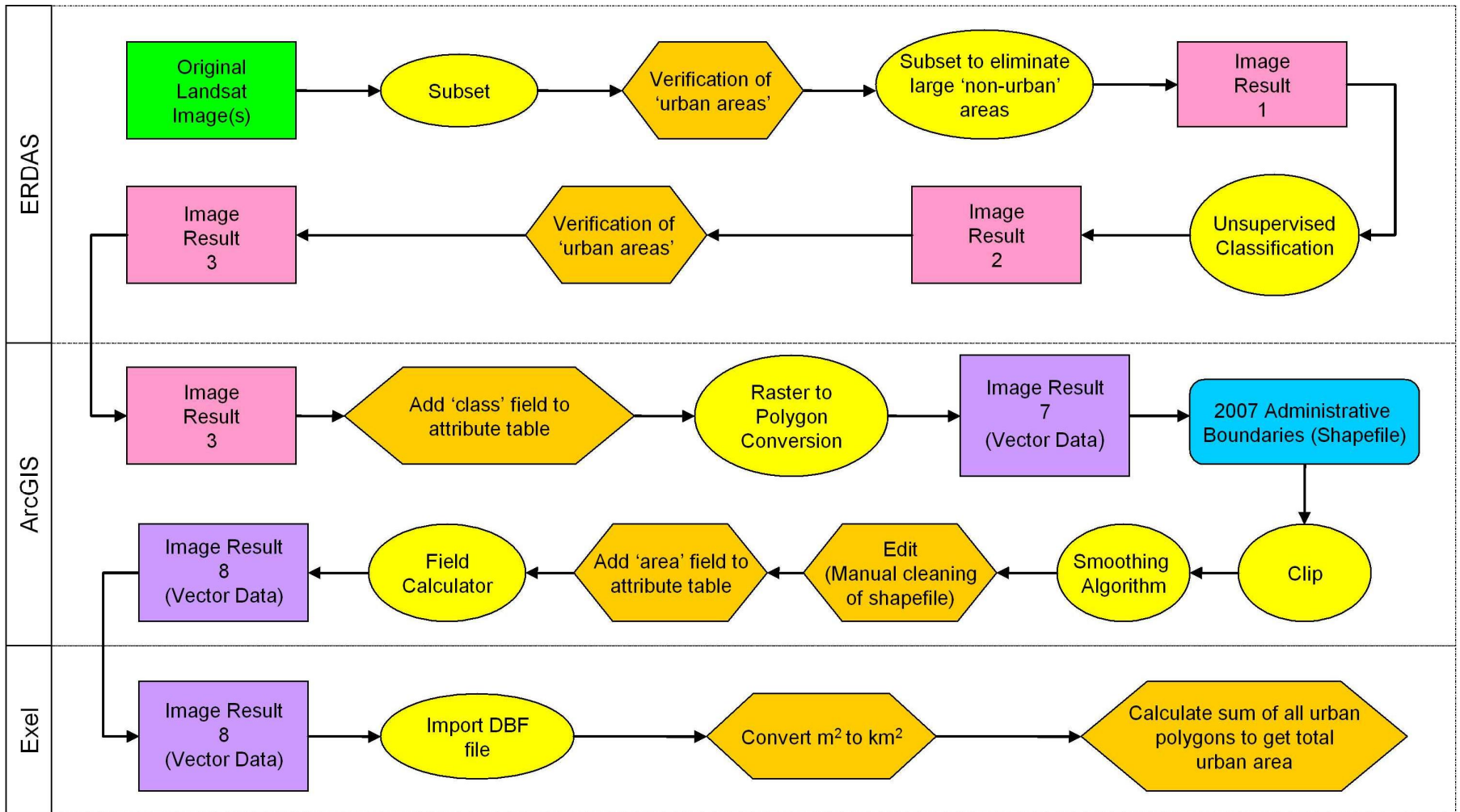


Figure 30: Methodology used to analyse the Landsat and topographic maps (x-axis component of correlation graph)

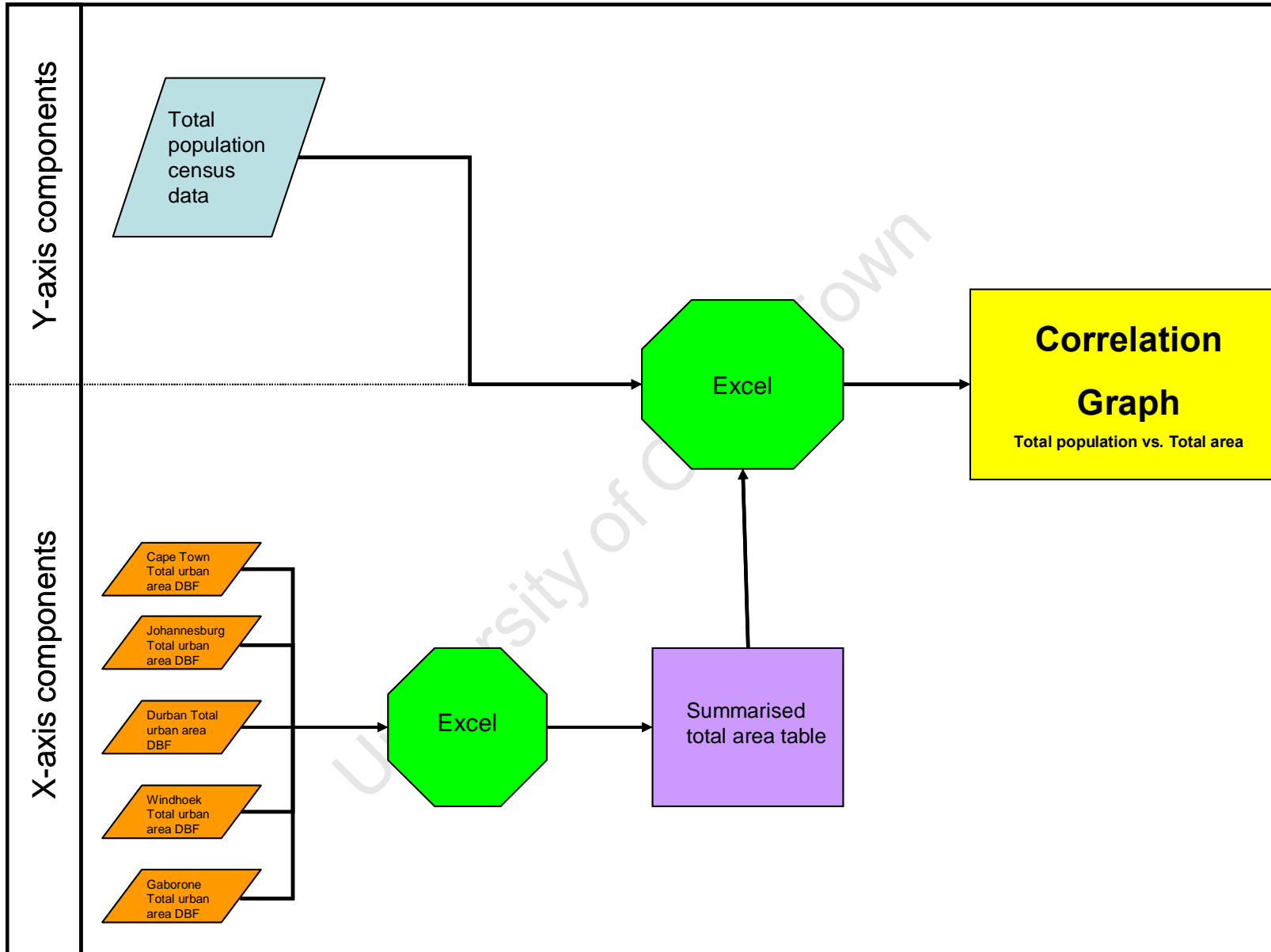


Figure 31: Methodology used to create the correlation graph (Total population vs. Total area)

4.1 Defining the study areas

The study areas are defined by their latest respective metropolitan boundaries, provided by the Demarcation Board of South Africa, for the South African study sites. As stated in Section 1.5, the study aims to test the feasibility of the devised methodology for mapping urban expansion in five Sub-Saharan African cities, within defined boundaries and at a fixed scale. The use of the administrative boundaries will ensure:

- Study sites have a constant total area throughout the time series;
- A constant scale will be used throughout the time series for each of the study sites, therefore allowing for comparative analyses to be made across the time series without changing the scale;
- The issue of urban sprawl²⁹ is eliminated whereby all areas occurring outside the municipal administrative boundary is excluded from the study e.g. the rapidly developing and expanding Midrand corridor between Johannesburg and Pretoria;
- The area being analysed occurs within a politically defined boundary; and
- Allow the methodology to be tested given that the administrative boundaries encompass a variety of different land cover types including urban regions, open spaces and in some areas, rural landscapes.

Gaborone and Windhoek's political boundaries were obtained from the Global Administrative Areas website however, the city boundaries were not as clearly defined as the South African study sites, and they covered much larger areas. For Windhoek, the urban edge was defined by the area used in the 2001 census count, which covered the area identified as urban in the topographic maps. Gaborone's area was slightly more challenging to define as the surrounding villages had been engulfed by the expansion of the city. These villages have recently reached suburb status within the city, although their land tenure is still tribal. The villages were incorporated into the study area as they are considered as part of the Gaborone urban area. A rectangular area was used to define the study site by using four x:y coordinates³⁰ to define the rectangle's corners and clipping the rectangle according to these coordinates. The same image extent (ground area) was used throughout the analysis.

²⁹ Refer to definitions

³⁰ Refer to definitions

4.2 Research Materials

This section describes the research materials used in this study. The primary software used was ERDAS Imagine 9.1 and ArcGIS 9.2.

4.2.1 Landsat Data

Remote sensing was used as a tool to monitor urban growth in Sub-Saharan Africa. In order to accomplish this, a continuous, image dataset was needed which had been identified in the form of NASA's Landsat images. The dataset is valuable because all the images are orthorectified as well as geodetically accurate with resolutions between 30m and 80m (Tucker, 2004). Landsat Thematic Mapper (TM), Multi-Spectral Scanner (MSS) and Enhanced Thematic Mapper (ETM+) images will be used for this study. Landsat has been improving and expanding its dataset since 1972. The consistency and quality of the data makes it a good source in order to analyse changes that occur on the earth's surface (NASA, 2007; Tucker, 2004). The data was projected in Universal Transverse Mercator (UTM).

Vast amounts of literature have highlighted a variety of remote sensing techniques that have been used to calculate the extent of urban areas. However, the methodology used in this study involves the unsupervised classification method (ISODATA algorithm) that is quite general and can be applied in a variety of other analyses e.g. studies of bush encroachment. An important aspect to note is that the analysis of urban areas is largely based on the assumption that the areas determined by the cluster analyses are in fact urban³¹.

Urban areas in the Landsat data are addressed by considering both the definition of urban in terms of this study and by taking the primary land use into account as described by the CD:NGI (Section 1.5). The urban areas identified in the Landsat data were therefore man-made structures including residential areas, industrial areas and transport routes and commercial areas.

Although in some cases two Landsat tiles were required to fill the extent of the study areas, mosaicking of the images prior to classifying them was however not required nor was it advisable. The signatures of the same land cover classes in two different Landsat scenes are different, mosaicking the images would alter the original data and thereby affect the classification.

³¹ Refer to definitions

Table 10: List of images to be used in the study

(Data Source: GLCF, USGS)

Area	Date	Image	WRS:P/R
Cape Town	1972	MSS	1:184/083
	1991	TM	2:175/083
	1991	TM	2:175/084
	2000	ETM+	2:175/084
	2000	ETM+	2:175/083
Durban	1972	MSS	1:180/081
	1991	TM	2:168/081
	2001	ETM+	2:168/081
Johannesburg	1972	MSS	1:182/078
	1991	TM	2:170/078
	1991	TM	2:171/078
	2002	ETM+	2:171/078
	2002	ETM+	2:170/078
Gaborone	1972	MSS	1:184/077
	1991	TM	2:172/077
	2002	ETM+	2:172/077
Windhoek	1973	MSS	1:191/076
	1989	TM	2:178/076
	2001	ETM+	2:178/076

4.2.2 Population Data

The population data for the South African study sites were obtained from Statistics South Africa (Stats SA) as well as historic statistics records that were available from the University of Cape Town's Government Publications Library. Namibia's National Planning Commission, Central Bureau of Statistics (Demography Department) provided Windhoek's historic and recent census data. The data required for Gaborone was obtained from Botswana's Central Statistics office.

Since only the total population for each city was required, there was no data preparation needed prior to its application in the analysis.

One of the major limitations of the study is that the census data was not available for the same years that the Landsat images were available for. The later census data (mostly from the 2000s and onwards) was available for all the cities in roughly the same years which was a result of the United Nations advice of conducting full population censuses in years that ended either in 0 or 1.

The following census dates are available in order to obtain the total populations of each city:

Table 11: List of the census data used in the analysis

(Source: StatsSA, Botswana Central Statistics Office and Namibia Central Bureau of Statistics/Demography)

Study Site	Year	Total Population
Cape Town	1970	793757
	1996	2563095
	2001	2893240
Durban	1970	541543
	1996	2745926
	2001	3090123
Johannesburg	1970	635769
	1996	2638233
	2001	3225809
Windhoek	1973	69,111
	1989	134985
	2001	233529
Gaborone	1971	17718
	1991	69435
	2002	187116

4.2.3 Accuracy Assessment Data

In 1994 the CD:NGI compiled South Africa's first National Land Cover Dataset in shapefile format, which was subsequently updated in 2001. Urban areas were classified into 3 categories (as defined by the CD: NGI and explained in Section 1.5), including:

- Urban / built up: Commercial
- Urban / built up: Industrial / transport
- Urban / built up: Residential

These classes were grouped together to form the generalised urban layer which was to be used in the analyses to represent the end date of the time series for the South African study sites. Due to

the level of accuracy of the data, it would also be appropriate to use as the reference layer when conducting the accuracy assessment.

For the purpose of the analysis, it was deemed necessary to obtain the 1:250 000 topo-cadastral maps in order to extract the urban areas for years prior to the release of the Landcover Datasets. The urban areas will be extracted using an unsupervised classification technique, which should be relatively uncomplicated as all urban areas are depicted as yellow polygons.

1:250 000 Topo-cadastral maps were obtained from the CD: NGI, for the South African study sites, each of which has being derived from 32 1:50 000 component maps (CD: NGI, 2010). These maps were selected as the scale incorporates the full extent of each study area as well as depicting urban areas, with a negligible amount of generalisation. This map series is also preferred for both regional planning and administrative purposes (CD: NGI, 2010). As with the Landsat images, the same administrative boundaries and methods were used to define the study areas, particularly in the case of the South African study sites.

One of the study's limitations presented itself during the data collection phase whereby recent topographic maps for Windhoek and Gaborone were unattainable. Thus only two out of the required three topographic maps could be utilised in the study. All the Landsat images were classified in the study.

The above mentioned dataset would be used to evaluate the accuracy of the unsupervised classification.

4.3 Methodology

4.3.1 Data Preparation

Spatial subsetting was applied to all the images to minimise the spatial extent of the Landsat tiles, thereby focussing the analysis on the study areas as defined by the administrative boundaries, this would also therefore eliminate potential spectral signatures in the scene that could influence the unsupervised classification process, as larger areas theoretically have more spectral signatures as there are more surfaces present in the scene. Subsetting was achieved by defining a rectangular area covering the extent of the respective study site was exported from the original tile. This resulted in each Landsat image having the same spatial extent throughout the time series for each respective study site.

The image subsets were further reduced by making use of aerial photography and freeware such as Google Earth to identify and remove large non-urban areas from the scenes. This was done to eliminate large areas e.g. wetlands (such as Zeekoevlei in Cape Town and mining areas in Johannesburg), forest and agricultural land that may influence the classification as the aim of the classification is to only extract urban³² areas from the images. By eliminating areas that have been verified (by means of visually analysing images and relying on indigenous knowledge) as non-urban, the possibility of classifying areas incorrectly is also reduced (i.e. the amount of spectral signatures in the images are reduced, thereby reducing the possibility of confusion that could result during the classification).

During this process, only subsetting and clipping techniques were implemented in order to reduce the amount of spectral signatures by eliminating areas that were verified to be non-urban in terms of the definition used in this study. The administrative boundaries were not used to clip the data during this stage of the process.

4.3.2 Data Analysis

The analysis was based on visual interpretation which was limited to a three band (RGB) colour composite. Once the images have been further reduced, leaving only the relevant areas to be analysed, an unsupervised classification was performed on the data. The Iterative Self-

³² Refer to definitions

Organizing Data Analysis Technique (ISODATA) clustering algorithm was applied to the dataset. The amounts of classes used to perform the classification differed for each image which was particularly due to the fact that the number of spectral signatures in each image was unknown, it is however noted that the amount of spectral signatures present in the respective scenes had been reduced due to the subsetting and manual clipping techniques. This sometimes resulted in the classification being performed many times on the same scene to determine the appropriate amount of classes. The final classified images were selected based on the accuracy of the classification to extract different urban surfaces e.g. buildings made from different material and different infrastructure surfaces (e.g. roads). The classification function also provided the option of producing the output image in either greyscale or in the same colours observed in the original image, in most cases the latter option was selected, although in some cases greyscale images provided better results than colour images as it made the visual interpretation of the images marginally easier, allowing urban areas to be more easily identifiable.

The resulting classified images and the unclassified images were then geographically linked in terms of the view, allowing the two images to be synchronised while assigning the urban classes. The manual classification involves the use of a crosshair that identifies the attribute of the pixel it focuses on. The attribute data contained the class of the pixel which could then be changed in the raster attribute table. All the identified urban classes were assigned unique colours (Appendix Figure 1 to Appendix Figure 5).

Once the raster urban classes were created, they were imported into ArcGIS. The attribute tables were edited to include a field called 'Class' this field was going to be used to create the binary dataset (urban vs. non-urban). Urban pixels were assigned the value of 1 and non-urban 0. ArcToolBox provided a conversion tool to convert raster data to vector data thus creating the various urban polygons for the respective time slices. In cases where two Landsat tiles were required for a single time slice, the two separate shapefiles were merged. The resulting shapefiles were subsequently overlaid with the administrative boundaries relevant to the corresponding study site and clipped to produce the final shapefile containing urban areas within the defined study area (i.e. administrative boundaries).

To calculate the areas of the identified urban areas, a VBA script was used in the ArcGIS field calculator, namely:

```
Dim dblArea as double
Dim pArea as IArea
Set pArea = [shape]
dblArea = pArea.area
```

The database file obtained from the shapefile was then imported into MS Excel. The database file contained all the data that can be viewed in the attribute table, but excel was used as a quicker means of calculating the total area. The sum of the areas generated by ArcGIS were calculated and converted to provide the total urban area in square kilometres.

4.4 Creating the graph: Correlating total urban population and total urban area

The final phase is to determine the correlation between the total urban population vs. total urban areas, where total urban population is represented on the y-axis and total urban area on the x-axis.

Most countries conduct censuses at regular intervals every five to ten years. The data obtained is important as it informs government policy making, planning as well as administration. In terms of demographic and social research, it informs business, industry, labour and the public. Ultimately population censuses provide disaggregated data that defines the characteristics of the population in small geographic areas and communities (StatsSA, 2001). The spatial extent of census data is usually on a national scale, although in some cases, there may be a demand for a census to be conducted over a smaller scale.

An Excel spreadsheet was created with the total urban area and total urban population, taken from census data, for each year in the time series. The results for each city were graphically represented.

4.5 Reference Data

The end date of the time series (i.e. the year 2001) was also the year in which the second National Land Cover Dataset was released by the CD:NGI, this was used as a reference against which an accuracy assessment could be performed, thereby testing the accuracy of the methodology in extracting urban areas. The first National Land Cover Dataset was produced in 1996 and also used in this study, however, personal correspondence with personnel from CD:NGI revealed that shapefiles such as those produced for the National Landcover Dataset was not available for the earlier required years (i.e. 1970s) The solution to overcome this challenge was to utilise the 1:250000 topo-cadastral maps to extract urban areas for the required time slice in the time series.

The 1:250000 topo-cadastral maps for the 1970s were easily obtained, and the year of production coincided (or was very near to) the dates of the Landsat images, it was decided that they would be subjected to a similar classification as proposed in the methodology in order to extract the urban areas. The resulting layers would then be used as reference data for the earlier dates in the time series in order to determine the difference in the results obtained from the classification in terms of identifying urban areas. These layers required some rectification using GIS in order to produce accurate urban polygons. Due to the additional errors introduced by making use of this method, the urban areas were only extracted to provide a representation of the urban areas to complete the time series and were not used as part of the accuracy assessment. It is important to note that for any study where reference data is utilised, it is advisable that the data remains unchanged and that no analyses are performed which might result in the data being manipulated and thereby becoming unreliable as a reference data source as reference data are assumed to be accurate and obtainable from reliable sources.

4.5.1 Preparation of additional reference data

Windhoek's topographic maps for 1977 and 1983 were obtainable from CD:NGI due to the country being under South African rule at the time of the production of the topographic maps, however, Gaborone's 1968 topographic map was obtained as a JPEG image and the 1991 map as a hard copy. The hard copy was required to be scanned in order to create an electronic version, after which, both of Gaborone's maps needed to be georeferenced.

4.5.1.1 Georeferencing/ Geometric Correction

Georeferencing means to define the existence of something in physical space (ESRI, 2008). When georeferencing a raster image, map coordinates are usually used to define the location and assign a coordinate system. This allows the raster dataset to be analysed with other geographic information (ESRI, 2008).

The raw image (topographic map) was imported into ERDAS alongside a separate viewer containing an already rectified image of the relevant study area. The Polynomial geometric model for correction was selected. The rectified image was used to obtain the Ground Control Points (GCP), which mainly used features which were easily identifiable on both the image and topographic map. To ensure accuracy, more than 10 GCP were used in the rectification process. The UTM projection was used as the preferred projected co-ordinate system, whilst the WGS84 datum was used. Once all manual GCP points have been placed, ERDAS automatically placed additional GCP points corresponding to the input GCPs based on the chosen geometric model. Once these points have been verified and/ or adjusted the input and references were saved, resulting in a georeferenced image.

4.5.2 Extracting urban areas from topographic maps

The topographic maps were used as reference data for the 1970s classification for the South African study sites and as the only reference data sources for Windhoek and Gaborone. Although it is noted that the use of the topographic maps is not ideal, it was needed to complete the time series. The accuracy assessment implemented in this study only uses the latest available information (NLC dataset, 2001) to evaluate the accuracy of the results.

The process of extracting urban areas from the 1970s topographic maps was considerably easier than obtaining them from the Landsat images. Due to the simplified nature of the topographic maps, fewer classes were created during the unsupervised classification. The urban areas on the topographic maps were generally of uniform colour, which simplified the identification and extraction processes. The classified rasters were exported from ERDAS and imported into ArcGIS where the identified urban areas were converted into vector data (shapefiles). The data was then manually edited to eliminate the gaps in information left by the text from the topographic maps. Thereafter the same VBA script was used to calculate the total urban area.

The data was used to create similar graphs by correlating the total population with the total urban area generated from the topographic maps in order to serve as a comparison for the graphs obtained using Landsat imagery.

4.6 Total Urban Expansion

The total urban expansion area was calculated for each study site by subtracting the initial total urban area obtained from the classification results from the final area in square kilometres.

$$\text{Total Urban Expansion} = U_{\text{final}} - U_{\text{initial}}$$

Equation 6: Total Urban expansion

4.7 Accuracy Assessment

To determine the feasibility of the methodology, an accuracy assessment was performed on the data. Since only one class has been extracted from the Landsat images, and the data has been converted from raster to vector format in order to be compared to the referenced data (which was originally obtained in vector format), the use of an error matrix would not be an appropriate method. Obtaining census data, Landsat imagery and reference data for the same year was a major limiting factor in this study. The accuracy assessment was performed on all the data, although it is notable that the data that meets the criterion of having both Landsat image and reference data years as close as possible is tabulated below:

Table 12: List of the data to be used in the accuracy assessment

Study Site	Census Year	Landsat Image Year	Reference Data Year
Cape Town	2001	2000	2001
Johannesburg	2001	2002	2001
Durban	2001	2001	2001

Since the reference data is in GIS shapefile format, and the classification results has also been converted to vector data, a simple technique has been devised to determine the accuracy of the methodology.

Initial data preparation of the reference data involved clipping the shapefiles using the same administrative boundaries that was used to clip the classifications. As defined in this study, the reference data urban classes were limited to:

Urban / built up: Commercial

Urban / built up: Industrial / transport

Urban / built up: Residential

The reference data was used to clip the classification results in order to produce the urban areas that were accurately identified by the classification. The total area of these classification results were calculated, producing the results in square kilometres (km²). Since the reference data is generally assumed to be correct and accurate, the percentage accuracy for the vector data was calculated using the equation below:

$$\text{Percentage Accuracy} = \frac{\text{Total area}_{\text{(clipped classification results)}}}{\text{Total area}_{\text{(reference data)}}} * 100$$

Equation 7: Equation used to calculate the percentage accuracy

The percentage accuracy therefore only reflects the accuracy of the methodology in identifying urban areas that corresponds with the reference data.

5 Results

The purpose of this section is not to provide a thorough analysis and discussion of the results, but rather to note general observations obtained from the classifications and to describe any evident trends.

The results will be discussed in detail in Section 6.

5.1 Summary

Table 13 provides an overall summary of the data and results obtained in the analysis.

The proceeding sections illustrate the results obtained from the:

- Classification of Landsat images for each study site (including a general observation report for each site)
- Urban areas represented by the reference data (National Land Cover Datasets and topographic maps)
- Total population vs. Total expansion graphs
- Landsat Classification vs. Reference data urban expansion graphs
- The difference between the two classifications (in tabular format)

Table 13: Summary of results

Study Site	Census Year	Total Population	Image Year	Class Area (km ²)	Ref. Data Year	Ref. Data Area (km ²)	Accurately identified urban areas (km ²)	Accuracy (%)
Gaborone	1971	17718	1972	9.3	1968	1.7	No Data	No Data
	1991	69435	1991	28.5	1991	19.0		
	2002	187116	2002	72.5	No Data	No Data		
Windhoek	1973	69111	1973	9.8	1977	10.3	No Data	No Data
	1989	134985	1989	24.8	1983	11.9		
	2001	233529	2001	39.0	No Data	No Data		
Johannesburg	1970	635769	1972	103.5	1970	277.9	82.6	29.7
	1996	2683233	1991	378.7	1994	618.2	304.2	49.2
	2001	3225809	2002	796.3	2001	634.9	581.0	91.6
Durban	1970	541543	1972	44.8	1970	184.8	41.0	22.2
	1996	2745926	1991	103.6	1994	570.4	96.5	16.9
	2001	3090123	2001	136.2	2001	639.5	133.4	20.9
Cape Town	1970	793757	1972	209.9	1970	148.0	76.9	51.9
	1996	2563095	1991	238.4	1994	558.2	250.9	45.0
	2001	2893240	2000	433.0	2001	617.0	446.8	72.4

5.2 Results per study site

This section contains the results illustrating urban expansion according to both the classification and reference data represented as separate maps for each study site. The time series results for each respective city are displayed as overlays in order to present a visual illustration of the urban expansion that has occurred over the time series. Note that this does not take the happening and dynamics occurring within the city into account.

Only the most recent administrative boundaries were used in order to ensure that the study area remains constant for each study site throughout the time series. The use of historic administrative boundaries would be inappropriate as boundaries tend to be shifted over time by municipal authorities.

Regarding the reference data, for the South African study sites the National Land Use Dataset was obtained from CD:NGI which illustrates the National land use and land cover for 1994 and 2001. There was no historic data available for the 1970s and urban areas from 1:250000 topographic maps were extracted to serve as the reference data for this period. In the case of Windhoek and Gaborone, there was no NLC data available and the topographic maps were the only source of available reference data.

The urban areas extracted from topographic maps (i.e. to represent the urban area during the 1970s in the time series, thereby completing the time series) required extensive editing in order to create the layers. This was particularly due to the labels present on the maps which created holes in the classification layers, however, every effort was made to eliminate this problem. Windhoek and Gaborone topographic maps were obtained as JPEGs and hard copies respectively, which then required them to be georeferenced. The process of georeferencing is described in section 4.5.1.1, which also accounts for the slight offset of the images. The information obtained from the topographic maps serves to represent the urban area during that time period in order to complete the time series and it is acknowledged that the use of this method has the potential to introduce additional errors in the classification. It is for this reason that the information obtained from the topographic maps will not be used as a reference layer to determine the accuracy of the methodology.

The total urban expansion area for each city was calculated in order to produce the values needed to create the x-axis of the graph similar to that illustrated in Figure 1, in a Sub-Saharan Africa context. For the purpose of this study, two graphs were created, to represent the classification results and reference data respectively.

The observations relating to each map in this section only discusses the general noted trends of the results obtained from the classifications. A more thorough analysis, motivation and possible reasons for the observed expansion trends are discussed in detail in Section 6. For all the graphs in this section, the census dates are reflected on the graph, followed by the year the Landsat image was taken, which is shown in brackets.

University of Cape Town

5.2.1 Cape Town Results

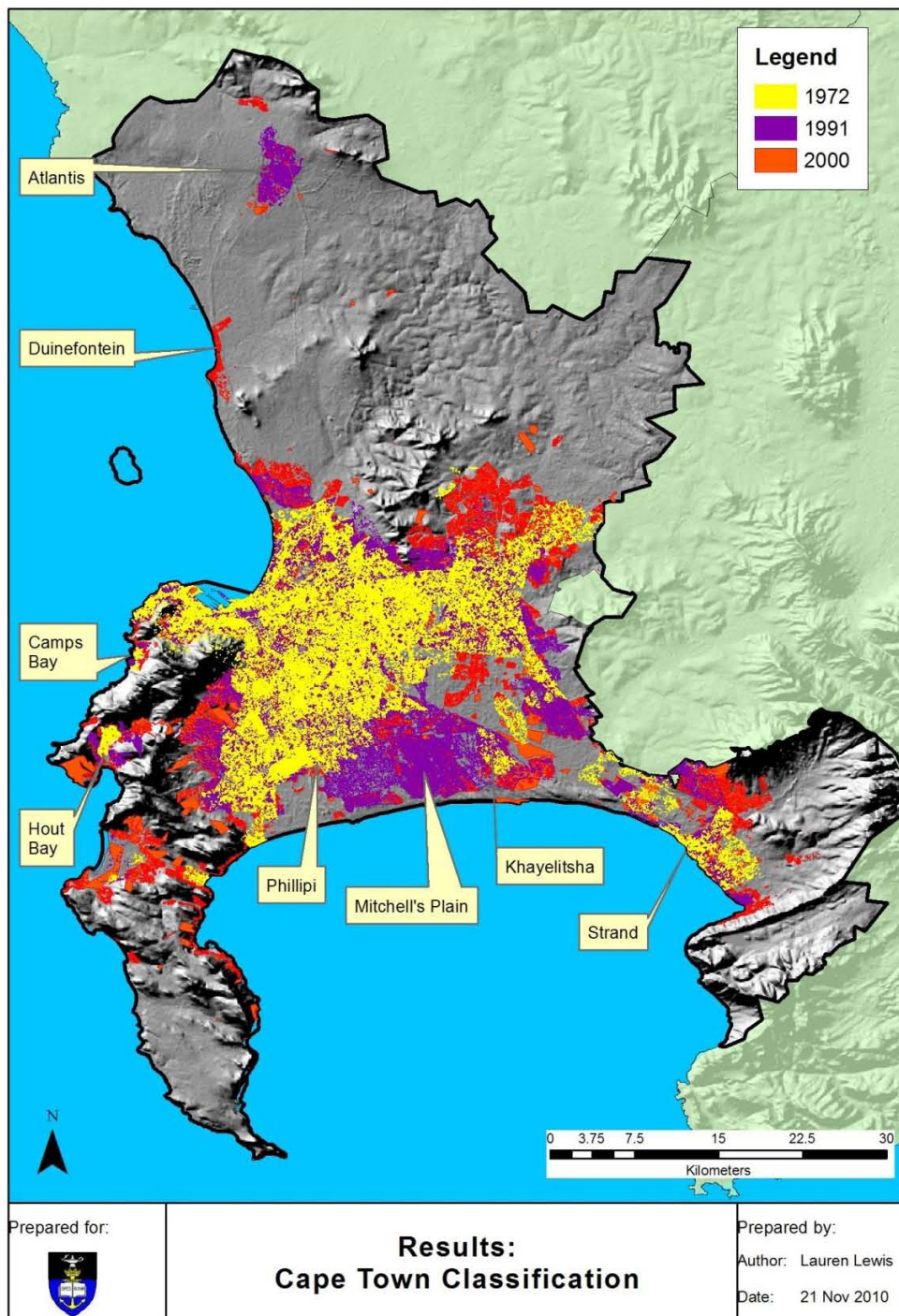


Figure 32: Cape Town classification results

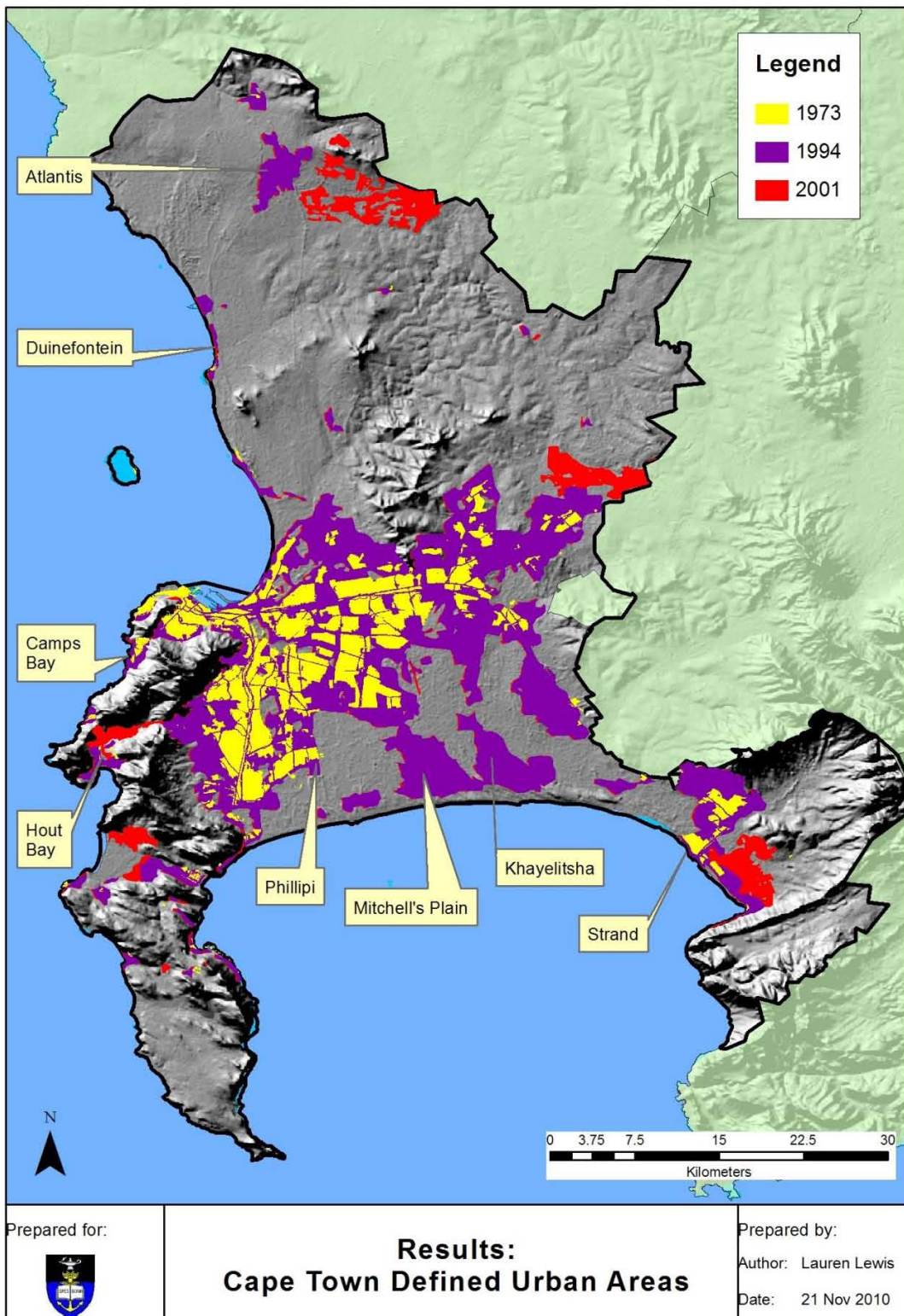


Figure 33: Cape Town reference data map

The 1973 layer illustrated in yellow on the map (Figure 32), shows that large scale development was already present in Cape Town, specifically on the Cape Flats and in the central business district (CBD) areas, which shows a high density of urban infrastructure. Camps bay shows a small area consisting of urban infrastructure and further south, the Hout Bay area appears as a small settlement near the harbour. Glencairn, Dassenberg and Kommetjie also appear to have been small settlements. Further eastwards, Somerset West shows that infrastructure is present. A similar trend is evident in Figure 33 whereby development is present on the Cape Flats and CBD area extending in an eastward direction. Khayelitsha appears as a small settlement during this period. Urban infrastructure is also present in the Strand area. The most noticeable differences between the 1973 classification and reference layer is that areas such as Mitchell's Plain, Phillipi and Khayelitsha which are currently densely populated areas, are not represented in the reference data. This is due to the forced removals and relocation of coloured and black communities during apartheid. Neither the classification nor the reference data indicates any settlement in Atlantis during this period.

The 1991 classification layer illustrated in purple on the map (Figure 32), shows the amount of development in Hout Bay has increased and is expanding northwards and up the mountain slopes. This trend is also evident in Camps Bay. The classification did not yield results of expansion in Glencairn, Dassenberg and Kommetjie. The Cape Flats shows dense settlement present in the Mitchell's Plain area, extending westwards towards the Phillipi area which was not present in the previous classification. Khayelitsha shows a drastic increase in infrastructure since 1973. The same trend is observed in Figure 33 where Mitchell's Plain and Khayelitsha both occupy large areas. The Atlantis and Melkbosstrand areas also show urban infrastructure which has developed after 1973 (Figure 32 and Figure 33). The Somerset West and Gordon's Bay areas are also shown to have expanded in both maps. In Cape Town as a whole, there is a general trend of outward expansion trend, where development tends to be occurring further up the mountain slopes in some areas. The mountains are also responsible for restricting development in Cape Town.

In 2001 (illustrated in red on the map (Figure 32)), the results of the classification do not show any large new areas of development, but rather increased outward expansion in the existing areas. This includes more development occurring further up the mountain slopes. Glencairn, Dassenberg and Kommetjie appear to have expanded dramatically, with some smaller areas

shown to have developed south of Glencairn. Duinefontein only appears in the 2001 classification, whereas according to the reference data it has been in existence prior to 1994. Figure 33 also shows some new areas that developed after 1994, including the area east of Atlantis which is not present in the classification. Further investigation using Google Earth revealed that infrastructure is present in these areas, although no dense development has occurred. Most buildings in the area are large and situated on big plots of land which could indicate commercial activities occurring in the area.

The urban areas for each map and each part of the time series was calculated and plotted on a graph against the total population (Figure 34):

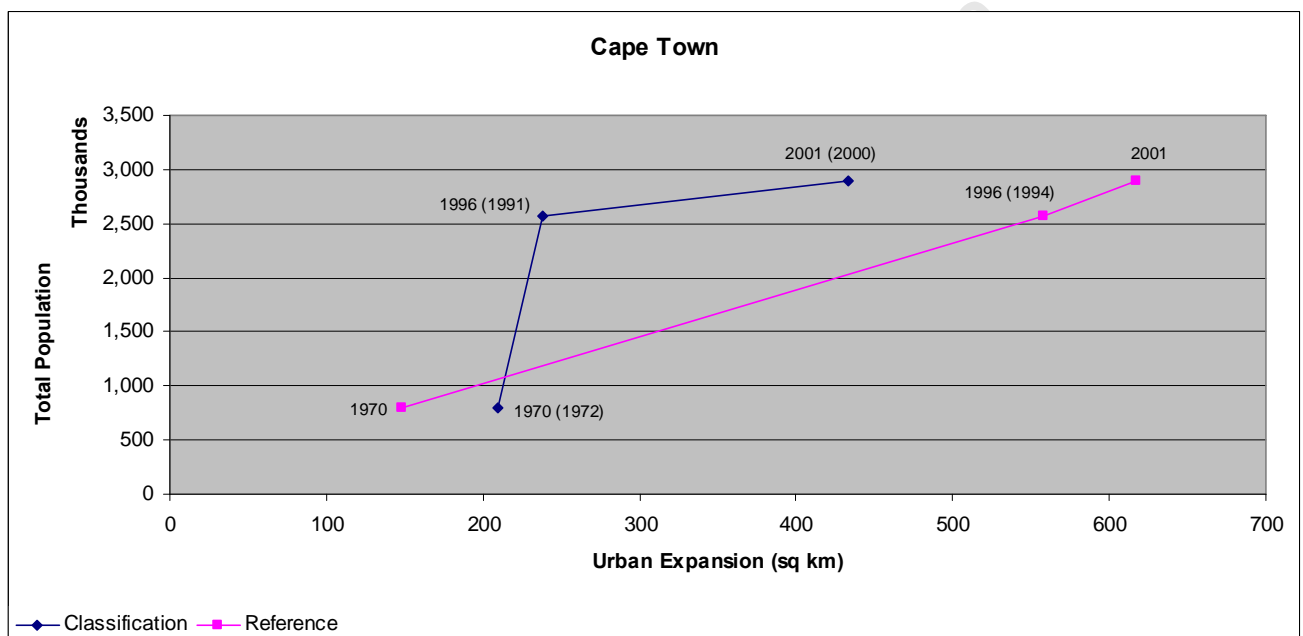


Figure 34: Cape Town comparison graph

The comparison between the classification and reference data for Cape Town shows that the reference data graphs appear to be linear compared to the results obtained from the classification. Initially the classification shows that the amount of urban area for 1972 was greater than the urban area represented in the reference data (topographic map). This could be a result of the image used for the classification being two years older than the reference data, although it could also possibly be due to challenges regarding the methodology.

The most dramatic difference in the urban expansion results is illustrated for the 1996 census year. Although the reference data (NLC 1994) and classification results differ by three years,

the difference in the amount of expansion that occurred appears to be too great for the classification to be considered accurate in this case. In addition, the classification results do not show that much expansion has occurred between the 1972 and 1991 images. Again, this brings the methodology and data into question. The results obtained from the classification in 2000 also showed an underrepresentation of the amount of urban area when compared to the reference data (NLC 2001). Notably, there is only a one year difference between the reference data and the image used for the classification.

University of Cape Town

5.2.2 Durban Results

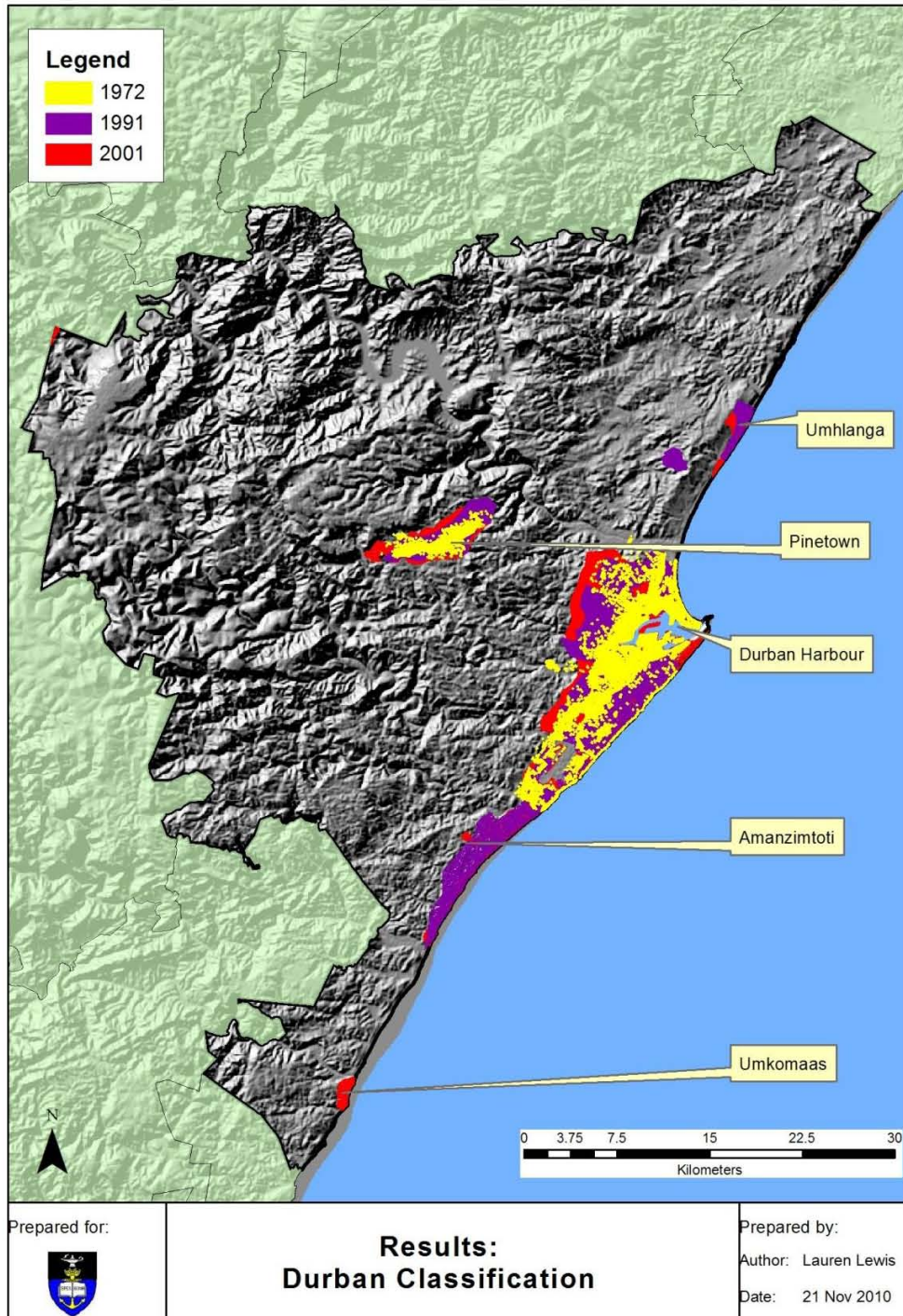


Figure 35: Durban classification results

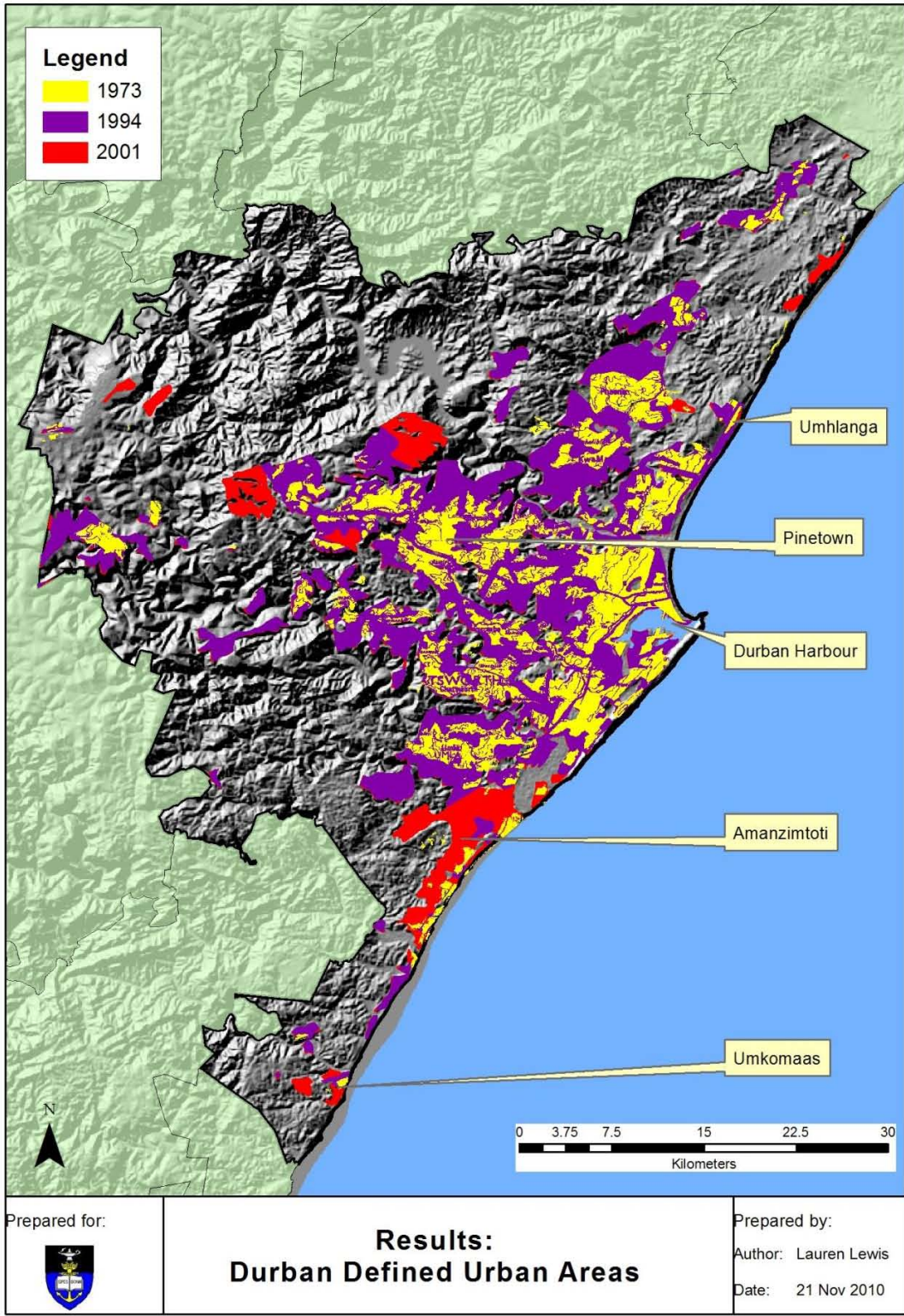


Figure 36: Durban reference data map

Durban's classification data compares to the reference data showed the biggest differences compared to all study sites. This could be due to a variety of factors including challenges with the data and / or methodology, the influence of rivers, valleys and riparian vegetation, the use of natural materials for housing and the tropical vegetation in the region due to the climate. The literature also discussed informal areas on the outskirts of the CBD where the possibility exists that dwellings were erected using natural materials thereby making it difficult to distinguish, alternatively, tall and / or dense vegetation exists in the outlying township areas.

Figure 35 shows development is mainly present around the harbour and expanding southwards and inwards roughly along the coastline throughout the time series. Some evidence of settlement is present further inland at higher altitudes, which has been identified as Pinetown. The classification identified dense settlement around the harbour since 1972, this is also evident in the reference data (Figure 36), however the reference data also indicates that settlement seems to have occurred over a much larger area for this time period, extending further inland.

Large scale development has occurred between 1973 (yellow layer) and 1991 (purple layer). Figure 35 shows that expansion still seems to occur in a north-south expansion trend along the coastline with the most densely developed area occurring around the harbour and extending west towards the interior. New developments can be seen on the coastline further north of the harbour. Pinetown has also expanded during this period. In contrast, Figure 36 shows that more widespread development has occurred by 1994. All areas have expanded dramatically since 1973 particularly moving away from the coast and towards the interior. These results differ significantly compared to the classification.

Figure 35 does not show a dramatic increase in the amount of development since 1991, although Umkomass is identified as a new settlement and was not identified by the classification in previous years. Figure 36 however, shows that the area had been established prior to 1973, but without significant expansion until after 1994. The most dramatic expansion between 1994 and 2001 occurred in the Amanzimtoti area south of Durban harbour. The reference data shows that the area developed along the coast and extended further towards the interior.

A notable success in this classification is that the dense built up area surrounding Durban harbour is identifiable in the classification since the beginning of the time series. Based on historic information this was a realistic representation of the area as the harbour was an important port in South Africa where goods transported from Johannesburg via the railway system was exported.

The urban areas for each map and each part of the time series was calculated and plotted on a graph against the total population (Figure 37):

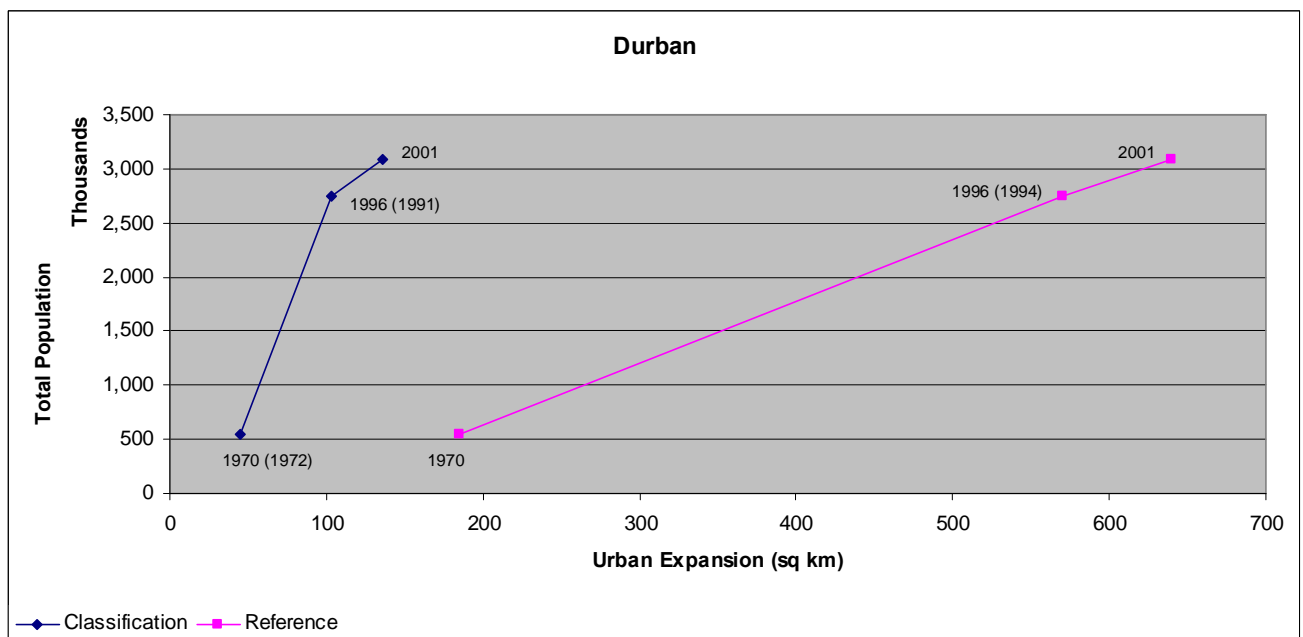


Figure 37 Durban comparison graph³³

As previously stated, there are vast differences between the urban areas depicted by the classification and reference data. The classification has a dramatic underrepresentation of Durban's urban area which could be due to a variety of factors, the primary cause being the difficulty in identifying urban areas due to the vegetation and variable terrain of the region. These challenges were unforeseen during this analysis, although it provided good insight into the limitations of the methodology (which are discussed further in the proceeding chapters).

Observing the results obtained, the classification produced a steep graph indicating limited urban expansion occurring in the region, with a high rate of population increase. The gradient

³³ Census years are indicated first and the year of the Landsat image/reference data is indicated in brackets.

of the slope also suggests that between 1991 and 2001, urban expansion seemed to be occurring at a faster rate, whereas the period between 1973 and 1991 it appears as though the population was increasing more rapidly than the urban area was expanding. Although this assumption is valid, the possibility also exists where more people are being accommodated in smaller areas i.e. population density is increasing. This was commonly implemented during apartheid whereby non-white communities were accommodated in hostels, flats and high-rise buildings. Based on the reference data however, it is clear that there are challenges regarding the methodology as the reference data produced a very linear result which indicates that the urban area was expanding at almost the same rate as the population was increasing. On closer inspection it is noticeable that between 1994 and 2001, the slope of the graph is more gradual, which means that the urban area was increasing faster than the population. The classification reveals that the total urban area does not exceed 200km².

At the beginning of the time series the classification shows an underrepresentation of the urban area compared to the reference data even though the image used was two years older than the topographic map. The inability of the classification to identify urban areas in the region is maintained throughout the time series for this study site as the difference between the amount of urban area identified in the classification and reference data increases through the time series.

5.2.3 Johannesburg Results

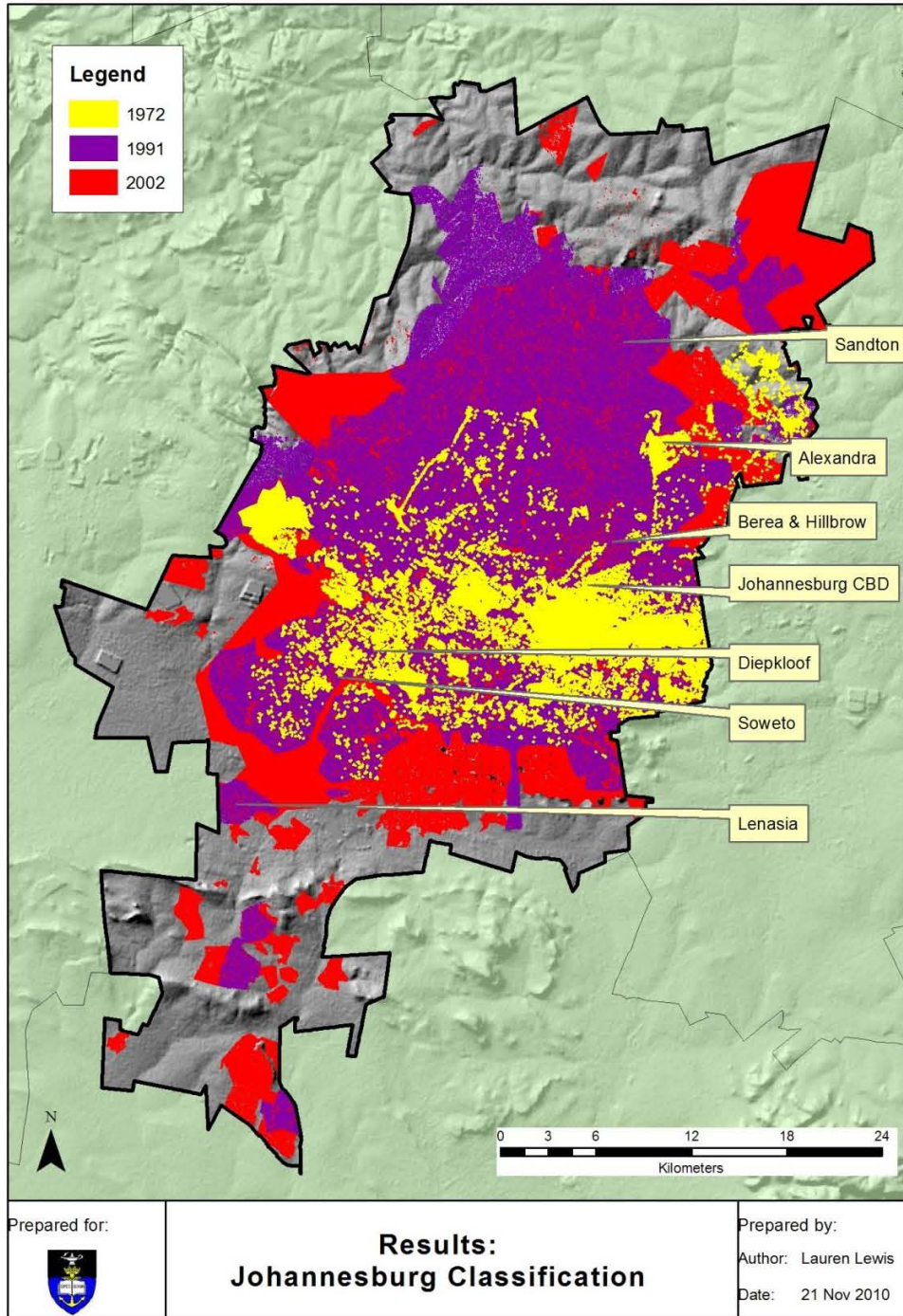


Figure 38: Johannesburg classification results

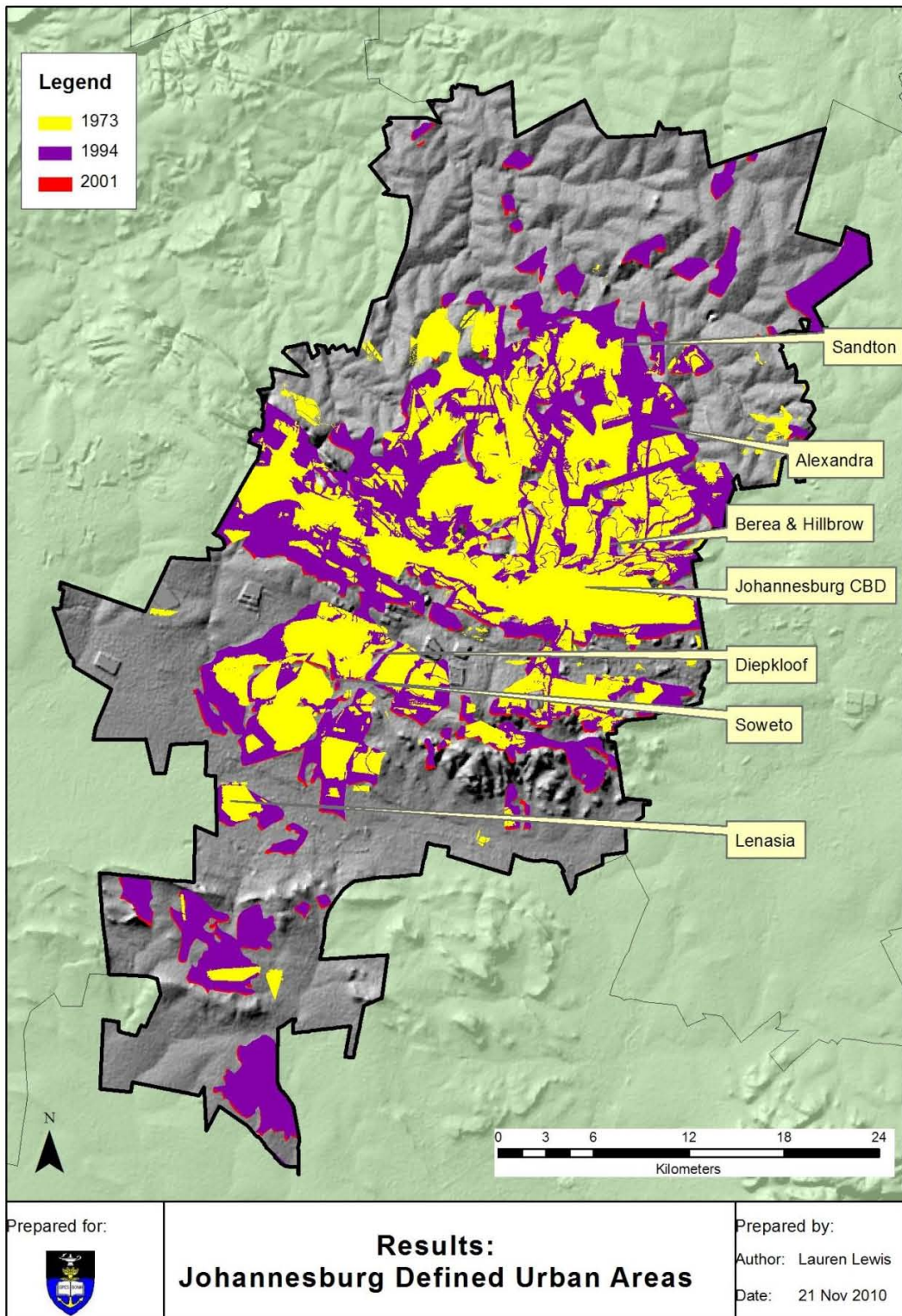


Figure 39: Johannesburg reference data map

The 1972 (yellow layer) classification results (Figure 38) shows a high concentration of settlement in the CBD area, which expands in an east-west direction. Further investigation revealed that these areas were adjacent to large mining areas (economic centres). Not many urban areas were identified north and south of this area besides Alexandra which is shown to have been a densely built up area as early as 1972, despite being located further away from the CBD due to the influence of apartheid during this period. Soweto and Diepkloof which are prominent present day townships are not shown to have high density developments or infrastructure according to the 1972 classification. For this study site the beginning of the time series showed the biggest differences regarding the amount of urban area present. The reference data suggests that in 1973, large scale urban development had occurred in the region which was not identified by the classification. Unlike Durban, the terrain was less varied, thereby indicating that the challenges are more likely related to the methodology and / or data.

Major development is seen to have occurred since 1973 as the 1991 (purple layer in Figure 38) results show a dramatic increase in urban infrastructure in the study site. Development is shown to have expanded vastly in all directions, particularly towards the north. The reference data (Figure 39) confirms that there was northward urban expansion occurring, although there is a large area identified by the classification that is not shown as urban in the reference data. This could be due to the definition of urban used in this study, whereby some urban classes e.g. small holdings were excluded from the reference data as these areas were often used for agriculture and not settlement or secondary activities such as industrial processes. Soweto and Diepkloof both show higher concentrations of infrastructure than in the previous (1973) classification, expanding southwards, indicating densification in the area, however this is not reflected in the reference data as the 1973 information indicates that the area was largely built up. There are large open spaces which appear to be undeveloped mainly on the northern and southern outskirts of the city, although the 1991 classification illustrates that a large amount of these peripheral areas have been developed after 1973.

Further infrastructure is evident in 2001 (red layer) in Figure 38. The most noticeable development is evident in the outlying areas which appear to have expanded quite rapidly in a ten year period (since 1991), as well as the development of new peripheral areas. The newer developments are particularly noted in the northern areas, although a vast amount of land in the peripheral landscape still appears largely undeveloped, which is mainly evident in the

southern areas. The reference data (Figure 39) does not show much additional expansion since 1994, which most of the areas only expanding slightly outwards and is barely visible beneath the purple layer. One possibility to account for the expansion depicted in the graph (Figure 40) is that the 1973 reference layer is possibly masking areas in the other reference layers which are not depicted as urban.

In the northern areas of the classification there appears to be infrastructure present in the 1991 which is not evident in the 2001 layer. This could be attributed to the quality of the image used. Observations using Google Earth showed that although infrastructure is present, it is a low density area with large plots of open land. The areas south of Soweto was identified by the classification as being built up, however the reference data did not indicate urban area in terms of the definition used for this study. Using Google Earth again, it was evident that a large portion of the area was used in the Reconstruction and Development (RDP) housing project, with many single storey housing units situated on the land, making it a high density settlement area. Lenasia was identified in the 1991 classification whereas the reference data indicates that it has been in existence prior to 1973. Both the classification and reference data shows isolated developed areas in the south of the study site, which reflects positively on the methodology. These areas are townships situated on the far outskirts of the CBD.

Figure 40 illustrates the results obtained from the classification vs. the reference data:

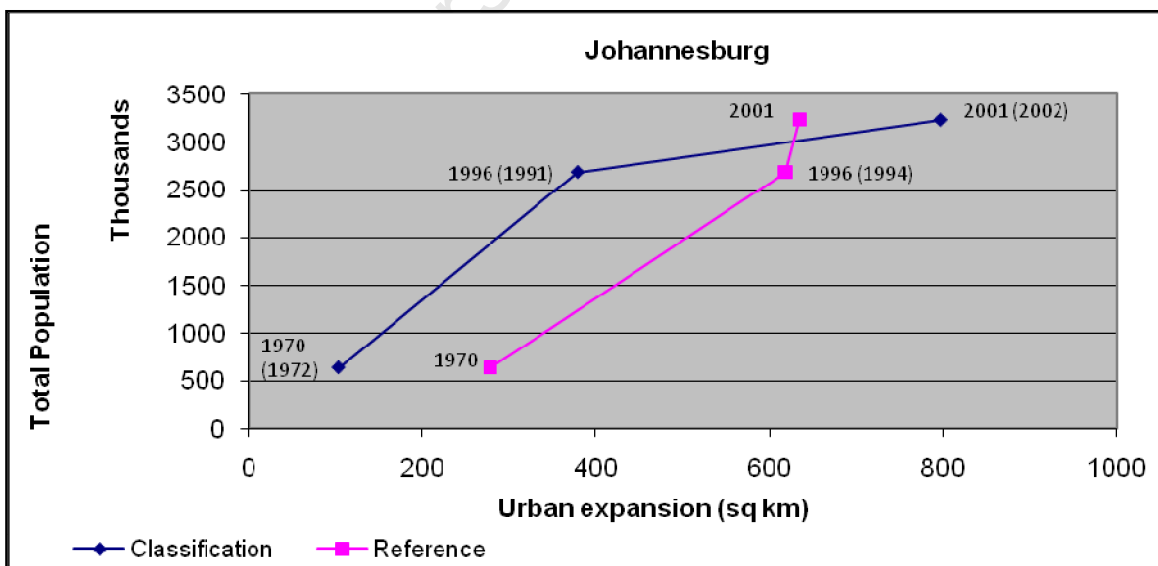


Figure 40: Johannesburg graph comparison

Like the other South African study sites, the classification for Johannesburg revealed an underestimation of the amount of urban area. This is noted in all parts of the time series despite the 1972 and 2002 images being older than the reference data. The biggest underrepresentation is evident in 1996 (census year). Notably, in the graph the reference data suggests that in the period between 1996 and 2001, there was a steep increase in the population, while minimal urban expansion occurred.

A common trend in both graphs is that between the first two points of the time series the gradients are fairly steep indicating that the population was increasing at a faster rate than the urban area was expanding. This period was also notably during Apartheid, and a similar trend as indicated in Durban's results was noted whereby large populations were being accommodated in high rise buildings. In Johannesburg this is particularly evident in places such as Hillbrow, Berea and Alexandra. This resulted in higher population densities. This is however not applicable between the second and end point of the time series where the classification graph show that the urban area is expanding at a faster rate than the population is increasing. This period represents the post-apartheid period and urban expansion is noted to be occurring at a much faster rate. This could be due to the RDP developments occurring over large areas with single story dwellings being provided to township residents. The single storey accommodation results in lower population densities, but larger developed areas. This differs dramatically when compared to the reference data for the same period, where considerably less urban expansion is depicted and population seems to be increasing at a much faster rate. This could be due to the housing developments occurring on land which was not classified as urban in terms of the definition used in this study.

5.2.4 Windhoek Results

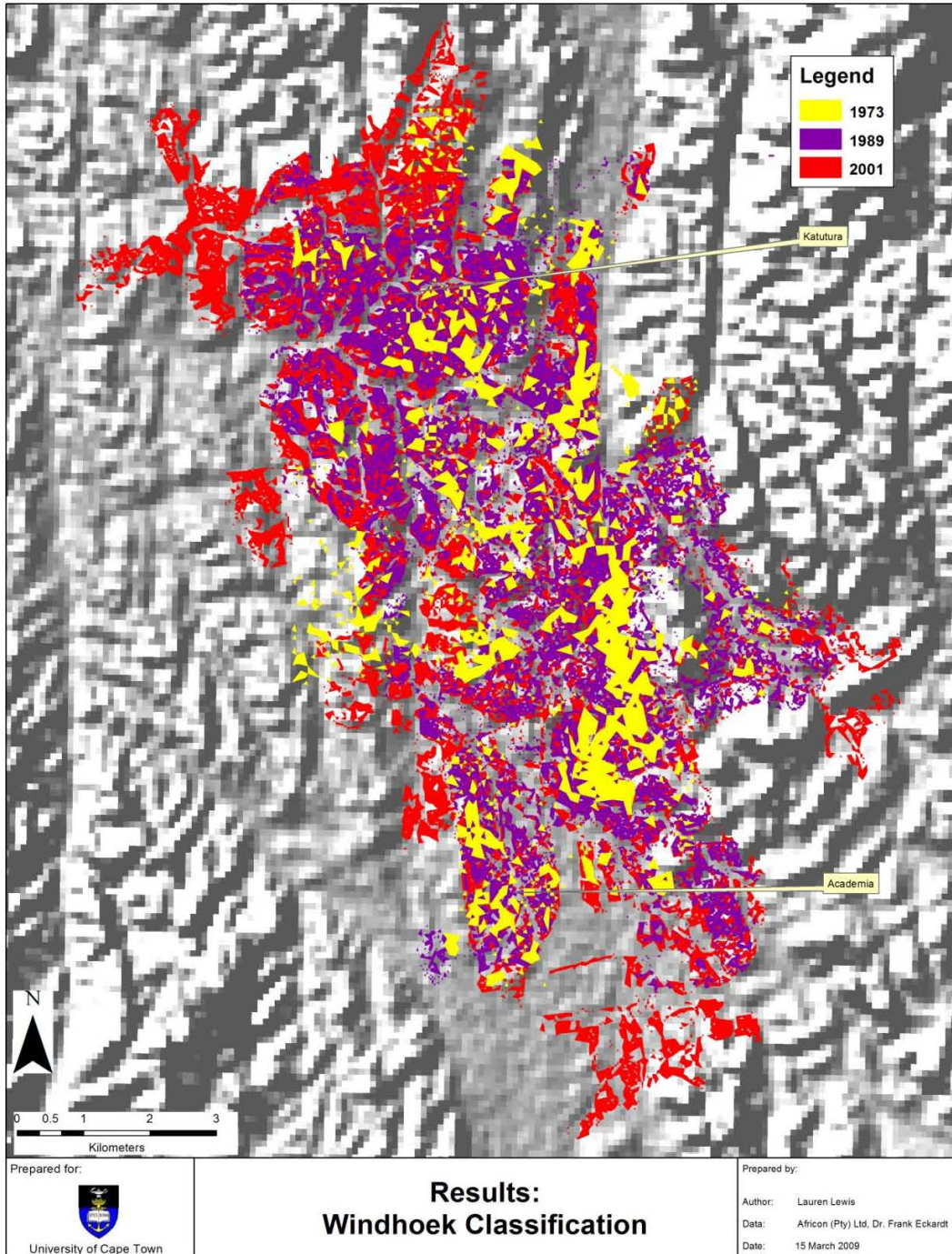


Figure 41: Windhoek classification results

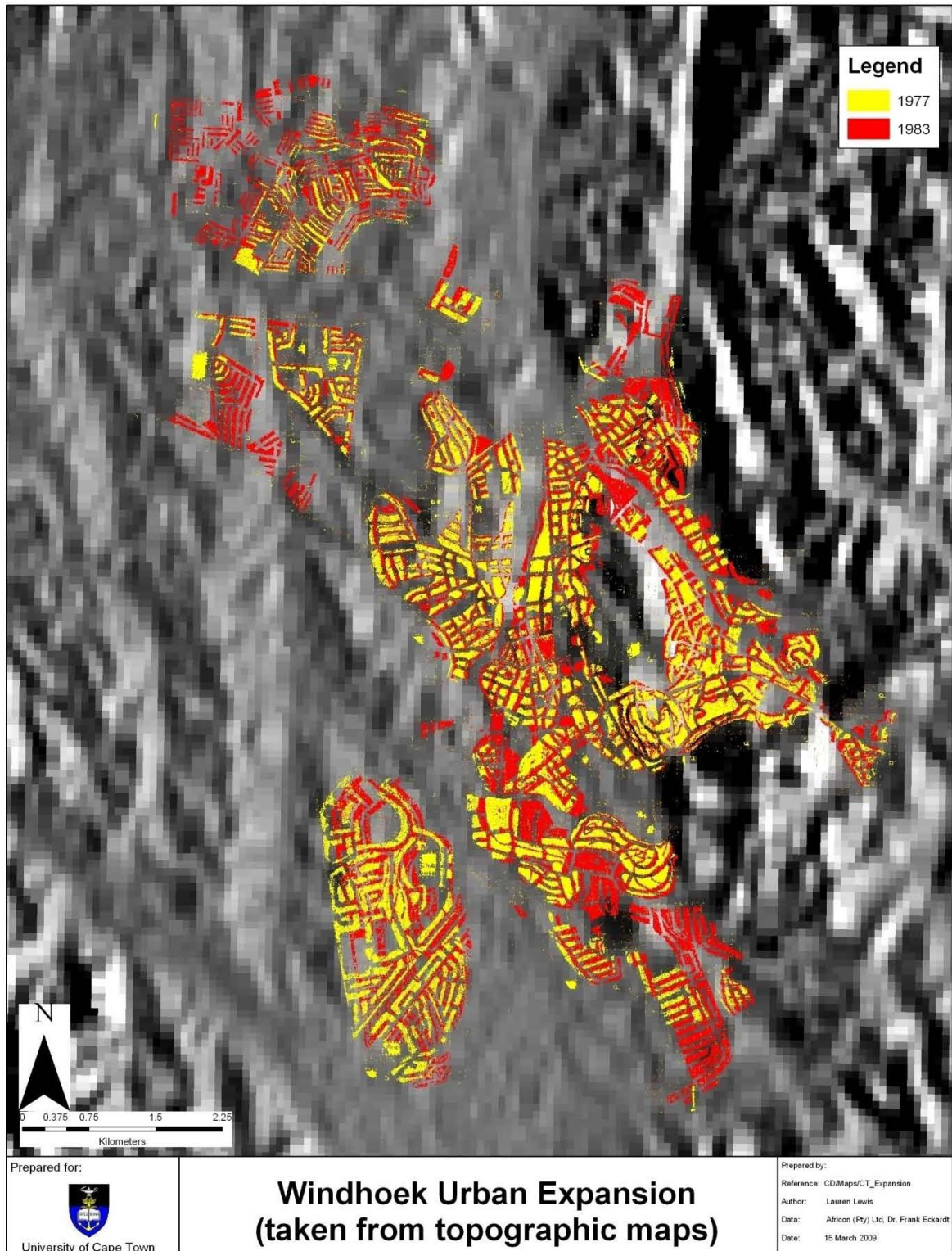


Figure 42: Windhoek reference data map

In 1973 (yellow layer) there was very little settlement in the area. Evidently, the infrastructure that was present was sparsely spaced over the region. The central business district is evident as it is the only area which appears to have a large concentration of infrastructure present. The historical information highlights that Windhoek is a relatively young city, which would account for the smaller area it occupies when compared to the South African study sites. The settlement in the southern most area of the city was identified to be the University of Namibia using Google Earth.

The results show a much higher concentration of urban infrastructure in 1989 (purple layer). Expansion also seems to be moving outward from the earlier settlement areas, which could be a result of both development occurring within the city and also due to the in-migration of people to seek better living conditions and employment opportunities in the city.

Further expansion is evident in the 2001 classification results (red layer), although there appears to be a restriction in development on the eastern and western sides of the city. The most growth appears to be occurring in the northern area, in a north-north westerly direction. As described in the literature, people who migrated to the city, specifically the non-white population, settled in the townships in the northern areas which resulted in the areas expanding southwards towards the CBD. There also appears to be a new settlement in the southern most area of the city which on further investigation using Google Earth is shown to be a residential area.

Although adequate reference data was not available for Windhoek, available topographic maps were used to provide a means of comparison for the classification. The urban areas were extracted using the same methodology applied to the topographic maps in the South African study sites. The results were graphed below:

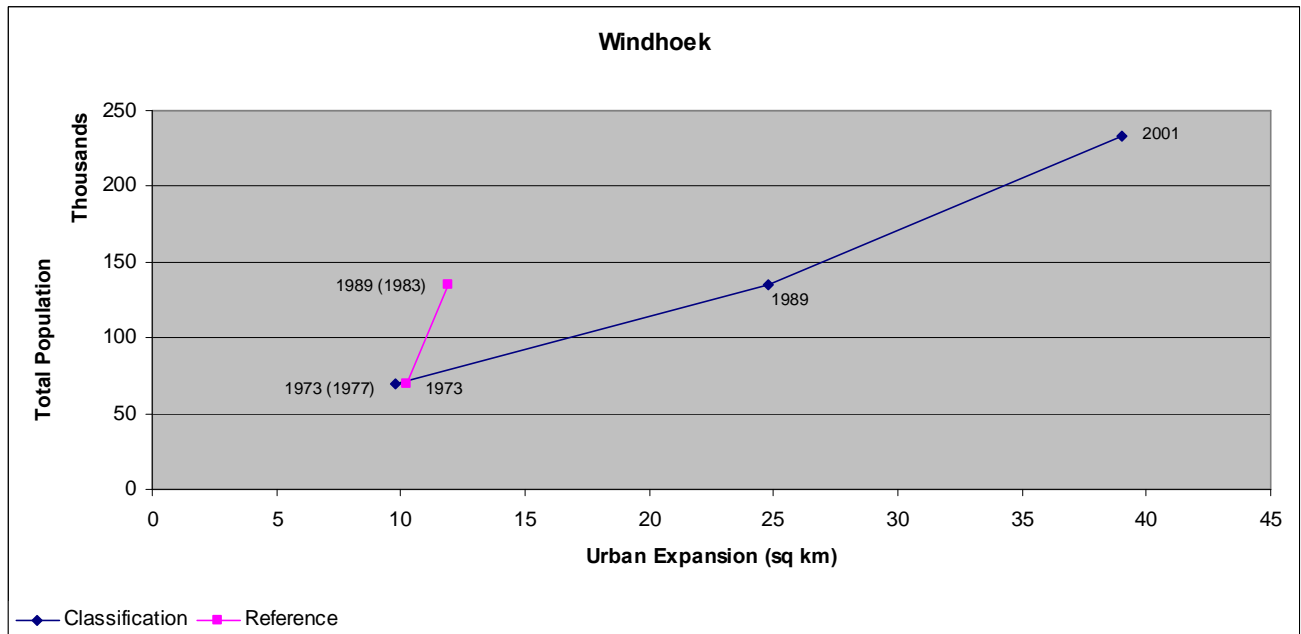


Figure 43: Windhoek graph comparison

The immediate noticeable difference is that unlike the South African study sites, the classification results show almost the same amount of urban area for the starting point in the time series. This is however not maintained in the second point of the time series where the classification shows that the urban area accounts for a much larger extent than the reference data suggests. Windhoek was also under the influence of the South African apartheid regime during this period and the population growth was largely attributed to in migration, resulting in the establishment of townships particularly in the northern areas such as Katatura. The topographic maps used as the reference data for this period (1988 census date) could not have recognised the established townships as urban areas, thereby causing the underrepresentation illustrated in the reference data. The reference data also shows that between 1977 and 1973 (image years) the population was increasing at a much faster rate than the urban area was expanding. In contrast, the classification data shows an opposite trend for that period, suggesting that the urban area was expanding at a faster rate than the population was increasing. The change in gradient between 1988 and 2001 shows that the rate at which urban expansion was occurring had decreased, alternatively, it could also indicate the population was increasing at a faster rate.

5.2.5 Gaborone Results

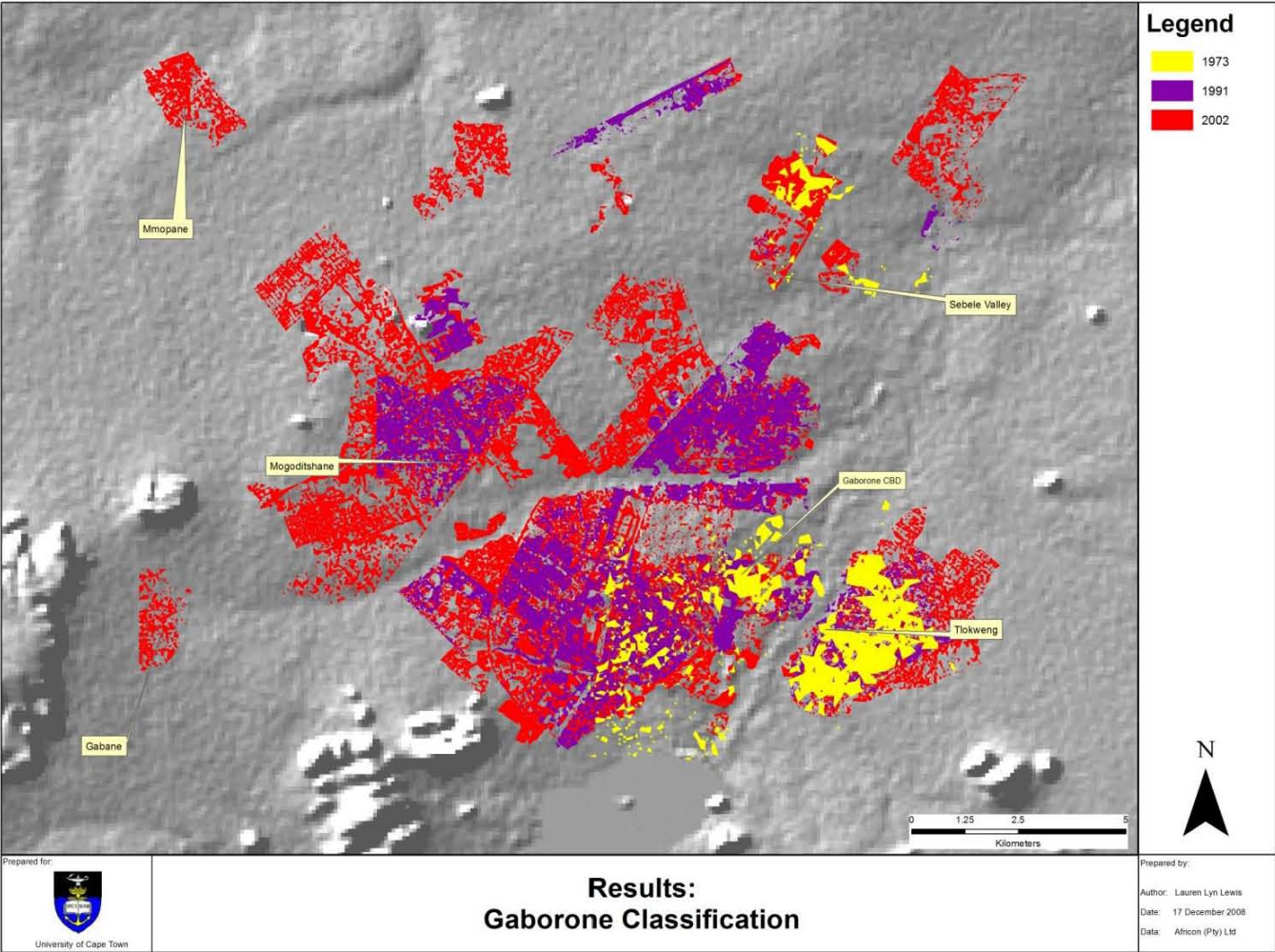


Figure 44: Gaborone classification results

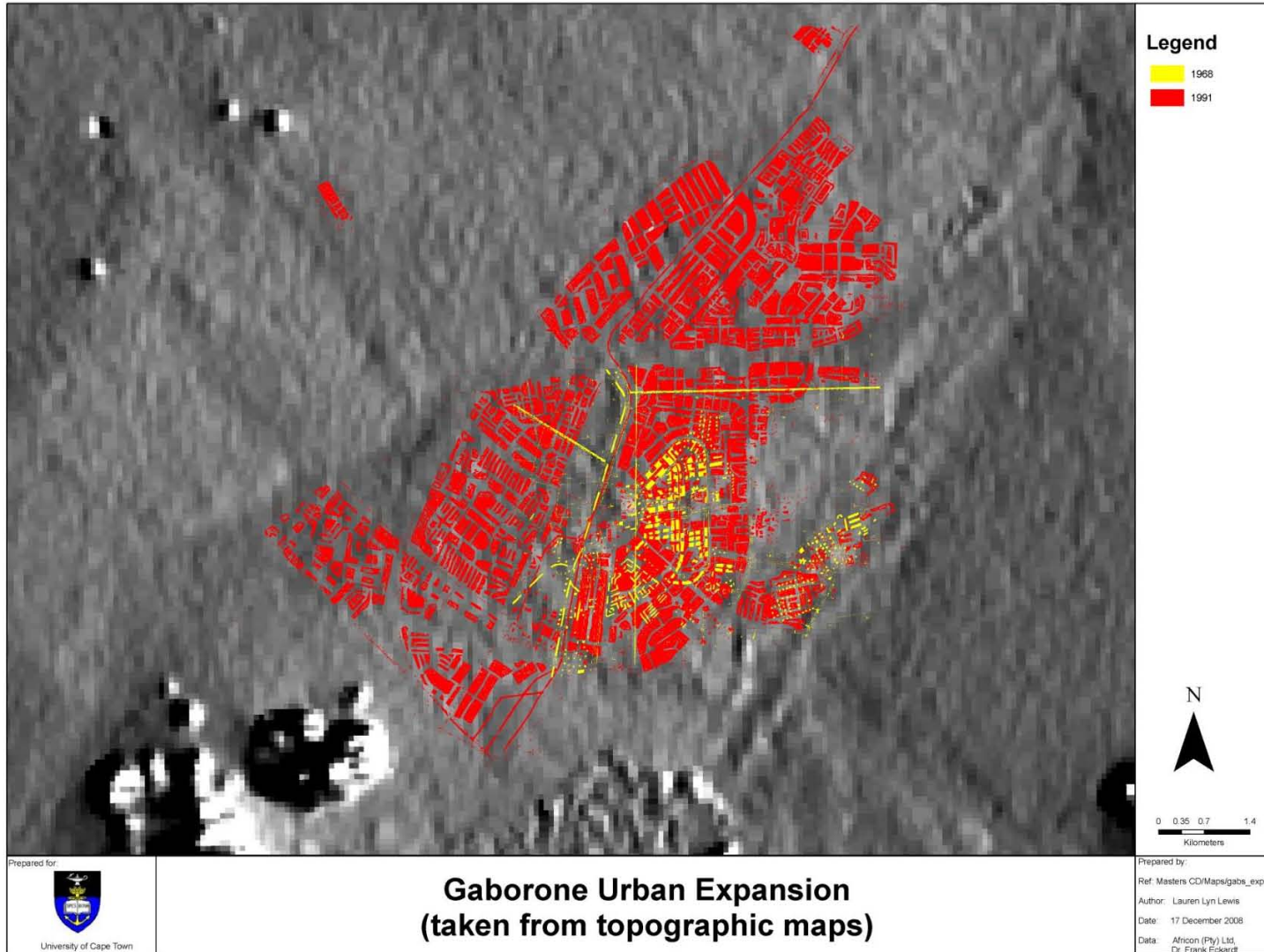


Figure 45: Gaborone reference data map

Gaborone is a relatively young city which over the years has expanded outwards to incorporate several outlying villages. In 1973 the densest concentration of infrastructure appears in the south-eastern corner of the map which was a small village situated in close proximity to the CBD. Smaller sparse settlements are evident slightly westward, but there appears to be a distinct separation between the two. Another settlement appears further north. The reference data used was not ideal for this analysis (evident in Figure 45) as the definition of urban used to produce the topographic map excluded the surrounding villages. The reference data shows minimal urban infrastructure divided by road networks.

By 1991 there has been a dramatic increase in urban infrastructure which is also evident in the reference data. The city was well planned with defined borders evident between areas as the development appears to be very rigid (Figure 44 and Figure 45). Development has expanded mainly in a northward direction. An isolated area which appears to be very linear is situated far north of the CBD, it was later determined to be Gaborone International Airport. The reference data Figure 45 is still not ideal for this analysis as surrounding villages which are considered a part of Gaborone were not indicated as urban areas on the topographic map.

Further dramatic outward expansion is evident in the 2002 results. The amount of infrastructure has increased dramatically since 1991. New areas in the western region show settlement, although in many cases these areas were previously in existence as villages on the outskirts of Gaborone. The expansion of the villages as well as expansion of the city has resulted in some borders separating the two being undefined, while in other cases, the villages have become part of the suburbs of Gaborone. Notably however, there are still areas showing defined borders present in the settlement patterns.

Similar to Windhoek, although the reference data was not appropriate for this analysis, the information was still used to produce the graphs below:

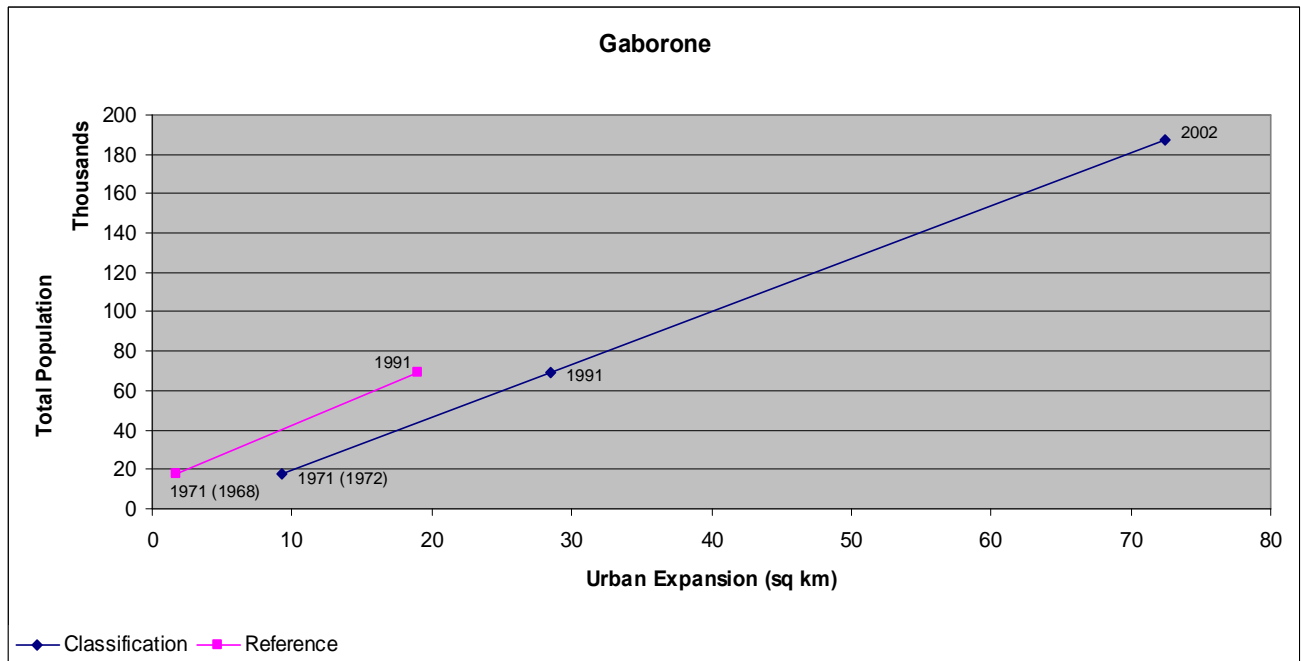


Figure 46: Gaborone graph comparison

The reference data shows less urban area throughout the time series, although this could be due to the topographic maps not taking the surrounding villages into account, although the reference data used at the beginning of the time series is four years younger than the image used in the classification. The reference graph and classification graph appear to run parallel to each other, both showing urban expansion to be occurring faster than population increase. The most dramatic growth in population is shown to have occurred between 1991 and 2002.

The classification seems to maintain the same gradient throughout the time series, which could be due to natural population increase and little in-migration as villages were located relatively close to the CBD which meant that people seeking career opportunities would not need to travel far and would be able to return to their places of origin on a daily basis. Gaborone was also a well planned town which was uninfluenced by apartheid thereby allowing planned settlements to be developed with little division according to race and/or social status.

5.3 Comparison between Classification and Reference Data Graphs³⁴

The purpose of this section is to provide a comparison between the graphs produced for each study site. Each individual site has been discussed separately in the preceding chapter.

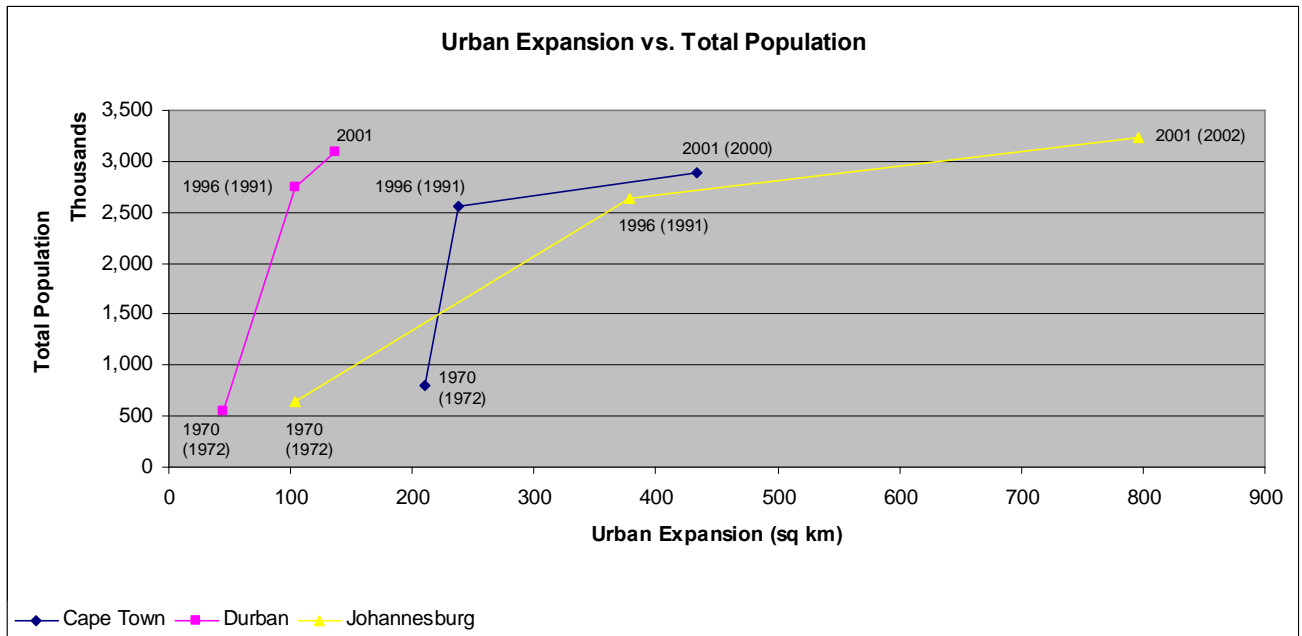


Figure 47: Comparing the classification results for all South African study sites

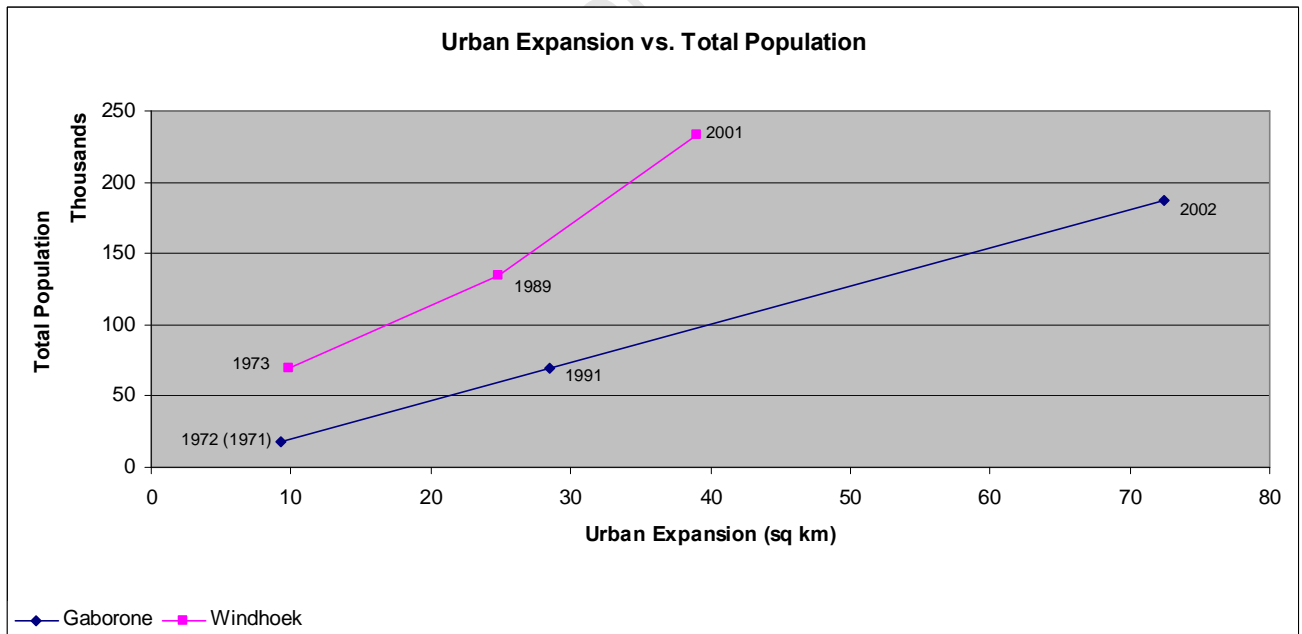


Figure 48: Comparing the classification results for Windhoek and Gaborone

³⁴ Windhoek and Gaborone are much smaller and younger cities than the South African study site and had to be illustrated on separate axes in order to clearly read the graphs.

Comparing the results illustrated on the classification graphs (including both Figure 47 and Figure 48), Gaborone had the most linear graph, while all the South African study sites seem to show a similar trend whereby initially the population appears to be increasing at a faster rate than the urban area is expanding after which there seems to be an increase in the expansion of the urban areas and a decrease in the rate of population increase. Windhoek shows an opposite trend to the South African study site, initially having a faster rate of urban expansion and slower population growth, followed by a faster rate of population increase and slower urban expansion.

Figure 47 shows Durban has increased the least in terms of the size of the urban area. It also has the steepest graph indicating that population has increased more rapidly than the amount of urban infrastructure has increased. At the beginning of the time series for the South African study sites, Durban had the lowest total population followed by Johannesburg and then Cape Town. At the end of the time series, Johannesburg had the highest total population followed by Durban and then Cape Town. The increase in urban expansion in Cape Town appears to have been much slower between 1972 and 1991, which is similar to the trend evident in Durban's graph. The total population in these years has increased dramatically compared to the amount of urban development that has occurred. Between 1991 (year of image) and 2001 the inverse appears to occur where the amount of urban development has increased dramatically compared to previous years. Johannesburg shows the most dramatic increase in urban expansion compared to the other study sites (both Figure 47 and Figure 48). It also has the highest total population in 2001. The amount of urban land occupied in 1991 exceeds the amount of urban land covered in all the other cities for that year, and in 2001 covers almost double the urban area that Cape Town occupies. Windhoek occupies the smallest urban area in 2001 compared to the other study sites, while Gaborone has the smallest population in 2001 (Figure 48). Windhoek's graph appears to show a constant population increase as well as urban expansion increase until 1989 when population begins to increase at a faster rate. The population and area covered is dramatically smaller than that of the South African cities. Even in 2001 the population remains below 250 000. Gaborone tends to show urban expansion and population growth occurring at a constant rate throughout the graph. The total population in 2002 is less than Windhoek's population in 2001, but appears to cover almost double the urban area. Throughout the time series Gaborone always had the lowest total population, noting that in 1991, Gaborone's population exceeded 50 000 people, compared to Windhoek

whose population exceeded 50 000 in 1973. In general the total population has shown a much more dramatic increase in the South African cities than in Windhoek and Gaborone. The total populations in the South African cities in 1972 exceeded the 2001 and 2002 total populations of Windhoek and Gaborone respectively.

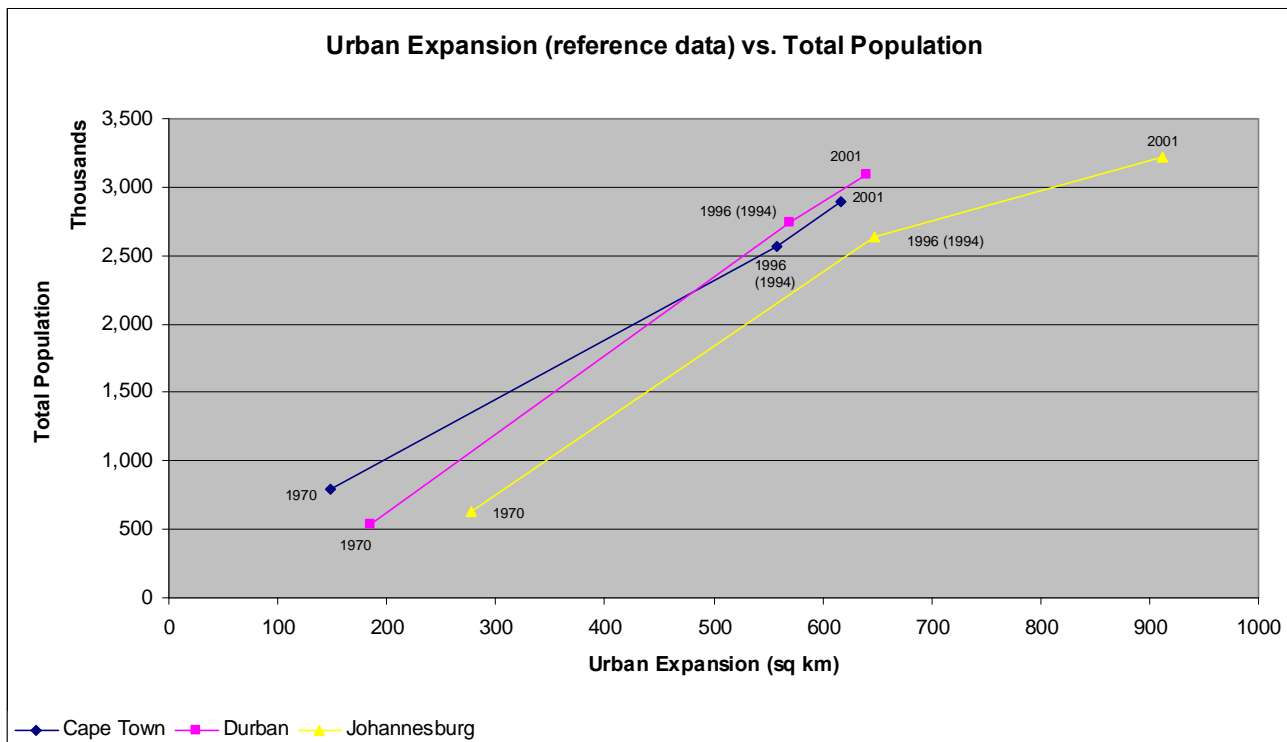


Figure 49: Comparing the reference data results for all South African study sites

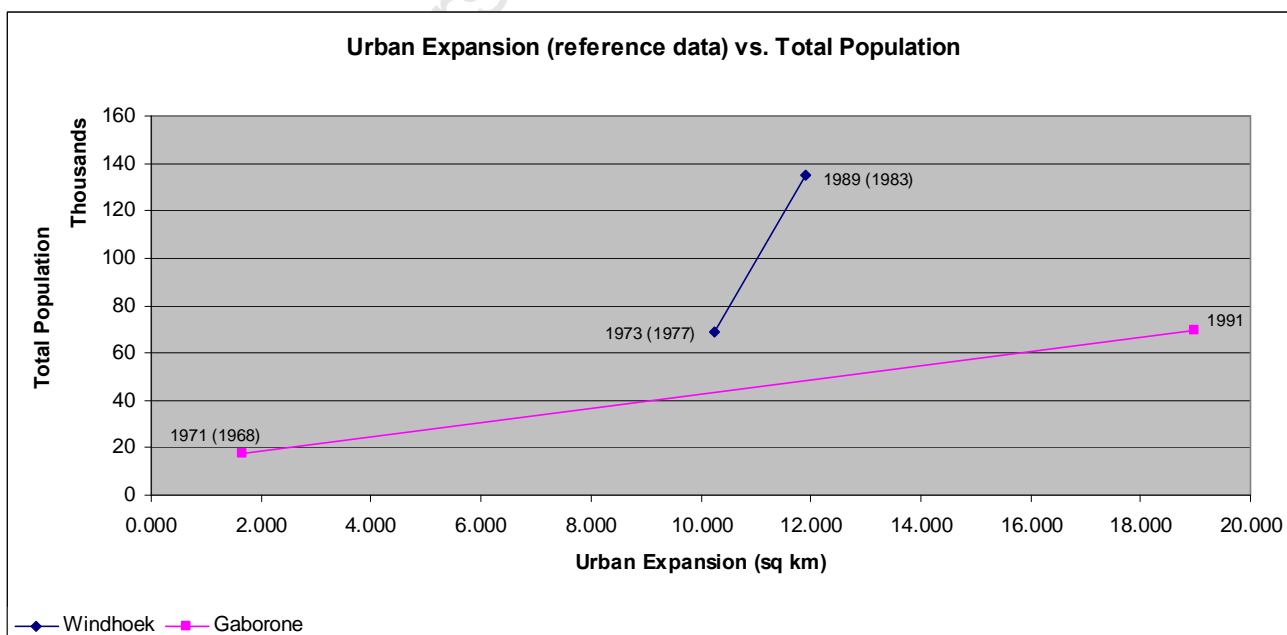


Figure 50: Comparing the reference data results for Windhoek and Gaborone

The general trend noted in the graphs (Figure 49 and Figure 50) shows that the reference data produced more linear graphs than the results of the classification. For Cape Town and Durban there seems to be an almost constant rate of increase in urban expansion and population increase throughout the time series. In contrast, Johannesburg clearly shows a change in the gradient of the slope between 1994 and 2001 whereby the urban area seems to be expanding at a faster rate than previously. Cape Town's reference data graph is the only graph to show an increase in the gradient of the slope between 1994 and 2001 which suggests that the population was increasing at a faster rate than urban expansion.

Figure 50 is not useful in identifying changes in population increase or urban expansion, due to the limited availability of data which only allowed two points in the time series to be created. The graphs do however illustrate that Windhoek's population was increasing at a much faster rate than the urban area was expanding. This rate seems to exceed the rate of population increase in all other study sites. Gaborone's graph shows the opposite trend with the urban area expanding at a faster rate than population increase.

5.4 Further analysis of the results

Table 14: Amount of urban expansion that occurred over the time series³⁵

Study Site	Time Period (Class)	Expansion (class) (km ²)	% Growth (Classification)	Time Period (Ref. data)	Expansion (Ref. Data) (km ²)	% Growth (Ref. Data)
Gaborone	1972 - 2002	63.2	87.2			
Windhoek	1973 - 2001	29.2	74.9			
Johannesburg	1972 - 2002	692.9	87.0	1970 - 2001	633.9	69.5
Durban	1972 - 2001	91.4	67.1	1970 - 2001	454.7	71.1
Cape Town	1972 - 2000	223.3	51.6	1970 - 2001	468.9	76.0

Table 14 indicates the total amount of urban expansion that occurred in the study site over the time series as well as the percentage growth that occurred. The classification results indicate that Johannesburg's total urban area increased by 692.9km² over the time series, showing the most growth when compare to the other study sites. Windhoek showed the least amount of urban growth over the time series (29.2km²). In terms of the growth percentages, Gaborone shows the highest growth of 87.2%, marginally higher than Johannesburg with 87.0%.

³⁵ The grey highlighted area indicates that there was insufficient data available to perform the analysis, however, this is addressed in Table 15

Although Windhoek shows the lowest growth in terms of area, the growth percentage exceeds both Cape Town and Durban with 74.9%. Cape Town is shown to have the lowest growth percentage of 51.6%.

In terms of the reference data, Johannesburg shows a similar amount of growth over the time series as the classification data with 633.9km². However, the percentage growth is calculated to be much lower at 69.5%. Notably for both Durban and Cape Town the percentage growth indicated for the reference data is higher than indicated by the classification.

The table below was produced in order to compare the classification results to the NLC reference data for 1994 and 2001 for the South African study sites. Windhoek and Gaborone were included below to observe the amount of urban expansion that occurred from 1973 . 1989 and 1972-1991 respectively as these years are the two points in the time series that corresponds with the two reference data points.

Table 15: Percentage of urban expansion that occurred in Gaborone and Windhoek over the first two time periods in the time series

Study Site	Time Period (Class)	Expansion (class) (km ²)	% Growth (Classification)	Time Period (Ref. Data)	Expansion (Ref. Data) (km ²)	% Growth (Ref. Data)
Gaborone	1972 - 1991	19.2	67.4	1968 - 1991	17.3	91.2
Windhoek	1973 - 1989	15.0	38.5	1977 - 1983	1.7	13.9

Between 1972 and 1991 Gaborone expanded by 19.2km² according to the reference data, which amounts to a growth of 67.4%. This differs vastly to the reference data which indicates that the urban area expanded by only 17.3km², however, it has been noted that the reference data available does not take the surrounding villages into account. The reference data shows Gaborone's percentage growth to be 91.2%. Windhoek's results also show a notable difference between the classification results and reference data. The classification shows that the urban area expanded by 15.0km² between 1973 and 1989, which equates to a percentage growth of 38.5%. The reference data indicates that the urban area only expanded by 1.7km² which is considered to be very little expansion, however, this could be due to the time period between dates (1977 . 1983) being only 6 years. The use of this reference data for the analysis was therefore not ideal, although it has been noted that this information was the only

reference data available for the duration of this study. The percentage growth was calculated to be 13.9%.

5.5 Accuracy Assessment

The accuracy assessment was only conducted on the South African study sites as the NLC data was provided by the CD:NGI and was only available for South Africa. The results of the classification were initially produced in raster format and were required to be converted to vector format in order to allow it to be compared to the reference data. As previously stated, the reference data provided is considered to be accurate and it would therefore be inadvisable to convert the data which could potentially alter the information. The vector format as well as the urban class being the only class extracted during the classification thereby eliminated the use of the error matrix as an accuracy assessment method. An alternative method was therefore determined in order to evaluate the accuracy of the classifications. Using the equation provided in the methodology (Equation 7), the percentage accuracy was calculated for the results. This reflects the urban area identified in the classification (and verified by the reference data), as a percentage of the reference data's urban area. This method therefore also eliminates areas that have been incorrectly identified as urban by the classification. The maps provided in this section provide visual representations of:

- The urban areas accurately identified by the classification (and verified by the reference data);
- The original classification results; and
- The reference data.

Producing the layer that identifies areas accurately determined as urban by the classification will therefore allow for the visual assessment to reveal errors produced by the classification.

The 2001 NLC reference data and associated classification was viewed as the ideal dataset to be used in the accuracy assessment as the reference data corresponded closely with the year of the Landsat image used for the classification. Common problems identified in performing the accuracy assessment on the 1972 and 1991 classification data includes:

- The 1972 classification data is 2 years older than the reference data used (1970);
- The 1991 classification is 3 years younger than the reference data used (1994)

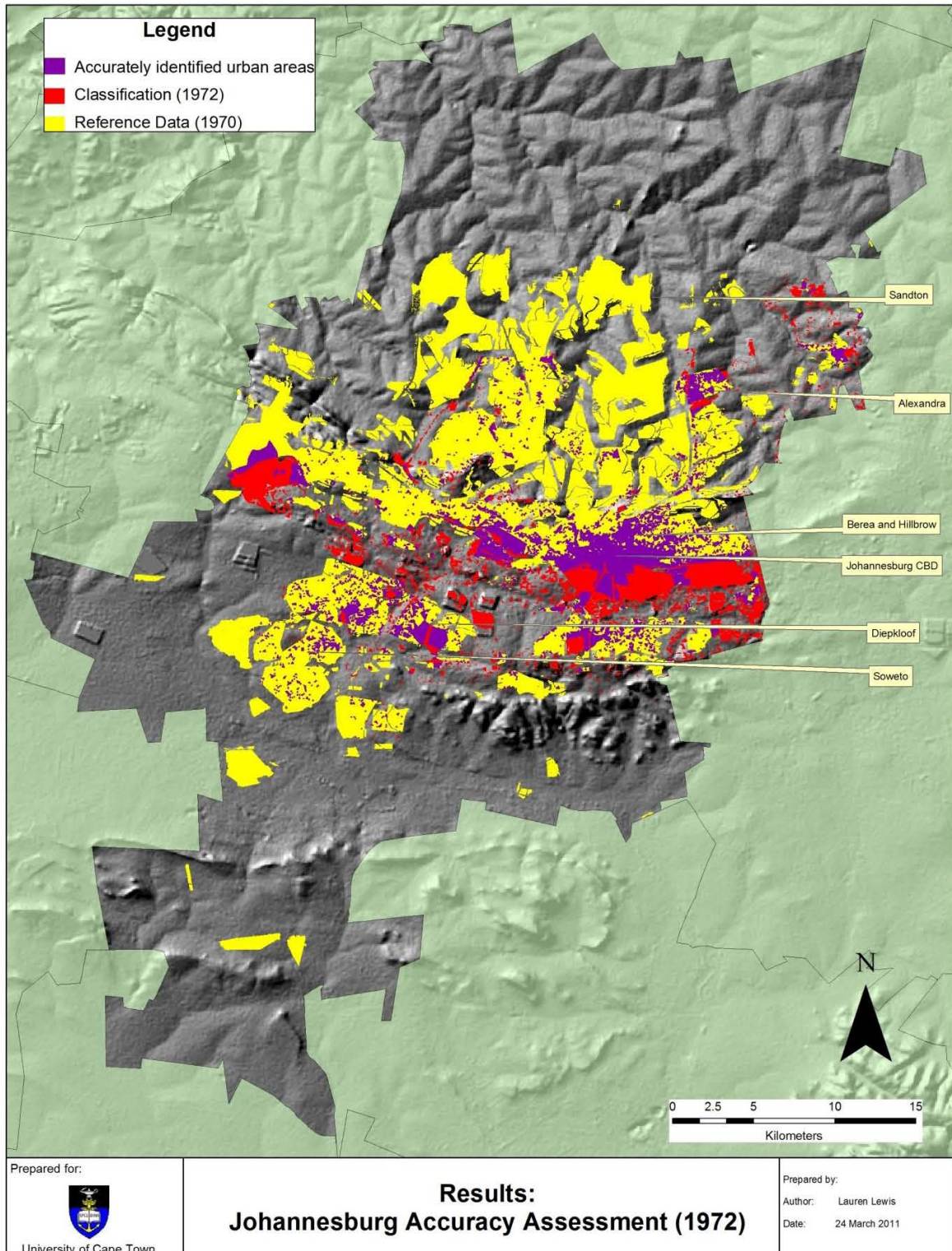


Figure 51: Johannesburg accuracy assessment 1972

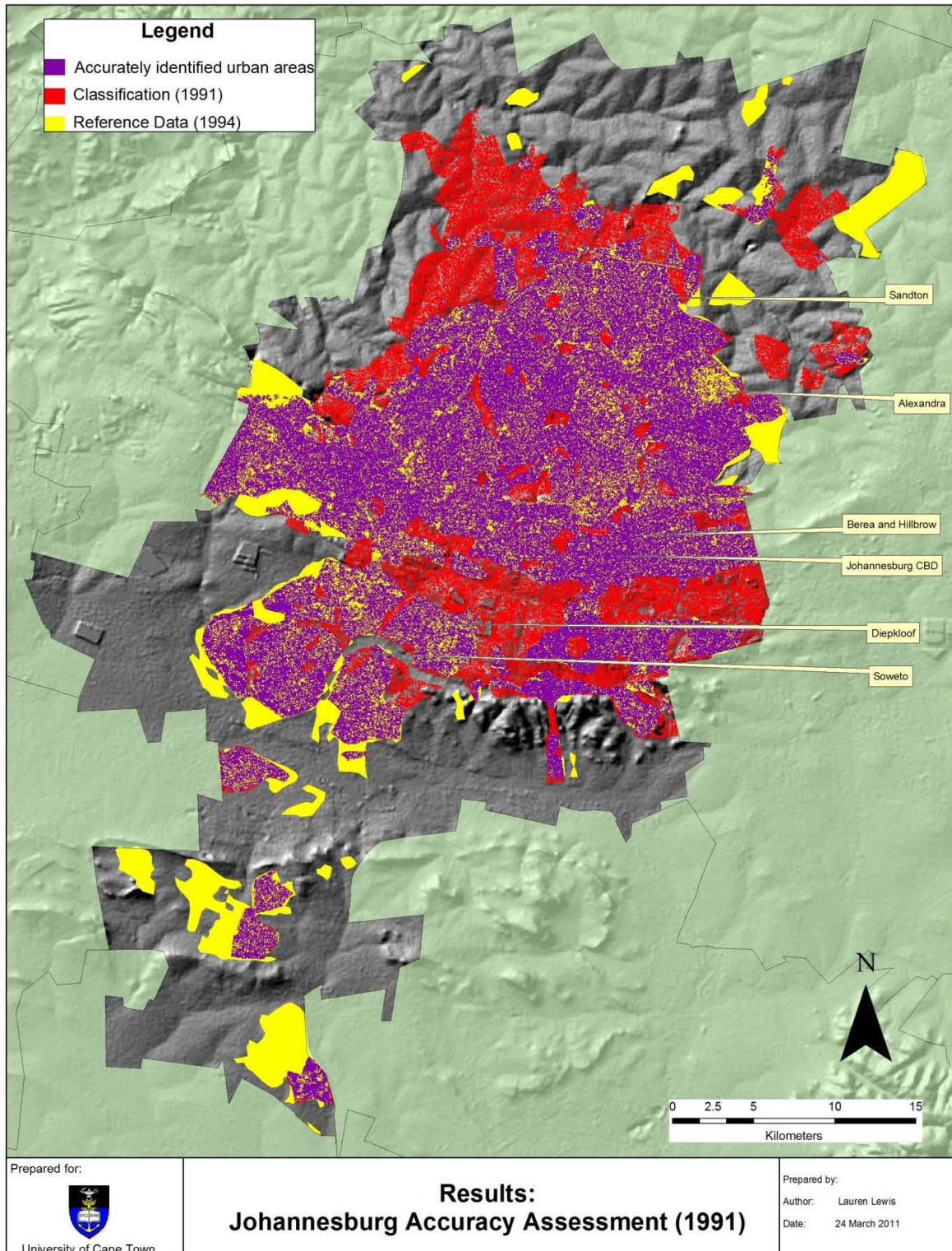


Figure 52: Johannesburg accuracy assessment 1991

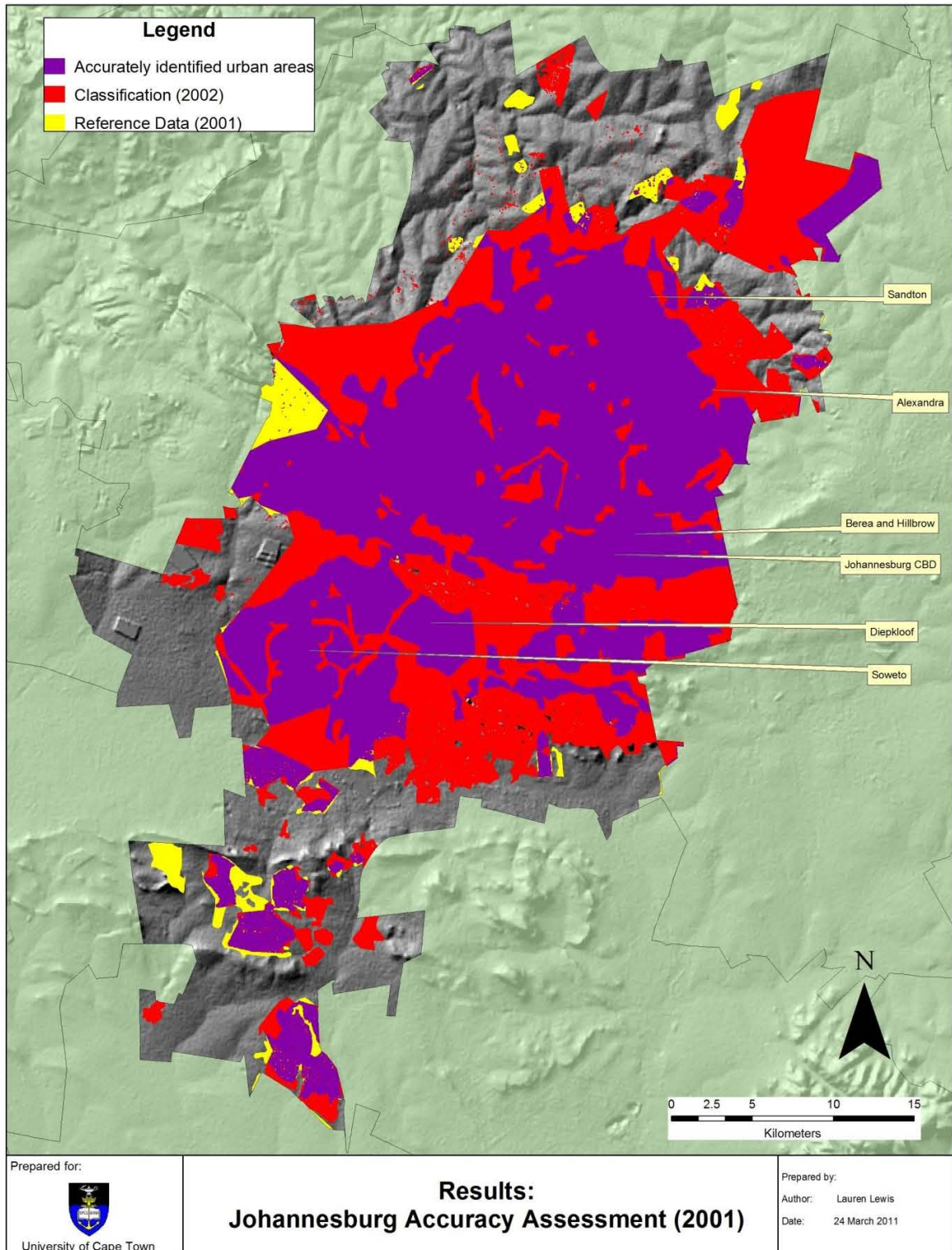


Figure 53: Johannesburg accuracy assessment 2002

Table 16: Johannesburg Accuracy Assessment Results

Reference Data	Year	Classification		
		1972	1991	2000
	1970	29.7%		
	1994		49.2%	
	2001			91.6%

The percentage accuracy of Johannesburg's classification tends to improve dramatically through the time series. The lowest accuracy was achieved in the 1972 classification with 29.7%. This is evident by the dramatic underrepresentation shown in Figure 51 (purple layer). Notably, the classification (red layer) primarily identified the areas adjacent to the mines, omitting large urban areas both north and south of the mines (Figure 51), however, Alexandra which is situated further north of the CBD area had been accurately identified by the classification (purple layer).

The classification improved to 49.2% in the 1991 classification where it is evident that the accurately identified urban areas (purple layer) have extended considerably in both north and southward directions. This is a notable improvement compared to the 1972 classification results, although at the same time there are areas the classification (red layer) identified as urban which the reference data indicates as non-urban (Figure 52), particularly in the mine areas. Another notable area which has been identified as urban by the classification occurs in the north western area of the study area.

The best result achieved in terms of percentage accuracy was calculated to be 91.6%, illustrated in the 2000 classification (Figure 53). The classification (red layer) shows an overrepresentation of the urban area, this could be attributed to errors regarding the classification or built up areas which do not fall into the definition of urban as defined in this study. The classification results also leaves little/ no evidence of the reference layer, which is only evident on the outskirts of the classified area.

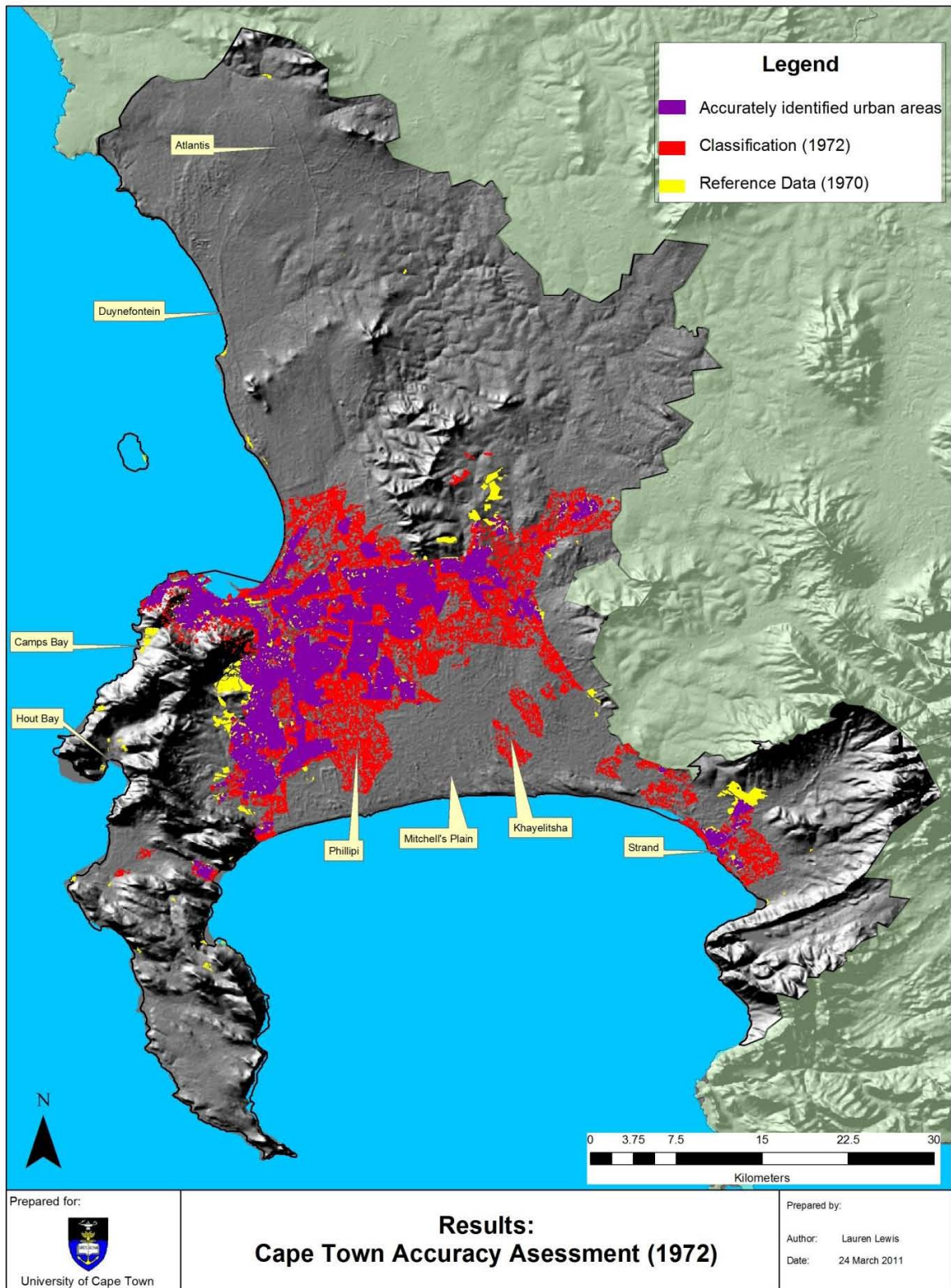


Figure 54: Cape Town accuracy assessment 1972

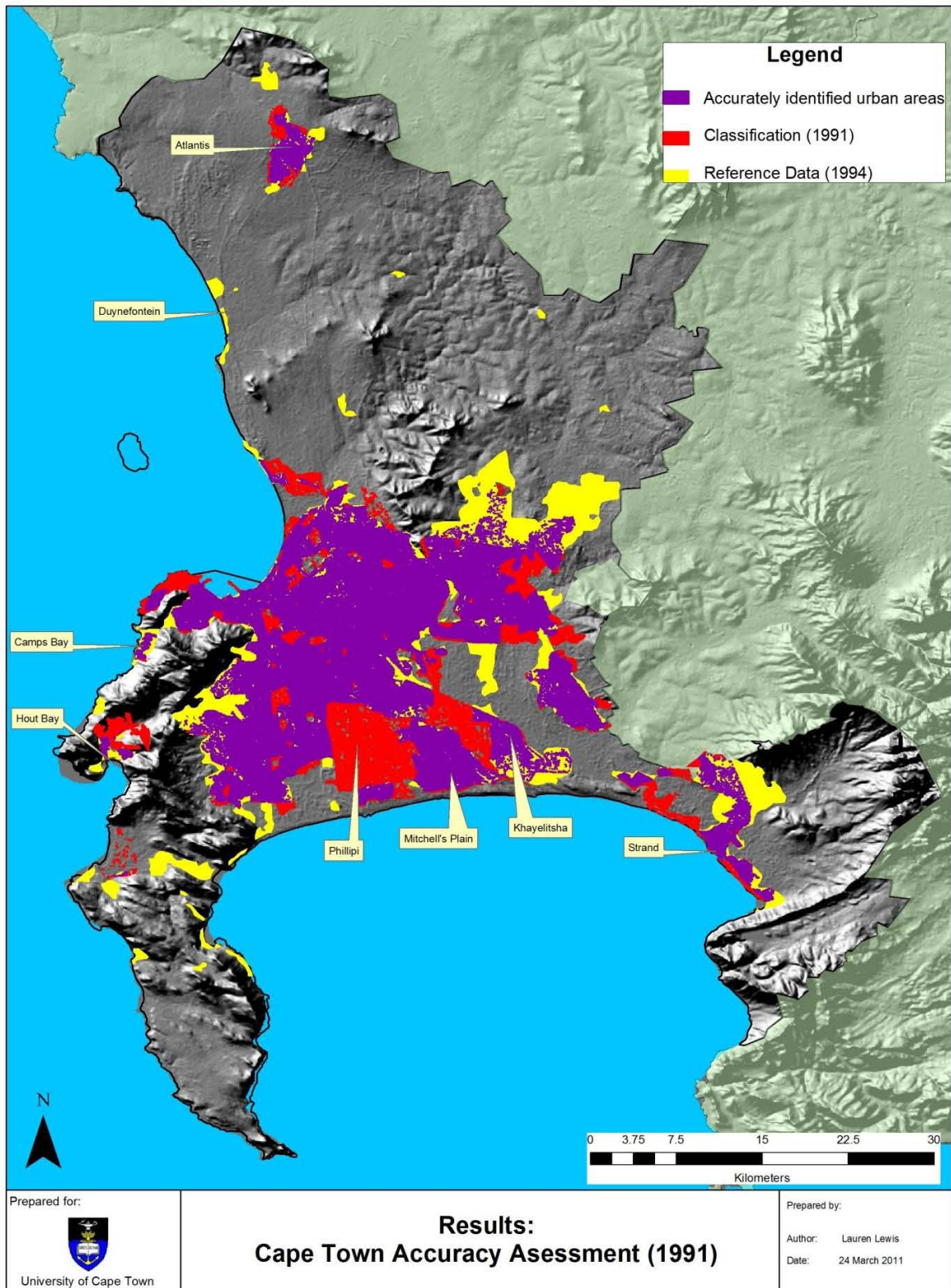


Figure 55: Cape Town accuracy assessment 1991

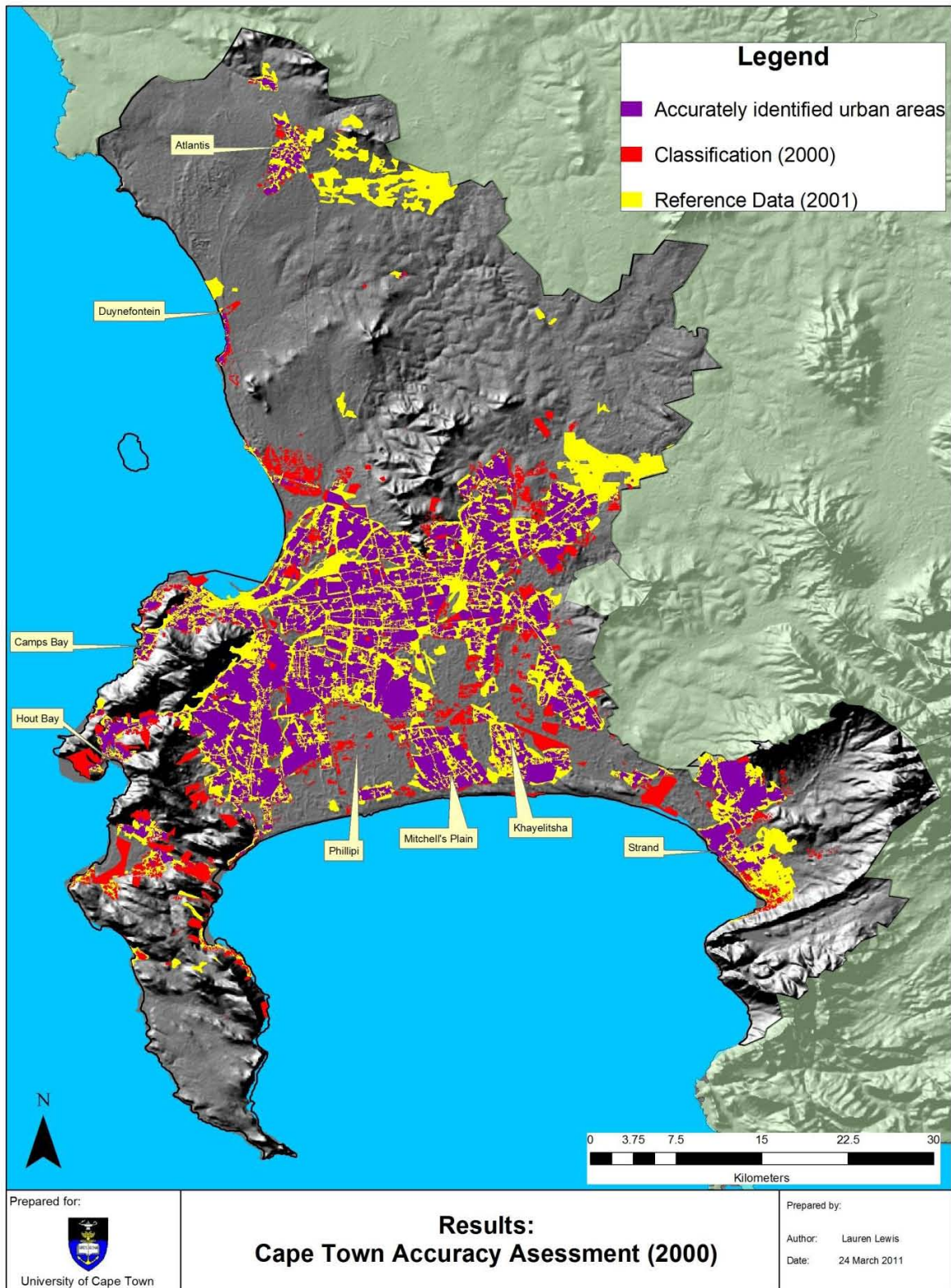


Figure 56: Cape Town accuracy assessment 2000

Table 17: Cape Town Accuracy Assessment Results

		Classification		
		1972	1991	2000
Reference Data	Year			
	1970	51.9%		
	1994		45.0%	
	2001			72.4%

The accuracy achieved for the 1972 classification was 51.9%. In this case the reference data cannot be determined to be free of human error as the urban areas were extracted from topographic maps in order to produce the reference data. Visual representation in Figure 54 shows that large areas which were identified as urban by the classification were not considered to be urban based on the reference data. A possible explanation for this occurrence is that the reference data is 2 years older than the classification data and could therefore be underrepresenting the urban area.

The 1991 classification produced an accuracy of 45.0%, although it is noticeable that large non-urban areas have been identified as urban by the classification (red layer). The urban areas identified by the classification closely follow the urban areas indicated in the reference data. One issue that has been noted is the classification identifying Phillipi as urban. Large scale settlement has occurred in this area resulting in the establishment of informal dwellings, thereby reducing the amount of area used for urban agriculture. The reference data could therefore also be potentially incorrect in identifying this area as non-urban. Similarly, in-migration to Khayelitsha has also resulted in fast urbanisation of the area and could therefore also be underrepresented in the reference data.

The results obtained for the 2000 classification revealed more of the reference data visible through the overlying classification layer (Figure 56), although it is important to note that the classification largely produced accurate results, which reflects positively on the methodology. The classification was also able to determine that no urban development occurred on the steep mountainous slopes (specifically Table Mountain) where development is clearly limited. An overall accuracy of 72.4% was obtained for the study site, which is a satisfactory result based on the comprehensible and simplistic methodology.

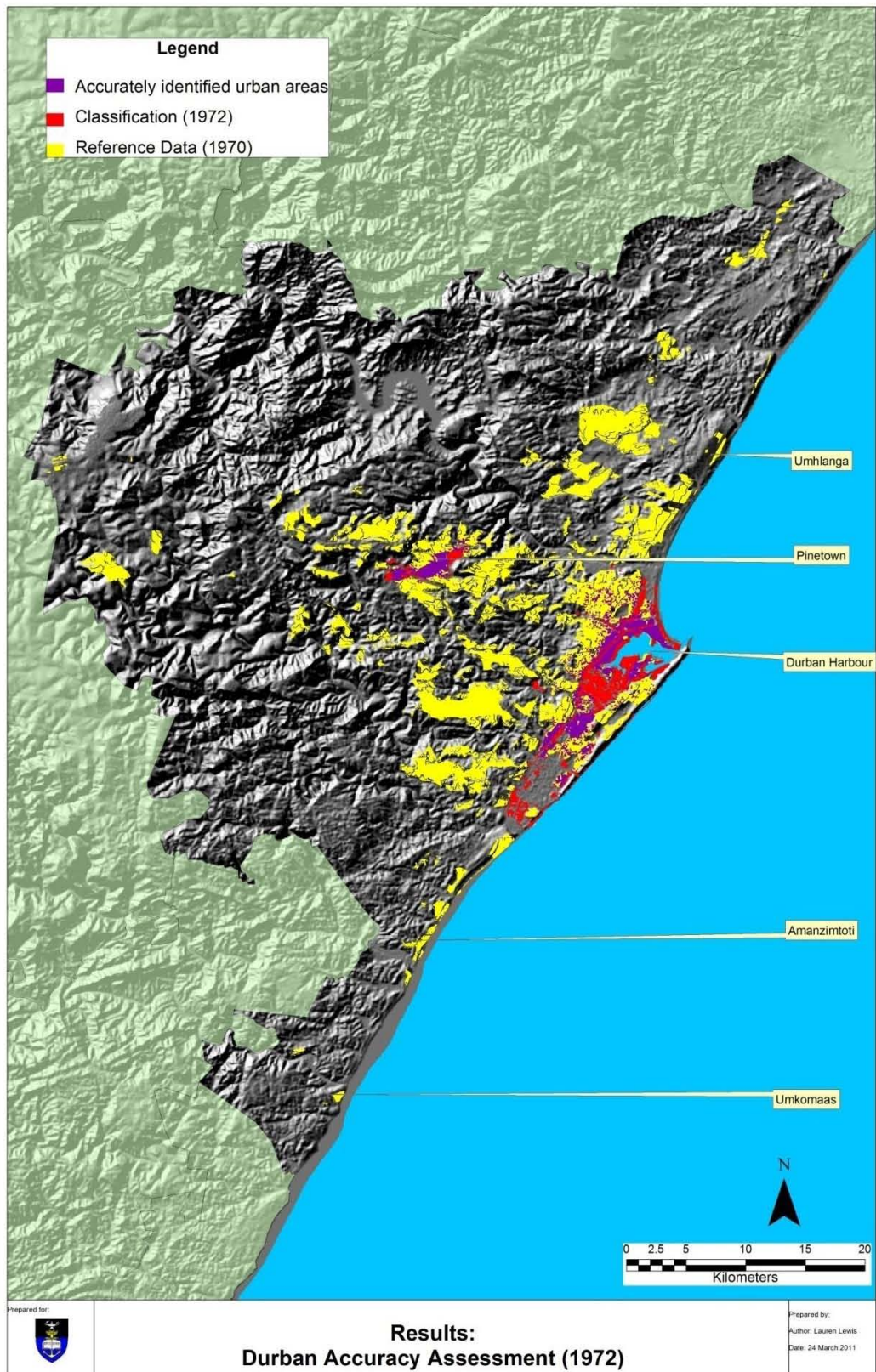


Figure 57: Durban accuracy assessment 1972

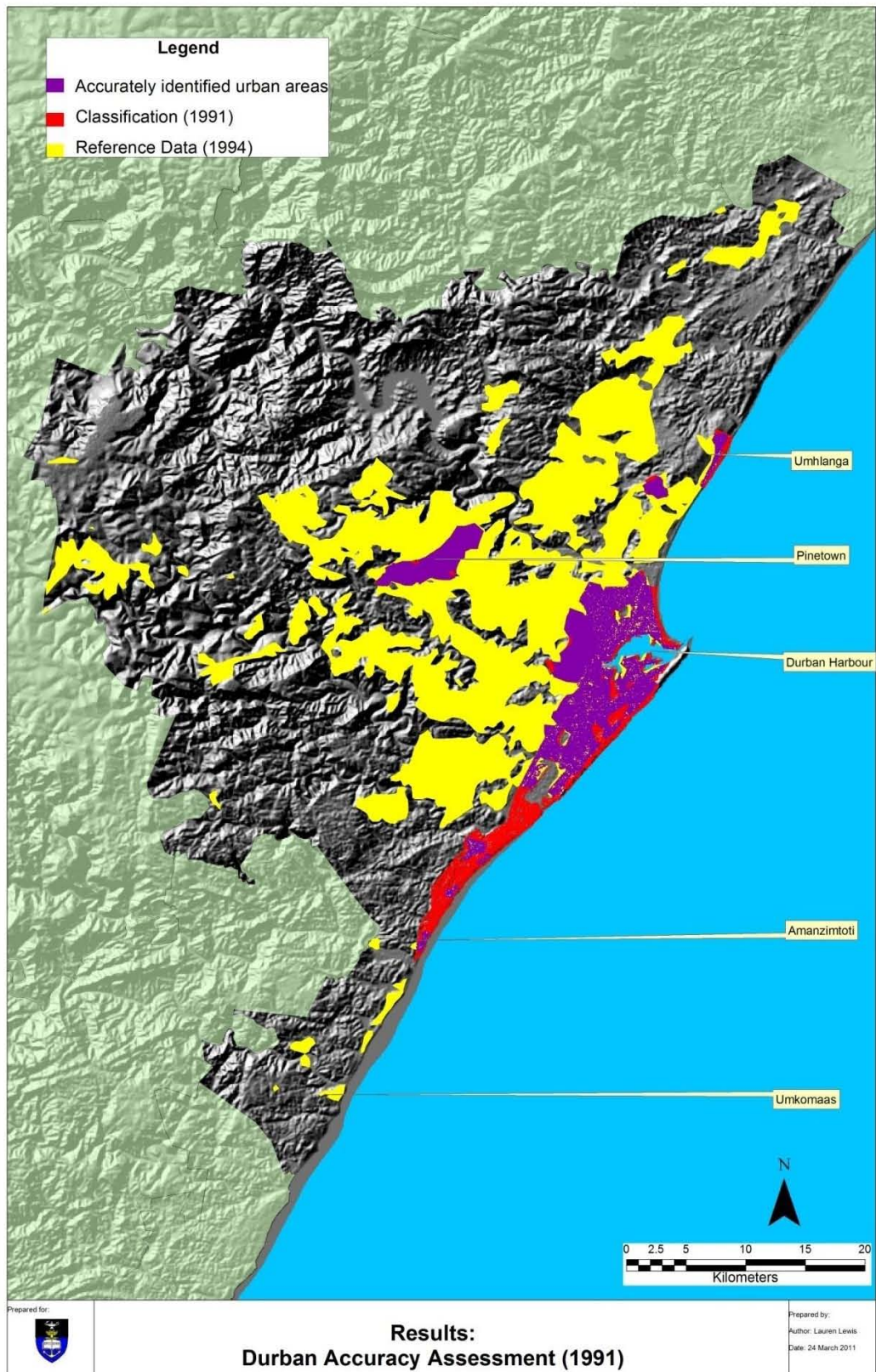


Figure 58: Durban accuracy assessment 1991

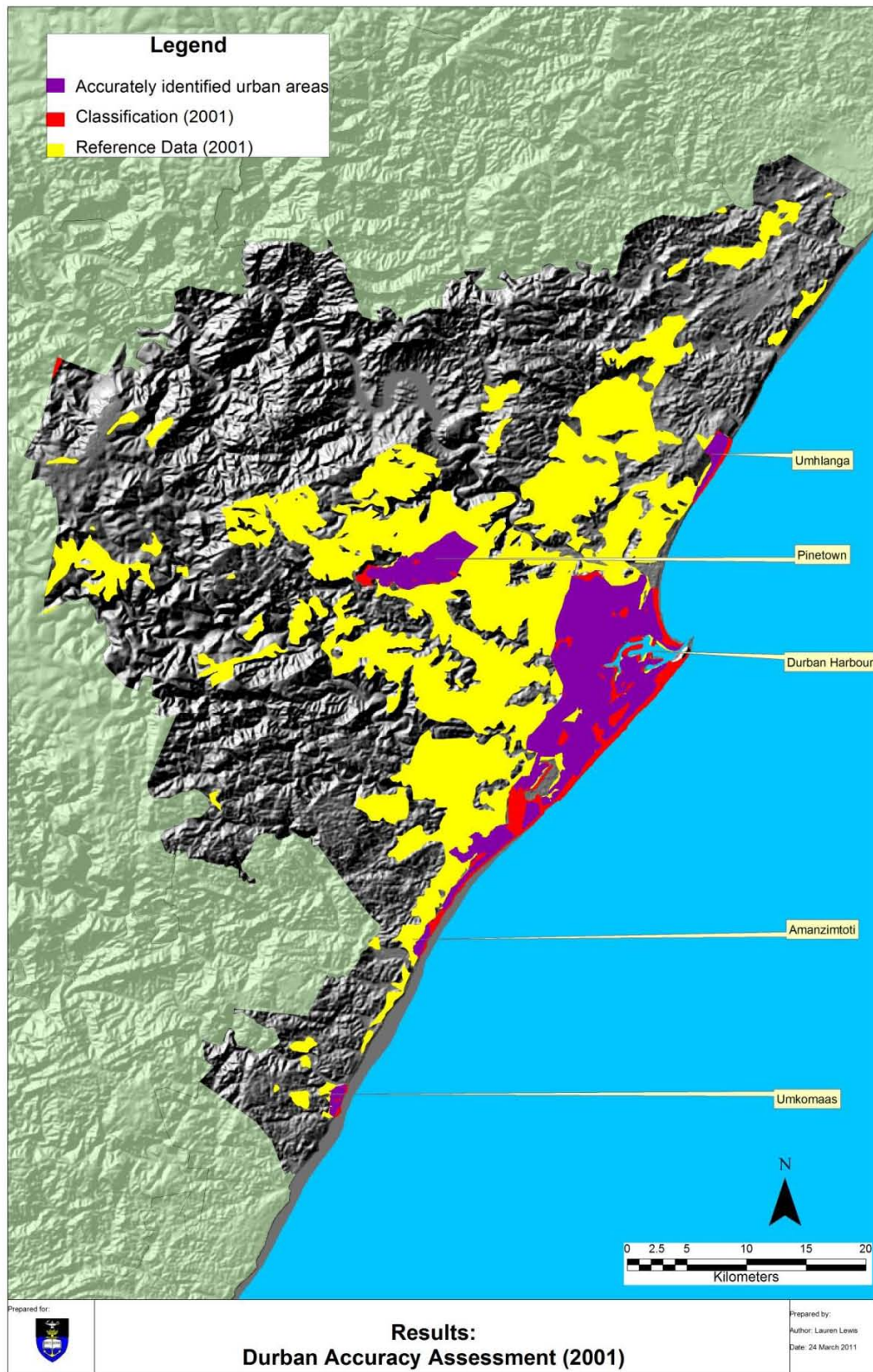


Figure 59: Durban accuracy assessment 2001

Table 18: Durban Accuracy Assessment Results

Reference Data	Year	Classification		
		1972	1991	2000
	1970	22.2%		
	1994		16.9%	
	2001			20.9 %

Notably in all the results achieved, very low accuracy levels were reflected by Durban's data. The study site differed from the previous two as the terrain was extremely variable with dense vegetation and humid climate. Based on the history of the study site, the outskirts consisted of large township areas which consisted of informal infrastructures and also had lots of vegetation present, river courses (including riparian vegetation) and nature reserves situated adjacent to built up areas. The abundance of greenery in the area proved to be a challenge for the methodology as areas with dense infrastructure such as the harbour and surrounding areas have been identified, but the areas on the outskirts were undetected. The quality of the imagery could also be responsible for the poor results obtained. Visually, Figure 57 to Figure 59 all show a gross underrepresentation of the urban areas when comparing the classification to the reference data

The 1991 classification results proved to be the least accurate, achieving an accuracy of only 16.9%. An improvement in the accuracy is evident in the 2000 classification results, producing 20.9%. Unexpectedly, the most accurate results were achieved for the 1972 classification (22.2%), although this information is noted to be questionable as the reference data was obtained from topographic maps which may have introduced human error into these results.

In summary, if only the latest data was considered in the accuracy assessment, the information illustrated in Table 19 would have been applicable. Evidently Johannesburg produced the highest level of accuracy (91.6%), followed by Cape Town (72.4%) and Durban with the least accurate information (20.9 %). The lower accuracy levels achieved in the 1991 classifications could be a result of the difference between the year of the reference data and the year of the classified Landsat image, while the 1972 accuracy could be attributed to the quality of the reference data.

Table 19: Accuracy assessment results

Study Site	Ref. Data Year	Ref. Data Area (km²)	Image Year	Accurately identified urban areas (km²)	Accuracy (%)
Johannesburg	2001	634.3	2002	581.0	91.6
Durban	2001	639.5	2001	133.4	20.9
Cape Town	2001	617.0	2000	446.8	72.4

University of Cape Town

6 Discussion

The analysis used a variety of datasets, namely remotely sensed images, vector data and census data, each of which provided a different aspect to enhance the quality of the analysis. The main component of the study was the remotely sensed images (raster data) that was analysed using an unsupervised classification technique to identify the urban areas. In order to provide a means of comparison for the remotely sensed images, the NLC datasets (1994 and 2001) were obtained as the reference data for the South African study sites. However, this information was not available for years prior to 1994, so topographic maps were obtained and the urban areas also extracted. The classification of the topographic maps were necessary as there were no historic 1:50000 shapefiles available from CD:NGI to serve as reference data for the 1970s time slices in the time series (CD:NGI, pers comm.). The GIS vector data (administrative boundaries) were used to define the urban boundaries of the areas i.e. keep the total area of each study site constant throughout the time series. The census data was used in the final stage where the total urban area was correlated with the total population.

6.1 Remote Sensing Perspective and Methods

Remote sensing has historically been used as an independent land use classification tool, however, despite efforts to establish new classification algorithms, over the past two decades there has not been much improvement (Wilkinson, 2005). Based on a study conducted by Rozenstein and Karnieli (2010), combining GIS and remote sensing techniques were shown to improve the overall accuracy of land use classification by up to 10%, hence the approach taken in this study. Although there are varieties of techniques used to monitor urban expansion, most of them are intensive and focused on one primary site. The approach differs in this study, where the importance and value lies in the ability to be able to monitor urban expansion occurring in multiple study sites by implementing an effective classification technique, supported by previous research methodologies.

6.1.1 Data Selection and Availability

Both Lu and Weng (2005) and Angel et al (2005) had in previous studies identified Landsat TM and ETM imagery as being ideal given the scale of the study sites. The MSS imagery however, was considered to be unfavourable as the coarser resolution results in features becoming

distorted at larger scales (Lu and Weng, 2005). Notably, the spectral and spatial resolution of the Landsat MSS, TM and ETM imagery improves with time as described in Table 7 and summarised in Table 20 below:

Table 20: Summary of Landsat specifications

Scanner	Resolution (m)	Bands
MSS	80 m	4
TM	30 m (visible, near & middle IR); 120 m (thermal IR)	7
ETM+	15 m (panchromatic), 30 m (visible, near & middle IR)	8

For the purpose of this study, only low resolution Landsat MSS satellite imagery was available for the 1970s period in the time series leaving no other viable alternative. The remainder of the time series primarily used medium resolution Landsat imagery (TM, ETM) which has a higher spatial resolution resulting in a lower degree of generalization than the low resolution MSS images. The scale of the study sites also played a role in the selection of the imagery as the medium spatial resolution reduced the amount of spectral clutter in each image without having too much generalization as experienced with low resolution imagery, and also avoiding excessive spectral clutter produced by high resolution imagery.

6.1.2 Pre-processing

Pre-processing techniques were employed in a variety of studies. In the absence of historic data, Elnazir, Xue-zhi and Zheng (2004) as well as Manonmani and Suganya (2010) scanned and georeferenced topographic maps (1:50 000) produced in 1974 and 1976 respectively as reference data in time series analyses. Rosenstein and Karnieli (2010) applied radiometric and atmospheric correction to a Landsat TM image using the dark object subtraction method. The corrected image was then registered to an updated orthophoto which would allow the Landsat image to be compared to the orthophoto and additional maps which were subsequently also geo-registered. Land classes were also manually digitized from the orthophoto to be used as reference data.

Angel et al (2005) subsetting images to only include the required areas in the study. This study also used subsetting of the original Landsat images as a pre-processing technique to eliminate

peripheral areas occurring well outside the study site as well as areas that could be verified as non-urban areas within the study site by making use of historic imagery such as aerial photography where available and Google Earth. The primary purpose of subsetting is to reduce the amount of spectral clutter in the extent and provide a smaller, more relevant site on which to run the classification.

Topographic maps were used as the reference data for the 1970s period of the South Africa sites time series, and for Windhoek and Gaborone's entire time series. Although the South African topographic maps had already been correctly georeferenced, Windhoek and Gaborone's topographic maps were required to be scanned and georeferenced using GCPs.

In most cases, pre-processing techniques are employed to enhance the results achieved from the study. As observed in this study, the ideal situation would have existed if aerial photography or higher resolution satellite imagery existed throughout the time series for the same years as that of the Landsat imagery in order to truly be able to evaluate urban areas and eliminate non-urban areas. Scanning and digitizing from topographic maps is subject to human error, which could also be avoided in many studies if sufficient electronic spatial data was available, however at present there is no emphasis in capturing historic spatial data electronically, which increases the dependence on historic topographic maps.

6.1.3 Unsupervised Classification

The unsupervised classification was selected primarily because no field work was conducted during this study and therefore no knowledge of classes present in the scene existed e.g. Menz and Bethke, 2000; Angel et al, 2005; Schneider, 2007; Thapa and Murayama, 2009; Rozenstein and Karnieli, 2010. In order to produce a coherent supervised classification Elnazir, Xue-zhi and Zheng (2004), Thapa and Murayama (2009), Thapa and Murayama, 2006; Hadeel et al, 2009 and Ma and Xu, 2010 demonstrated that intensive fieldwork and knowledge of the study site is required in order to assign the appropriate amount of classes. In a comparative study of classification techniques, Rozenstein and Karnieli (2010) demonstrated that the accuracy achieved using unsupervised classification techniques was higher than the accuracy of supervised classification techniques.

This study considered a variety of approaches to identifying urban areas, however visual interpretation from remote sensing images is limited to a single band or a three-band (RGB) composite. In addition, manual digitizing is seen as tedious and highly subjective, therefore considering the size of the study sites, an automatic remote sensing classification approach was viewed as the most practical and appropriate approach (as supported by Bolstad, Gessler and Lillesand, 1990). Based on the literature, the supervised and unsupervised classifications (notably the k-mean and ISODATA algorithms) are the most frequently used techniques in remote sensing.

Work conducted by Menz and Bethke (2000), Angel et al (2005) and Thapa and Murayama (2009) concurred that when different imagery is used (i.e. Landsat MSS, TM and ETM), and the exact amount of spectral signatures are unknown, one cannot use the same amount of clusters for each image in the unsupervised classification. For this study the appropriate amount of clusters varied from 30 to a maximum of 50. On completion, each classified image was compared to appropriate aerial photographs, Google Earth satellite imagery and topographic maps to verify urban areas and rectify any areas which were incorrectly classified, taking particular note of large areas that were not manually eliminated during the pre-processing phase, a similar technique employed by Elnazir, Xue-zhi and Zheng (2004) and Manonmani and Suganya (2010).

The effects of spectral resolution on the classification were apparent particularly in the poorer resolution MSS images, although improving in the TM and ETM+, which is generally favoured in Classification studies. Compared to Windhoek and Gaborone, the MSS generalisation property was less notable in the South African study sites due to the larger sizes of the cities. A particular generalisation problem experienced, although only to a small degree, was that the variability of the urban surfaces in terms of colour and surface type, created a greater dependence on the use of aerial photography and higher resolution images in order to ground truth the data

In this study, field work was not feasible, given that 5 study sites were being analysed and historic data was limited. In general, field work plays an important role in improving results of real time situational analysis. It would also have been beneficial to establish contact with urban historians for each study site who would be able to provide an account of the respective

historic urban landscapes. As noted, the unsupervised classification approach taken in this study is supported by many authors (namely Menz and Bethke, 2000; Angel et al, 2005; Schneider, 2007; Thapa and Murayama, 2009; Rozenstein and Karnieli, 2010) as no field work had been conducted and no prior knowledge or familiarity with the sites existed.

Defining a standard amount of clusters to be used was also not practical as different imagery was used. For future studies, making use of the same resolution imagery throughout the time series might aid in establishing a defined amount of clusters..

6.1.4 GIS Integration

Results obtained in vector data format in a study conducted by Rozenstein and Karnieli (2010) required a conversion to raster data, which was done using GIS software. This produced a binary dataset of urban and non-urban areas, making it easier to calculate the extent of each urban area and therefore also the amount of expansion that occurred between each time slice, similar methods had been considered by both Angel et al (2005) and Ma and Xu (2010). In order to maintain defined study sites and therefore provide accurate comparisons of urban expansion between time slices, Angel et al (2005) and Rozenstein and Karnieli (2010) used administrative boundaries to clip the resulting datasets. The initial classification results achieved in this study represented urban areas in raster format. GIS software was used to implement the raster to vector conversion in order for the results to be in the same format as the reference data (which is intended to remain unmanipulated). Error matrices are used to assess the accuracy of raster datasets with multiple classes hence were not considered here. Following examples of previous studies, administrative boundaries were then used to clip the study sites, thereby defining the areas. The final stage involved the sum of the urban polygon areas being calculated per scene to produce the total urban area for each time slice of each study site.

In previous studies, Angel et al (2005), Elnazir, Xue-zhi and Zheng (2004), Rozenstein and Karnieli (2010) and Manonmani and Suganya (2010) in the absence of electronic spatial data used topographic maps as reference data, a technique also used for the 1970s period of the time series in this study, and for Gaborone and Windhoek's entire time series. The remainder of the South African study sites used the NLC dataset as reference data to be utilized in the accuracy assessment (as discussed in Section 3.2).

As in the studies conducted by Ma and Xu (2010) and Thapa and Murayama (2005), the urban areas identified in the classifications were superimposed with one another to provide a quantitative and qualitative analysis of urban expansion in each study site. The reference data was also superimposed on one another as a comparison.

An important step in this process is that the resulting vector data has been clipped to the administrative boundaries in the final stage of the analysis, prior to calculating the total urban areas. It is not advisable to clip the actual satellite images, particularly using GIS software as it often results in an alteration of radiometric properties in the image data. The use of topographic data as reference data is not highly favoured as the process of scanning and georeferencing could add an element of user subjectivity thereby altering the reference data.

6.2 Error Sources

6.2.1 Urban Definitions (different locations and different countries)

The definition of urban used in this study included all built up areas which could be identified by the classification. The same definition was applied to the reference data (NLC datasets), thereby excluding small holdings and urban agricultural areas. Despite the attempt to have both the classification and reference data in line with the definition, the classification results still showed (in most cases) an underrepresentation of urban areas when compared to the reference data. This could be due to a combination of a variety of factors including the resolution of the data possibly being inappropriate in some cases thereby causing the methodology to be ineffective in identifying all urban areas, user subjectivity could also be present in the analysis as well as the possibility of the reference data including peripheral areas or areas which are not totally in line with the definition of urban used in this study. The resolutions of the images also presented a minor challenge where more generalisation was experienced in the poorer resolution imagery, particularly for Windhoek and Gaborone. This however did not have a severe impact on the study.

Although the definition of urban differs between countries, this study overcame the problem by using a single definition applicable to all study sites. It is important to note however that problems will arise if it is ever the intention to compare urban areas between countries by using results of independent studies (e.g. using the results of a South African urban study to

compare to the results of an urban study conducted in another country, using the local definition of urban). The differing definitions (which can be observed in the United Nations Demographic Yearbooks) could potentially yield inter-country results incomparable.

6.2.2 Urban in the Remote Sensing

The methodology can be viewed as somewhat subjective since aerial photography, reference data and/ or indigenous knowledge of the areas are required in order to verify (and possibly eliminate) non-urban areas during the data preparation process and to validate urban areas after the classification stages. The methodology allows for human error to be introduced into the analysis, particularly when deciding on the appropriate amount of classes to be generated during the unsupervised classification. However, the unsupervised classification has been frequently utilised in previous studies, particularly where the user was not completely closely familiar with the study areas, yet is still able to produce with a relatively high level of accuracy (e.g. Menz and Bethke, 2000; Angel et al, 2005; Schneider, 2007; Thapa and Murayama, 2009; Rozenstein and Karnieli, 2010). Supervised classifications on the other hand were primarily used in studies where the distinct urban classes were required by the user (e.g. Elnazir, Xue-zhi and Zheng, 2004, Thapa and Murayama, 2006; Hadeel et al, 2009; Ma and Xu, 2010) this was also acknowledged by Rozenstein and Karnieli (2010).

The major problem throughout the analysis was found to be the variation between the dates of the different datasets. Much consideration went into matching up the dates of the various data types as closely as possible. The difference in dates could therefore have played a crucial role in the difference in total urban area. The census data was found to be the most regular datasets as the study sites followed the United Nations recommendation of conducting censuses during years ending in either 0 or 1 (this is discussed further in section 3.3.1).

The accuracy assessment revealed that the methodology was suitable in identifying urban areas which was demonstrated in all study sites as evident expansion trends are visible in the results. The Cape Town results illustrate that the methodology is able to distinguish urban areas as the classification matches the reference data quite accurately. The shortfall noted in the Cape Town results is that the peripheral areas appear to be undetected by classification which could also bring to question whether the reference data included peripheral areas into

the respective urban classes or whether the classification did not succeed in identifying these areas as urban. The use of the NLC data sets were also ideal in this analysis as the vector data allowed specific urban categories to be used as the reference layer so as to fit the definition of urban used in this study.

Reflecting back on the primary aims of the study, the overall results provided a low cost technique to identify urban areas using a practical methodology which can be implemented by technical personnel with limited remote sensing capabilities. The shortfalls identified include the challenges associated with Durban's results whereby it is presumed that the vegetation, undulating terrain and physical features hampered the ability of the methodology to adequately identify urban areas. The methodology is also considered to be subjective, relying on human judgement in establishing the number of classes required to adequately identify urban areas and to verify the results using aerial photography. The relationship between urban expansion and population growth was unable to be clearly depicted as the urban expansion was determined by the results of the classification. To adequately understand this relationship, the total urban area of the reference would provide a more accurate result as both the census and reference data have both undergone rigorous quality assessments. The results of the classification can however be used particularly in regions where reference data is unavailable/ does not exist, in order to obtain a general overview of the urban expansion and population growth in the area.

6.2.3 Urban in the reference data: NLC

Using the NLC datasets as the reference was useful in this study as extensive research and analysis went into producing the dataset, which was a project of the CD:NGI. The major advantage of using the NLC datasets is that the definition of urban was able to be specified and the data was able to be manipulated so as to be in line with the appropriate definition of urban used in this study.

6.2.4 Urban in the reference data: Topographic Maps

The use of the topographic maps potentially introduced errors as the urban areas had to be extracted in order to produce shapefiles for comparison with the image classification. the use of topographic maps might not be entirely appropriate, literature reveals that topographic maps have been used as reference data in other GIS/remote sensing studies e.g. Manonmani and

Suganya (2010) and Elnazir, Xue-zhi and Zheng (2004), particularly where time series analysis dates back to the 1970s period.

The 1:50000 topographic maps used for Windhoek and Gaborone were the only available reference data. The study sites were small and both cities were able to be captured at a 1:50000 scale. These were evidently inappropriate reference data sources as the maps omitted urban boundaries and also do not provide enough land use information which would have been evident in aerial photography. An appreciation of a city and infrastructure can be achieved using Google Earth, however, the historic information particular at the decadal time scale is not routinely available. The lack of adequate reference data for Windhoek and Gaborone can also therefore be seen as a weakness of this study and highlights the limitations associated with using topographic maps as reference data.

The scale of the study sites also played an important role in the quality of the information provided by the topographic maps. Notably, the urban areas were more detailed in the 1:50000 maps, which made extracting urban areas more difficult. Although the problems introduced by using the 1:250000 topographic maps as assessment tools are related to the unknown accuracy and cartographic generalisation in the data, the increased generalisation made extracting the urban areas easier and also provided sufficient detail to allow for adequate comparisons to be made between the classification and reference data.

6.3 Accuracy Assessment

Lu and Weng (2005) assessed a variety of accuracy assessment techniques, however all the techniques are applied to raster datasets. The spatial results of this study were in vector format, therefore requiring an alternative accuracy assessment methodology. Also, Lu and Weng's methods largely involved combining spectral bands, textural data and temperature, which was beyond the scope of this study, although it is important to note that a variety of accuracy assessment techniques were considered for this study.

The accuracy assessment was conducted on all the dataset, however problems associated with the 1972 and 1991 classifications made the results unreliable. The 1972 accuracy assessment was based on reference data obtained from topographic maps which could

account for many errors such as errors produced during the georeferencing process, extraction of the urban areas from the topographic maps and the editing of the data to eliminate the gaps in information as a result of the text present on the topographic maps. The 1991 data is also 3 years younger than the reference data, which could be the cause an underrepresentation of urban areas at this point in the time series which is noted in all the study sites. The 2000/1/2 classifications provided the best information to be assessed in terms of accuracy as it closely corresponded with the reference data. Despite the challenges presented by the data, the accuracy assessment showed that the methodology was able to produce adequate results for two out of the three South African study sites.

Johannesburg's 2002 accuracy assessment produced the highest accuracy (91.6%) which was calculated by comparing the results obtained from the classification to the reference data. As depicted in the graph (Figure 40) and accuracy assessment (Figure 53), the classification revealed an underrepresentation of the amount of urban area, with the biggest difference noted for the 1996 (census year). The accuracy assessment of the preceding dates in the time series was low, producing accuracies of 29.7% (1972) and 49.2% (1991). The administrative boundary used to define the study area does not consider the expansion occurring beyond the boundary. However one of the aims of the thesis was to test the methodology and the ability to identify urban areas within a defined boundary, which required that the administrative boundaries were implemented to maintain a constant total area of the study site throughout the time series. Without these boundaries, additional challenges will be introduced particularly noting that Johannesburg is a megacity and the range of the time series starts in the 1970s, prior to it achieving this status. Currently development has expanded as far north as Pretoria, which would bring to question where the study area should end. For the purpose of this study, the use of the Johannesburg Local Municipality boundary was determined to be a feasible means of limiting the extent of the study area. The census data available for this area, which was provided in spatial format, was therefore also used in this study.

Overall results for Cape Town demonstrate the ability of the methodology to extract urban areas as the classification to a greater or lesser degree also mirrors the reference data. The lower accuracy achieved here was 72.4%, less than when compared to the Johannesburg results. Upon visual inspection (Figure 56), the peripheral areas identified as urban in the reference data were omitted by the classification. The accuracy results obtained for the 1972

classification was 51.9%, which could be due to the mentioned errors, as well as the temporal mismatch of two years between classification t and the reference data. The 1991 image produced 45.0% accuracy and showed the most dramatic difference in urban area when comparing the reference data to the Landsat image. The amount of classes used for this classification could have been too little or alternatively, the coarse resolution of the data could also have played a role in the classification of the images by introducing more generalisations. The final point in the time series (2000) also showed an underrepresentation based on the classification results, although there is a one year difference between the reference data and the image used for the classification. The resolution of the ETM+ image was much finer than the previous two images and the results show that the amount of urban area detected for this point had improved with a much smaller difference between classification results and reference data.

As previously discussed, Durban proved to be the most challenging study site as there was a gross underrepresentation of the amount of urban area present for all points in the time series. The results of the accuracy assessment were also considerably low. The 1972 classification achieved an accuracy of 22.2%, the 1991 classification 16.9%, and the 2001 classification achieved an accuracy of 20.9%. The underrepresentation of urban area, as well as visual inspection of the results reveals that the classification indeed detected urban expansion throughout the time series as there is a consistent trend of the outer lying areas not being classified as urban. The data used and the chosen techniques are not capable at retrieving urban area due to the nature of the terrain which is vegetation and highly dissected and the type of housing present.

6.4 A social interpretation of the spatial data

The historical influence of apartheid played a major role in the development and spatial planning of all South African study sites, including Windhoek. Gaborone however, was unaffected by the apartheid regime and allowed to develop without any influence from neighbouring countries. The effects of the historical influence on each study site are discussed further in this section.

The South African study sites include observations regarding a population density, which was directly affected by the apartheid regime. In many cases, informal settlements e.g. Khayelitsha, Umlazi and Soweto, resulted from people (mainly black South Africans) being forcibly removed from their previous place of residence (Vanderschuren, 2003; Christopher, 1994; Mohammed, 2002). The high density suburbs are often low-income communities, situated on the city peripheries (Hindson et al, 1992, p. 6). Free movement of people in the post-apartheid era has allowed migrants in search of opportunities in urban areas settle in these informal settlements. The lower density areas are usually home to middle to high income residents, residing in formal residential areas.

6.4.1 South African study sites

The historical influence of apartheid and post-apartheid spatial planning impacted all the South African study sites, however, the outcomes of these planning policies illustrate key differences which are evident in the findings.

Apartheid's influence on city planning and development

The present day post-apartheid city lays the foundation for assessing how the spatial aspect of social inequality shaped the dynamics of urban transformation. The racialised city is the most recognised apartheid legacy, particularly in terms of spatial development whereby race groups were allocated to different neighbourhoods (Schensul and Heller, 2011). Earlier city planning was however also largely influenced by topography and economic function.

Development land on the Cape Peninsula is largely restricted by the topography including oceans and mountain ranges (Table Mountain range down to Cape Point and the Overberg and Drakenstein Mountain Ranges restricting north-eastward development) (Figure 32 and Figure 33). From as early as 1972, urban expansion appears to be extensive in the study site, which can be attributed to Cape Town's historically significant economic function as a trading post, although notably large areas along the Indian Ocean coastline remained unpopulated. Outward expansion is evident in the time series with development extending inland.

Hout Bay and Camps Bay are evident as small settlements prior to 1973 (Figure 32 and Figure 33). Since 1937, Hout Bay's fishing industry encouraged development near the harbour (Hout Bay, 2008). Development has since increased dramatically with residential areas extending up

the adjacent mountain slopes (Figure 32 and Figure 33). Camps Bay's restrictive topography resulted in development occurring up the mountain slopes. The pristine coastline is popular with foreign investors and residential areas were and still are dominated by wealthy communities.

Gordon's Bay and the Strand area have more land available between the coastline and Helderberg mountain range. Initial development is shown to be closer to the coast (Figure 32 and Figure 33) with expansion occurring towards the interior which was due to an increase in popularity of the area.

The majority of early development is seen to occur on the Cape Flats and Cape Town CBD. A constant trend of expansion is evident in Figure 32 and Figure 33, although the majority of the development is shown to have been established prior to 1973. During the Apartheid era coloured and black communities were forced to settle in peripheral areas, resulting in the establishment of separate townships far from the CBD (Spinks, 2001). The highest population densities occur on the Cape Flats (Figure 8), particularly in Bonteheuwel, Bishop Lavis, Mannenberg and Khayelitsha³⁶ where present day population groups reflect the racial divisions enforced during apartheid. Other areas showing high density are Lavender Hill, Hanover Park, Belhar and Mitchell's Plain (Figure 8). During apartheid, white communities were given preference in terms of spatial planning and the forced removal of non-white communities provided new prime locations for the establishment of new white communities, particularly in areas nearer to the CBD.

Mitchell's Plain was established in 1975 and Khayelitsha in 1983. These areas were developed as coloured and black townships respectively. They were both established post-1973 (Figure 32 and Figure 33), which is evident in the 1973 classification results. Mitchell's Plain was established due to the Group Areas Act and people being forcibly removed from District Six to the Cape Flats (Ndegwa et al, 2006), while Khayelitsha was a result of the over-crowding and squatting in defiance of the Apartheid regime in Crossroads. Many of the coloured areas established prior to 1973 (Figure 32) appear to have high population densities (Figure 8). This is due to many residents residing in low cost houses, informal settlements or in high-rise apartments built during apartheid to accommodate people who were forcibly removed from

³⁶ Based on Census 2001 data (StatsSA, 2001)

areas such as District Six (Van Nes, 2002). Both Mitchell's Plain and Khayelitsha still attracts many individuals from other provinces seeking employment opportunities in Cape Town (Figure 6 and Figure 7).

Present day Durban has maintained its spatial legacies of apartheid as much of the city has remained unchanged. Durban's urban expansion pattern tends to radiate outwards from the harbour area (Figure 35). Both Figure 35 and Figure 36 indicate settlement in this area prior to the 1970s. This stems from the mid-1800s when Durban was a small settlement concentrated around the port, which has from those earlier years, been recognised as an important harbour for the importing as well as exporting of goods (Marx and Charlton, 2003). The city centre was also home to the wealthier population, having the best services and infrastructure (Marx and Charlton, 2003). Pinetown was also established prior to 1970 as a small settlement.

In 1913, the Land Act alienated indigenous people from the land, which forced them to seek wage employment on the colonialist's agricultural lands as a means of survival (Marx and Charlton, 2003). Mohammed (2002) describes the relocation of people to planned established townships such as Umlazi, Phoenix, Chesterville and Kwa Mashu; resulting in them currently being Durban's most densely populated areas (Figure 9). Apartheid spatial planning also sees these areas being situated towards the periphery and away from the harbour and CBD. As the manufacturing industry increased, so did the informal settlements on the periphery (Smit, 1997). This trend is also evident in Cape Town and Johannesburg (Figure 8, Figure 12 and Figure 13). The ruggedness of the terrain as well as abundance of rivers and river valleys was used as natural buffers in order to racially segregate communities during apartheid. The aim was to utilise these natural buffer areas in order to create racially homogenous areas (Marx and Charlton, 2003).

Johannesburg's flat terrain allowed for the outward expansion of the urban areas, resulting in the occupation of the largest area of all the study sites (Figure 47). The development of the region was primarily attributed to its economic function, with little topographical restrictions. Since the discovery of gold in 1886, people have been migrating towards the region. Mine owners exploited the availability of cheap black labour encouraging migrant workers to the area who settled in townships. Between 1950 and 1970, the economy underwent a transition period, becoming less dependent on primary activities. By the mid 1970s, offices were being

established in the northern suburbs, a trend which over time spread throughout the CBD area. The economy shifted its dependency towards secondary and tertiary activities, resulting in further urban expansion in the region (Fair and Muller, 1981; Beavon, 1997).

The apartheid influence also played an important role in the spatial planning of Johannesburg. Having survived apartheid, Alexandra is an established non-white suburb, amongst the white suburbs, situated north of Johannesburg CBD (Davie, 2003). In 1979 protests against the relocation of the black residents caused government to redevelop the area into a high density black suburb, as opposed to the total destruction of the area. Hillbrow and Berea were established in the 1890s as middle class white suburbs. By the 1970s whites began moving out of the areas, creating an opportunity for the coloured, Indian and black communities affected by housing shortages. The period leading to the change in the area's demographics is known as the greying of Hillbrow and was primarily due to landlords eager to fill vacant spaces thereby leasing to the non-white population (Morris, 1999).

1980 - 1990

During the 1980s it was becoming increasingly clear that apartheid could not be implemented as decreed by law and many policies eventually allowed some flexibility in its application. In 1986 the government allowed orderly urbanisation whereby a limited number of blacks could reside in official white urban areas, provided that there was sufficient housing available (Byrnes, 1996). The policy was directed at accelerating the process of industrialised and cultural change by relaxing the urbanisation constraints imposed by state planning. This resulted in large scale in-migration of the black population to urbanised areas, and a lack of sufficient housing ultimately resulted in the emergence of densely populated informal settlements. Political tension and instability also escalated (Smith, 1992).

In Cape Town, Phillipi, like Khayelitsha, was established during the eighties, hence not being evident in the 1973 classification. The area grew into a large settlement relatively quickly as many black communities who fled the former homelands settled in the area (Anderson et al, 2009). Phillipi (Figure 32) provides a good example of a problem faced in defining urban areas, the classification illustrated dense infrastructure occurring in the area and local knowledge verifies that there is indeed a densely populated informal settlement in the area, as well as

areas of large scale urban agriculture. The reference data illustrates a much larger non-urban³⁷ area comprising of urban small holding³⁸, the area is also much larger than the classification suggests which is not entirely accurate as in reality the informal settlement dominates a large portion of the northern area (which is not indicated in the reference data), thereby resulting in more urban area. The classification correctly did not identify the remaining agricultural area as urban. In Figure 32, spatially Phillippi is recognised as occupying a larger area than suggested by Figure 33. Throughout the time series, Figure 33 does not recognise any part of the Phillippi area as urban. This influences the graphs (Figure 34) as it affects the area calculation.

Atlantis was established as a coloured area during the late 1970s, due to the Group Areas Act (Warnich and Verster, 2004). This is verified by the results as the town is only evident in the post-1973 results (Figure 32 and Figure 33). Some expansion has occurred in the area, although development and outward expansion seems to be limited. According to Warnich and Verster (2004), the area remains underdeveloped thereby discouraging immigration to the area and hence slowing development and urban expansion. Population density in the area is also low (Figure 8). The development of Melkbosstrand and Duynefontein are evident south-west of Atlantis (Figure 32 and Figure 33). Melkbosstrand has evidence of earlier settlement prior to the 1970s in Figure 33., however large scale development only occurred post-1973 (Figure 32 and Figure 33) as a result of the establishment of Koeberg Power Plant (Eskom, 2008; Hart, 2008). During apartheid the area was established as a white community.

Durban has the second largest population of all the study sites (Figure 47 and Table 13) which could be due to the inward migration of people to the peripheral areas in search of work opportunities within the city. Indians were also brought into the area as cheap labourers on fixed term contracts. This further contributed to the need to expand of the city boundaries in order to accommodate the growing informal areas (Marx and Charlton, 2003).

Johannesburg's population increase was largely due to the immigration of labourers (miners) which peaked in 1986, when the economy was dependant on gold mining. Approximately 534000 miners, who were mainly black males, were employed in the Johannesburg mines (Harington, 2004). During this period there was also a dramatic increase in urban infrastructure

³⁷ In terms of the definition

³⁸ Excluded in the definition of urban used in this study

(Figure 38), which could also be attributed to the shift from dependence on primary activities (gold mining) to second and tertiary activities. Many companies have their head offices located in the Johannesburg CBD (Amprops, 1994).

Analysing the graphs (Figure 34, Figure 40)³⁹ for the period between 1972 and 1991, the general trend in the classification suggests that the populations were increasing at a faster rate than the urban areas were expanding. The findings could be attributed to the large scale immigration to cities as a result of the introduction of the orderly urbanisation policy. The densification of urban areas without concurrent urban expansion in all the South African study sites could be a result of the accommodation of people in high rise buildings and hostels.

1991 To present day post apartheid

South Africa has seen significant immigration to large cities since the end of apartheid, resulting in an upsurge in housing shortages. The Reconstruction and Development Program (RDP) adopted in 1994, has to date been the most viable manifestation of addressing the housing shortages by providing basic houses, roads and services. In many cities, the program has seen lower density sprawl, particularly in peripheral areas, although the increase in the housing backlog has also led to an increase in the amount of back yard dwellers.

For all the South African sites, development occurring in peripheral areas is evident in both the classification and reference dataset for the 2001 time slice. Upon investigation, it is evident that this expansion can be attributed to the development of peripheral low density gated communities and also the construction of RDP houses to address the housing shortages experienced throughout the country.

Analysing the population density maps for this period (Figure 8, Figure 9, Figure 12 and Figure 13) it is evident that the areas with the highest densities are those where informal settlements exist and also areas with many backyard dwellers. Back yard dwellers have historically been overlooked by housing policies that focus on upgrading and eradicating informal settlements, however, the post-apartheid provision of state funding for the poor has created a class of homeowners dependant on the income derived from backyard dwellers (Lemanski, 2009).

³⁹ Durban has been omitted due to the previously mentioned inaccuracies in the classification

Durban's results produced the most variability which was notably consistent throughout the time series, suggesting that the error is possibly due to the resolution of the imagery or variability of the terrain (particularly vegetation cover) and therefore not exclusively related to the methodology. Notably, the informal areas on the outskirts of the formal areas and CBD remained undetected throughout the time series, which could be due to the use of natural materials such as mud in the construction of their dwellings. The building material used tends to have similar spectral signatures to that given off by bare ground and vegetation, resulting in the classification being unable to differentiate between the different signatures (Figure 16 and Figure 17).

Densely populated areas such as Whetstone, Ntuzuma, Kwa Mashu, Clermont Town, Westridge, Monford, Chatsworth and Umlazi, are located further towards the interior of the country, away from the harbour (Figure 9). The poorer populations were located far from the well serviced central area, thus having minimal or no access to essential amenities (Marx and Charlton, 2003). These areas have remained undetected by the classification (as previously discussed), however are evident in the reference data (Figure 36) as being formally established prior to 1973. These areas continued to expand with the most expansion observed between 1973 and 1991. As a whole, much less expansion occurred between 1991 and 2001

After 1994 many miners in Johannesburg resettled their families in the areas along the reef, often in the townships (Harington, 2004). Despite the lack of services and uncomfortable living conditions, these areas continue to expand. The population density trend shows Alexandra, Hillbrow, Berea, Orlando, Meadowlands and Zola have the highest densities. Soweto and surrounding areas also have high densities. The northern suburbs and outskirts have the lowest population densities (Figure 13). Figure 12 illustrates the areas from which people were removed (based on Figure 10 (Christopher, 1994, p. 123)), using Census 2001 data to show population density. The higher density area is clearly shown to occur around Soweto, which, during the post-apartheid era has subsequently expanded due to in-migration and natural population growth. It remains a low-income, high density settlement, consisting of mainly black South Africans. Between 1996 and 2001 the population increased at a much slower rate than in previous years. The decreased dependency on gold led to job loss and emigration (Harington, 2004), although large scale resettlement simultaneously occurred where miners settled their families in areas along the gold reef e.g. Soweto and Diepkloof.

The classification graph (Figure 40) initially shows population and urban expansion increasing at fairly even rates. The population growth shows a decrease in the later years, compared to urban expansion which continues to increase at a faster rate. The reference data graph shows a similar trend, although during the early years population growth seems to be occurring at a slightly slower rate than the rate at which the population is increasing. The graph then changes to a gentler slope showing that the rate of urban expansion is occurring at a faster rate than population growth.

Significantly, the 1991 . 2001 period illustrated in classifications (Figure 34 and Figure 40) shows urban expansion to be increasing faster than the populations of both Cape Town and Johannesburg. This could be attributed to the mass rollout of state housing which essentially promotes less dense developments than what is currently witnessed in informal settlements.

6.4.2 Windhoek

Figure 48 illustrates that Windhoek occupied a much smaller area than the South African study sites. Initial development only began to accelerate after 1907, before losing momentum during the two World Wars, after which it soon picked up again (Njeru, 2008). This means that the city is relatively young compared to the South African study sites. After gaining independence in 1990, there was an influx of migrants to the area (The World Bank, 2002). This is evident in Figure 41 where urban expansion is evident in mainly north-westerly and south-easterly directions. Katutura is situated in the north-westerly corner of the city, which is the township where most migrants establish themselves (Frayne, 2007). Elevated terrain restricts east and westward development (Figure 41 and Figure 42).

The classification graph (Figure 43) shows that urban expansion was initially increasing slightly faster than the population, however in the later years the population growth rate and urban increase tends to be occurring at a steadier rate. Although there were no further topographic maps available in order to complete the time series, the available data suggests that the population increased much faster than the urban area expanded during the earlier years. From the graphs it is also evident that both urban extraction methods initially produced very similar results. Literature suggests that one of the main contributors to population growth is in-migration and settlement in the peripheral townships such as Katutura. Approximately 60% of Windhoek's population is located in Katutura, which covers only 20% of Windhoek's total area

(The World Bank, 2002). The in-migration movement was stimulated by the establishment of secondary and tertiary activities (Simon, 1995, p. 44), and began after independence in 1990. Table 14 shows that according to the classification the total urban area expanded by approximately 29.2 km² (75.0%) for the whole time series. Unfortunately no reference data was available to perform the same analysis of the whole time series, instead, comparison was made between the first two points in the time series for which data was available. The difference between the first two classifications in the time series shows that the classification indicates a 15.0 km² (Table 15) increase (38.5%) in the amount of urban area, while the reference data classification shows only a 1.7 km² (13.9%) increase. The topographic maps used as reference data were only obtainable for 1977 and 1983, whereas the satellite imagery was available for 1973, 1989 and 2001. The variation in the data is thus too great to draw accurate conclusions based on this classification and reference data.

6.4.3 Gaborone

Gaborone's location on a topographically flat area creates the ideal location for higher level urban planning in order to accommodate urban expansion. The site for Gaborone's location was chosen around 1964 (Maundeni, 2003) and therefore, like Windhoek, it is also a fairly young city as opposed to the South African study sites. The structured plan is evident in Figure 45, where development tends to expand outwards. Also, the airport is evident on the outskirts of the city, away from residential areas (Figure 44). The largest amount of urban development is evident in Figure 44, between 1991 and 2002.

Gaborone tends to show urban expansion and population growth occurring at a constant rate throughout the graph (Figure 48). Despite having the lowest total population for all the years, and compared to all the study sites (Figure 47 and Table 13), the total urban area according to the classification results is almost double that of Windhoek at the final data point. The lower population figures could be a result of the area only being chosen as the capital in 1964 (Maundeni, 2003; Sebege and Seane, 2008). Since the development of the area, urban expansion has already occurred and encroached on some of the previously peri-urban villages (Sebege and Seane, 2008). This is evident in Figure 44.

The most noticeable attribute of the graphs (Figure 46) is that they are almost parallel, although the classification graph suggests that the urban area was greater for all points in the

time series. The population and urban area increase shows to be constant throughout the time series. This is also observed for the topographic graph. There were no further topographic maps available in order to complete the time series.

Table 14 shows that the classified urban area expanded by approximately 63.2 km² (87.2%). The same problem existed for Gaborone whereby only two topographic maps were available to be used as reference data. Considering Table 15, the expansion classification indicates that the urban area expanded by 19.2 km², (67.4%) whereas the reference data shows a 17.3km² (91.2%) increase. Although the topographic maps were available for 1968 and 1991, similar to the satellite imagery which was taken in 1971 and 1991, the topographic maps could not be used as a reliable reference dataset as it excludes many of the peripheral villages which are included in Gaborone's urban area.

7 Conclusion

The study illustrates the feasibility of using Landsat MSS, TM and ETM imagery to monitor urban expansion in five Sub-Saharan African study sites and correlating the results with census data. Spatio-temporal data is currently in demand, particularly in the context of urbanisation in developing countries; however, as noted in this study, data availability plays a critical role in obtaining adequate results. Obtaining concurrent data from different data sources proved to be a central challenge. Dates for the different sources were therefore required to be as closely matched as possible in order to achieve viable results e.g. Gaborone's 1971 census data was matched with a 1973 Landsat image and 1968 topographic map. The matching of the data was the most practical alternative in terms of obtaining viable results using available data. This approach will be especially useful for areas where no prior urban expansion analyses have been conducted. The analysis illustrated the extent of spatial growth and the viability of using remote sensing and GIS in urban spatial analysis. Administrative boundaries played an important role in defining the study sites. For the South African sites, it identified the extent of each study site in terms of political demarcation boundaries. Windhoek's city extent was determined by the census data and topographic maps.

A definition of urban was provided so as to clarify the aims of this study. The administrative boundaries were used to define the study sites, and the built up areas within these boundaries that were obtained from the classification was considered as urban (this has been previously noted in section 1.5, and the complexity of defining urban is discussed in section 1.1 and section 2.1). The analysis identified urban areas as built up agglomerations, considering that the study sites were all major economic centres in the respective countries. Similarly, the census data provided the total population count for each study site. The topographic maps and NLC datasets were used as references data (South African sites).

The definition of urban used in this study was applied equally for all study sites, allowing comparison to be made between the classifications. Realistically, this is not the case and each country has a unique definition of urban. This suggests that independent urban area studies would not be comparable between countries. The definition of urban used by the CD:NGI in their NLC datasets also differed from the definition used in this study. The NLC datasets were available as vector data, with descriptions provided in their attribute tables which were used to determine the most appropriate definition to be used in this study only including built up areas. If

the original definition of urban in terms of the NLC dataset was used, the results would have been considerably different, notably the reference data would have a much larger urban area, particularly due to urban agricultural regions being included in the definition.

This study reveals urban expansion primarily on the peripheries of the study sites while inner city expansion is less evident. Present day population density increase is primarily influenced by immigration to already established inner city informal settlements (CoCT, 2005). The South African study sites illustrate increasing population densities primarily occurring in informal settlements due to an influx of immigrants. For both Cape Town and Johannesburg, formal development is also seen to be occurring on the city peripheries, resulting in outward urban expansion. These developments are characteristic of post-apartheid city planning comprising of higher income gated communities as well as state RDP development projects. Durban's results illustrate the shortfall of using Landsat's low to medium resolution imagery, particularly in sparse or lower density settlements since the informal areas radiating outwards from the formal CBD area remain largely undetected throughout the time series. Additional factors limiting detectability are the variable terrain, dense vegetation and the use of natural materials in the construction of dwellings. Windhoek, like the South African sites is also influenced by large scale immigration, particularly to the northern Katutura area where 60% of the population is located on 20% of the city's total urban area. Unlike the South African sites, Windhoek's immigration only began to rapidly increase after independence in 1990.

In contrast to the other study sites, Gaborone's widespread urban expansion resulted in the encroachment of previously peri-urban villages. This is the only such example in this study of population increase due to urban encroachment.

Urban management involves procedures such as mapping and monitoring which requires data from reliable sources as well as appropriate analytical tools in order to draw valuable conclusions which could ultimately be used in important decision-making processes.

Data availability was a major concern in the study. Comparisons between different countries proved to be challenging as there was a considerable amount of variation in the data e.g. different census years. The availability of uniform data was a major problem to overcome in the analysis. These include:

- The lack of administrative boundary data at town level in Windhoek and Gaborone.

- Reference data for Windhoek and Gaborone was difficult to obtain as NLC datasets for these countries appeared to be unavailable/non-existent. Topographic maps were ultimately used as the reference data which also proved to be a challenge as each government has their own departments responsible for housing and maintaining topographic maps. Only two topographic maps were obtained for each city, resulting in the reference data analysis being incomplete.
- Although the satellite images are available, in cases of large cities e.g. Cape Town, more than one Landsat tile was used in the classification. The reason for this is that Landsat operates on a path/row system as it circles the earth. Results were required to be merged in the final phases after being converted to vector data.
- The dates of the data do not correspond. This means that the satellite imagery, topographic maps and census data, each reflects a different point in time, thus the results are not entirely accurate in representing one specific moment in the time series. The most accurate time period is the last point in the time series for the South African study sites, where Landsat, NLC and census data were all closely matched to the year 2001.

Since the entire USGS Landsat archive was freely available to the public, dependence on the GLCF as a data custodian of free Landsat data has been reduced. The availability of the additional archived data also provided a wider range of dates to choose from, thereby allowed for the images to correspond more closely with the census data. This was therefore highly beneficial to this study. The response by the public to the opening of the archive was noted in media statement released by the USGS in August 2009 which stated that "One development of particular note is that the very oldest data in the archive, dating to over three decades ago, is being downloaded at unprecedented levels . with land-surface change detection emerging as a primary use of Landsat data+.

Besides the Landsat archive, data is becoming increasingly available to the general public as spatial analysis becomes more important in monitoring changes occurring on the surface of the Earth e.g. land use changes. Utilising these available spatial resources will aid in temporal analysis which could ultimately prove to be highly beneficial to economic, environmental and social sectors.

In terms of the methodology, the use of remote sensing and GIS proved to be important tools in the urban analysis and integration with census data. The shortfall lies with the quality of the data e.g. satellite imagery (specifically Landsat MSS images). Although Landsat data is freely available, the resolution of the imagery can pose a challenge, especially if the study was to be conducted at a smaller scale. The census data showed the relationship between urban expansion and population increase, although the data was available for all the selected study sites, there are cases where countries have not conducted censuses since the 1980s (and some the 1970s) (United Nations. 2001). It is therefore important to acknowledge that remote sensing can also be used to estimate populations e.g. Sutton (2001) and Zeug and Eckert (2010).

The temporal mismatch refers to images obtained for different observation periods. This has created a degree of inconsistency in the data as different times of the year reflect differently in images e.g. during the spring/summer, more vegetation will be evident whereas during autumn/winter more surfaces will be exposed. There is also the problem of time gaps between data sets. This is particularly evident in the South African sites, specifically for the period 1980 . 1990 where insufficient imagery was available. During this period the Landsat program was commercialised leading to a limited amount of data acquisition and archiving. Much of the Landsat TM 4 and 5 data were also not used due to extensive cloud cover, bad data quality and changing surface conditions (Tucker, 2004).

The ideal situation in this type of analysis would be that the Landsat images, reference data and census data are obtainable for the same year to provide a true reflection of the level of urban expansion and population growth at a particular point in time. This study has also revealed a need for reference data other than topographic maps in Sub-Saharan Africa. South Africa has taken a positive approach to producing NLC vector datasets and efforts to frequently update them, providing the country with much needed NLC data to serve as part of a variety of analyses including Spatial Development Frameworks, Environmental Management Frameworks, Environmental Impact Assessments and Disaster Management Plans to name a few. In addition, original datasets are available thereby providing users with high quality historic data.

The spatial resolution mismatch between decadal images (80m MSS and 30m TM) were encountered due to the different resolutions of the Landsat images. In terms of the spatial resolutions, none of the images had an adequate resolution to detect informal housing in Durban.

The generalisation could have been minimised if higher resolution images were used, although conversely, the scale at which the analysis was performed does not require high resolution satellite imagery as it would have resulted in an excessive amount of spectral bands which may have influenced the classification. An example of an earlier high resolution satellite image would be CORONA imagery which was initially used as an American government spy satellite with 2.5m resolution.



Figure 60: Early Corona image of the Pentagon, Washington DC, 25 September 1967
(Source: NRO, 2008)

Although the study was based on large areas, the problem of generalisation did not pose a challenge to the project. The limited amount of spectral signatures due to the poorer resolution of the satellite imagery, made the urban areas easier to classify. Higher resolution imagery would provide more spectral signatures for similar urban land cover, which would add significant complexity to the urban area identification phase.

The use of Landsat images proved to be quite feasible during the classification process of the study. The Landsat MSS images were slightly more challenging to classify due to the lower resolution. The TM and ETM+ images provided images with finer resolutions therefore providing less pixel generalisation, making the urban areas more easily identifiable and classifiable.

7.1 Recommendations

Throughout the study challenges have been observed which should be taken into account to improve the accuracy of future classifications. The following primary recommendations have been noted:

- The scale of the study sites should be taken into account to determine the appropriate resolution of the satellite imagery required. Course resolution imagery (Landsat MSS)

would be appropriate to utilise when classifying large areas, while smaller study sites would require finer resolutions in order to minimise errors relating to generalisation. In South Africa SPOT 5 imagery has been made freely available to academic institutions to aid in academic research. The USGS has also opened its entire Landsat archive and images are freely available for the general public to download.

- Ideally, reference data, satellite imagery and census data should be available for the same years which would improve the accuracy of the results and allow for the effective integration of different datasets. Topographic maps should also ideally be regularly updated and should coincide with census years. This would be particularly useful in developing regions in monitoring urban expansion and population growth. Technological advances and data availability is allowing for more data and information becoming available to the general public, particularly in the form of freeware applications such as Google Earth. Google Earth imagery is regularly updated giving users an idea of current ground conditions. In 2010 Google Earth began incorporating historic imagery into their image database allowing users to view imagery as a time series.
- In addition to an increase in the availability of information, it would also be preferable to utilize uniform imagery throughout the time series (e.g. use ETM images throughout the study for a single study site) to minimize errors produced by generalization and using different types of imagery.
- Obtaining reference data in electronic format is recommended to avoid having to scan and digitise from hard copies, which could result in human error being introduced into the reference dataset. This is of particular concern as at present there is no emphasis on capturing historic spatial data electronically, thereby increasing the dependency on historic topographic maps. Shapefiles at 1:250000 scales are also currently unavailable and it was revealed that only the most recent data is available for distribution and special requests would have to be issued in order to obtain archived vector data.
- In this study, fieldwork was not feasible, given that 5 study sites were being analysed. In general, field work plays an important role in improving results of real time/situational analysis. It would also have been beneficial to establish contact with urban historians for each study site who would be able to provide an account of the respective historic urban landscapes. It is therefore advisable that if practical, fieldwork should be conducted, regardless of the type of classification being implemented.

- A recommendation regarding the inner city happenings would be to focus on specific areas e.g. Khayelitsha (Cape Town) which is largely influenced by in-migration on an annual basis. Although in order to focus analyses on smaller areas, higher resolution satellite imagery will be required. The methodology will thus also be feasible for large scale analyses.

Understanding relationships between social and physical processes ultimately requires an understanding of physical space. The underrepresentation of African cities (e.g. Figure 1) on a global scale leaves scope for varieties of different types of research, as the conversion of land to urban use is considered the most significant and irreversible alteration to the earth's surface (Schneider, 2007, p. 286). Developing countries thus require focussed urbanisation studies which could limit the negative impact of future urbanisation.

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9 Appendices

9.1 Appendix 1: Basic GIS concepts and data models

9.1.1 Defining GIS

The definition of GIS is seen to apply equally to land information systems (LIS), automated mapping facilities as well as any other spatially referenced information management system (Taylor and Blewitt, 2006). Burrough (1986) defines GIS as:

'A set of tools for collecting, storing, retrieving at will, transforming, and displaying, spatial data from the real world for a particular set of purposes.'

GIS offers a variety of systems which deals with geographical information. Reality is represented as geographical elements which are defined according to two types of data constituents. The geographical or locational data element provides the spatial reference for the attribute (or statistical or non-locational) data (Maguire, 1991, p. 11). Doe (1987) describes geographical information as:

'Information that can be related to specific locations on the Earth. It covers an enormous range, including the distribution of natural resources, descriptions of infrastructure, patterns of land use and the health, wealth, employment, housing and voting habits of people.'

The terms *geographical* and *spatial* are often used interchangeably, although strictly speaking, there is a definite difference between the two. *Spatial* refers to any type of information about the location and can include engineering and remote sensing, as well as cartographic data. *Geographical* only refers to the information regarding the location on or near the Earth's surface in real world scales and space (Frank, 1988, p. 12).

The relationship between GIS and other information systems such as computer-aided design (CAD), computer cartography, database management systems and remote sensing has played an important role in establishing a definition of GIS. In many cases it is argued that GIS is a subset of all these systems (Newell and Theriault, 1990, p. 42) (Figure 61).

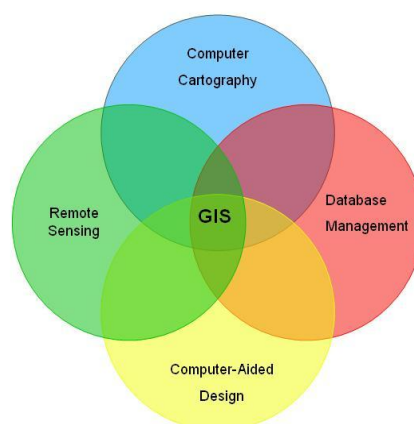


Figure 61: The relationship between GIS and other information systems

(Source: Maguire, 1991 (modified by author))

9.1.2 Raster Data Model

Raster datasets divide geographic space into an array of cells called pixels (Longley et al, 2001; Bernhardsen, 1999, p. 68; DeMers, 1997, p. 90). Each pixel is uniform in size and resolution is constant throughout the data model, which means that regions with few variations are as detailed as those with major variations and vice versa (Bernhardsen, 1999, p. 68). The pixels thus make up a two dimensional grid, or matrix (DeMers, 1997, p. 90). Every pixel also contains measured attribute values such as colour, elevation or an ID number (Chrisman, 1997, p. 6.; Wu, 2000). However, all detail regarding variation is lost as each cell is given a single value. Rasters are directly related to the frameworks that control space in order to measure attributes (Chrisman, 1997, p. 66). Raster images are normally obtained from optical scanners, digital cameras or other imaging devices. The resolution of the data is determined by the image acquisition device as well as the quality of the original data source (Wu, 2000). The pixels are specific for spatial locations and thus may be in a specific spatial reference system, but the resolution could be deliberately limited to act as a control. A noted disadvantage in utilizing raster data is that the quality of the images is dependent upon scale. If the image is scaled above its native resolution, the raster will be stretched and distorted (Wu, 2000). The main determinant of the raster's geometry is the hardware used (Chrisman, 1997, p. 66; Wu, 2000).

9.1.3 Vector Data Model

The vector model assumes that the real world can be divided into clearly defined elements. The model creates complex representations from primitive objects, namely points, lines and polygons (Chrisman, 1997, p. 62). All features in vector models are based on coordinates. For example, polygons are created by a string of line segments, which are in turn joined together at the vertices which are essentially points. At the base, points are represented by coordinates (Chrisman, 1997, p. 62; Wu, 2000). Every point on the map and every point on the terrain is uniquely located using two or three numbers in a coordinate system (Bernhardsen, 1999, p. 51). Thus surfaces can be modeled by creating a series of either regularly or irregularly placed points that act as vertices. Each point will then have a unique topographic value. Any three connected points will represent an area of uniform topography (DeMers, 1997, p. 102).

Vector data generally produces smaller file sizes than raster images. This is due to the need for raster images to accommodate all pixels, as Wu (2000) explains that each pixel makes up a portion of the spatial extent that the image covers, whereas vector data stores point coordinates. This serves as an advantage as vectors do not lose resolution when they are resized, which means that the data can easily be displayed at any scale, without physically changing the data.

When geometric images need to be accurately represented in CAD or GIS, vector data is usually the preferred model, due to it not being limited to pixels size and spatial resolution. Mathematical formulae can also easily be applied to the geometric features (Wu, 2000). Vector data also provides an easy description of topological⁴⁰ relationships. The advantages of both raster and vector data are provided in the table below:

Table 21: Relative advantages of raster and vector representations

(Source: Longley et al, 2001)

Issue	Raster	Vector
Volume of data	Depends on cell size	Depends on density of vertices
Sources of data	Remote sensing, imagery	Social & environment data
Applications	Resources, environmental	Social, economic, admin
Software	Raster GIS, image processing	Vector GIS, automated cartography
Resolution	Fixed	Variable

⁴⁰ Topologies, as defined by McKenney and Schneider (2007) as a collection of spatial objects that satisfy certain topological constraints; specifically, spatial data objects are only allowed to meet or be disjoint

9.1.4 GIS Spatial Analysis

The development of spatial analysis techniques emerged in the 1950s as quantitative and statistical geography (Openshaw, 1991, p. 389). Initially it was based on the statistical methods that were available to analyse spatial data (Berry and Marble, 1968, p. 389), but later it was extended to include mathematical model building and operational research methods (Taylor, 1977).

9.1.5 Raster to Vector Conversions

Converting raster images into vector representations is used in a variety of commercial applications including CAD and GIS. The operation allows for the representation and processing of raster data in terms of geometric and topological characters. Vector representation is frequently referred to as the skeleton of a raster shape (RL Labs, 2001).

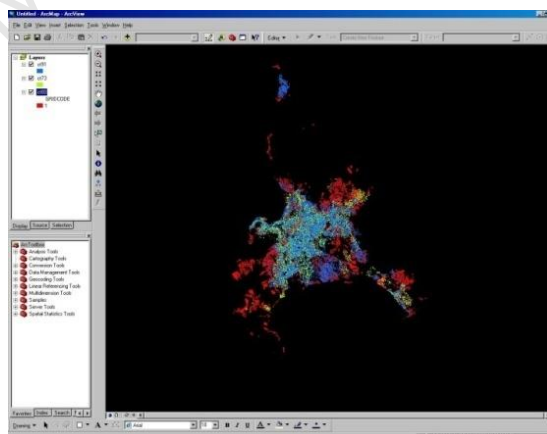
The vectorisation⁴¹ process as described below is taken from Wu (2000), unless otherwise stated.

The first stage of vectorisation involves the line tracing process that extracts the centre lines and boundary lines. The centre line tracks the centre pixel within a raster line until it reaches an intersection or the end of the segment. The boundary line method tracks the boundary of a colour region, resulting in closed polygons.

Many methods have been developed for line tracing, but ultimately they can be narrowed down to two groups: line thinning and line following. Line thinning is seen as a more general approach. It iterates through the image in multiple passes, eliminating the boundary pixels until only the skeleton pixels are left. The line following method uses computer intelligence to analyse line shapes, thickness and intersections, following the line centers. Line thinning based methods is usually used for fully automatic conversion of complex images, while the line following method is frequently used in semi-automatic interactive tracing.

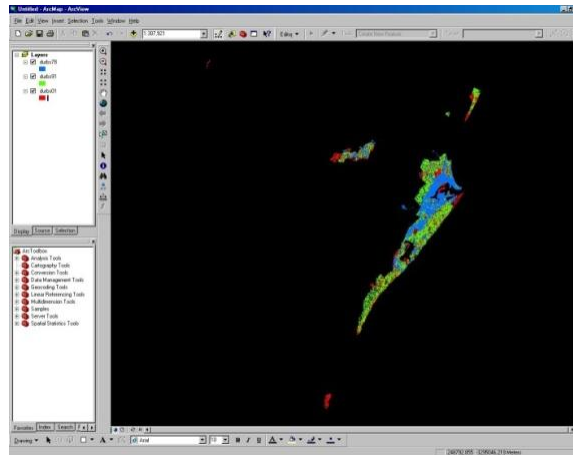
After the lines are extracted, they are labeled with line attributes or with elevation values if they are contour lines. Polygons are also generated from line segments. Control points are defined and applied to georeference the vector data to the assigned projection system.

9.2 Appendix 2: Data Analysis

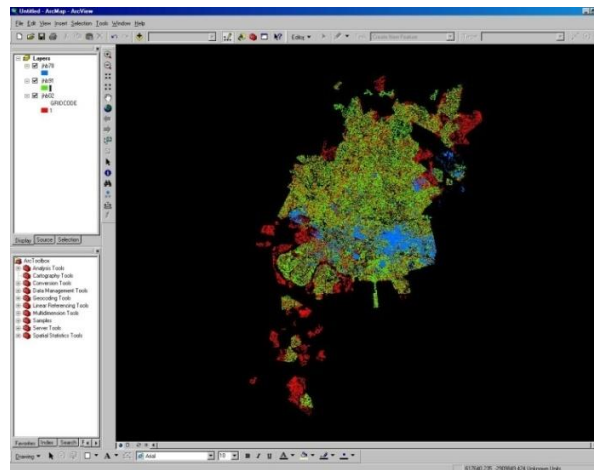


Appendix Figure 1: Cape Town's raster classification after being exported from ERDAS

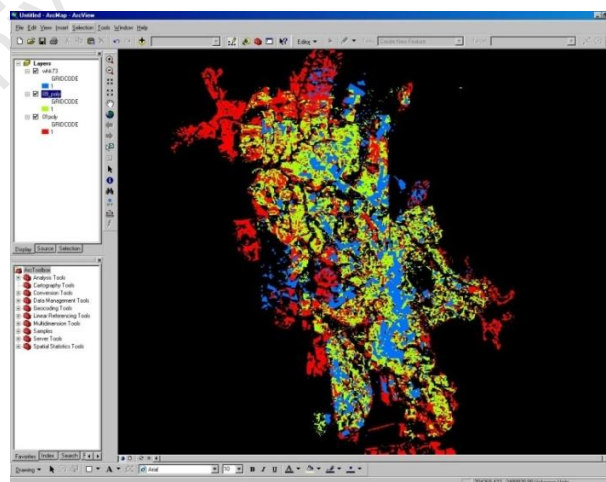
⁴¹ The process whereby raster data is converted to vector data (Wu, 2000).



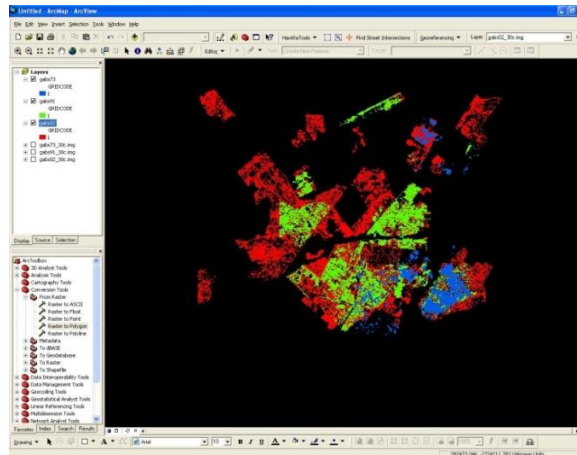
Appendix Figure 2: Durban's raster classification after being exported from ERDAS



Appendix Figure 3: Johannesburg's raster classification after being exported from ERDAS

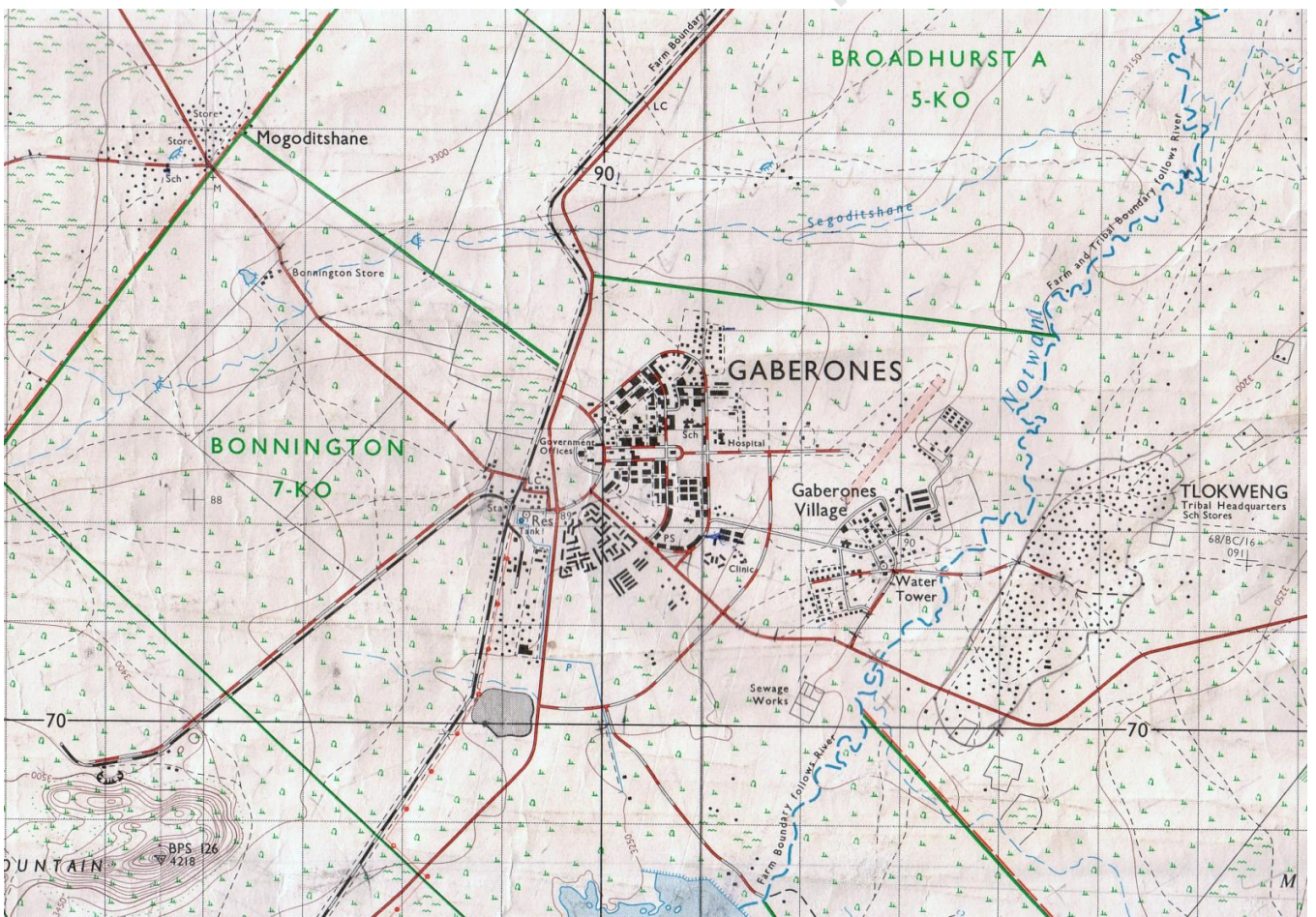


Appendix Figure 4: Windhoek's raster classification after being exported from ERDAS

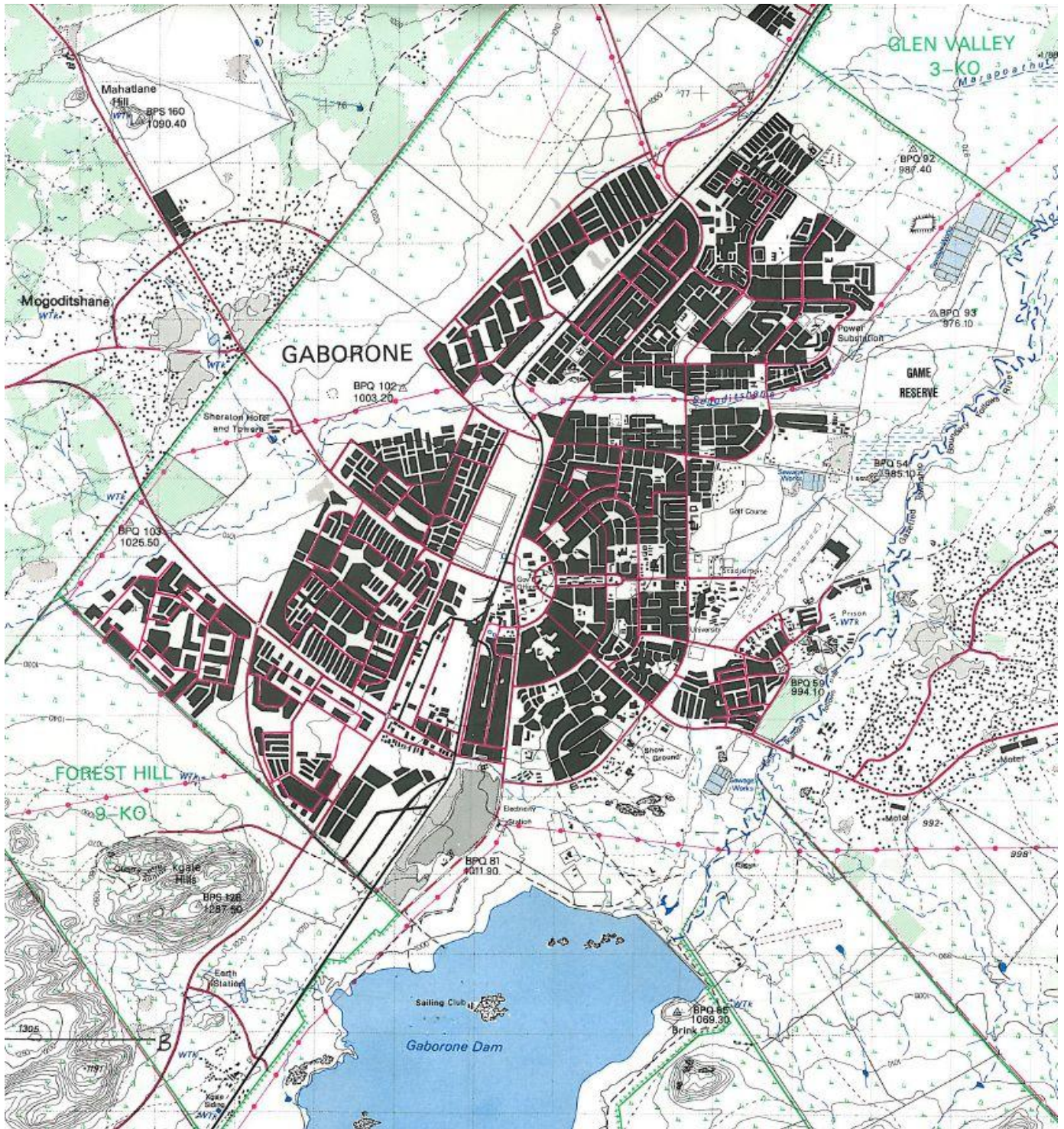


Appendix Figure 5: Gaborone's raster classification after being exported from ERDAS

9.3 Appendix 3: Topographic Maps



Appendix Figure 6: Gaborone 1968 topographic map



Appendix Figure 7: Gaborone 1991 topographic map

