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DEPARTMENT OF ENVIRONMENTAL MONITORING, PLANNING AND MANAGEMENT

MODELLING THE EFFECTS OF URBAN MORPHOLOGY ON ENVIRONMENTAL QUALITY OF NAIROBI CITY, KENYA

BY

OYUGI MAURICE ONYANGO

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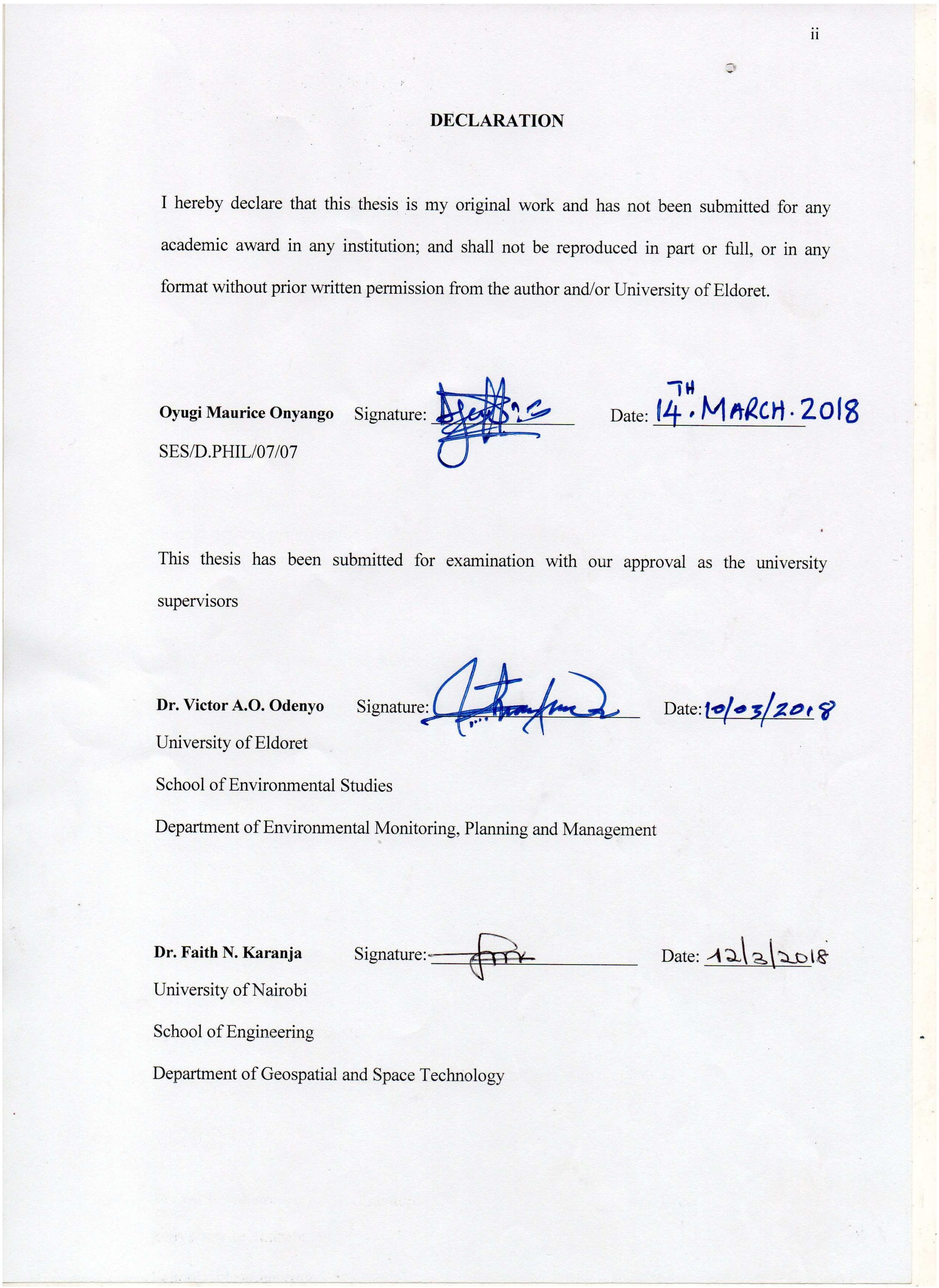

DECLARATION

I hereby declare that this thesis is my original work and has not been submitted for any academic award in any institution; and shall not be reproduced in part or full, or in any format without prior written permission from the author and/or University of Eldoret.

Oyugi Maurice Onyango Signature: ____________ Date: 14TH . MARCH . 2018
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This thesis has been submitted for examination with our approval as the university supervisors

Dr. Victor A.O. Odenyo Signature: ____________ Date: 10/03/2018
University of Eldoret
School of Environmental Studies
Department of Environmental Monitoring, Planning and Management

Dr. Faith N. Karanja Signature: ____________ Date: 12/3/2018
University of Nairobi
School of Engineering
Department of Geospatial and Space Technology

DEDICATION

This work is dedicated to my wife Beatrice .A. Oyugi and my children Edgar Oyugi, Patience Gudu and Peter .W.O. Oyugi who have been sources of encouragement and inspiration throughout the study period. *You are the wind beneath my wings!*

PROLOGUE

"Urbanization removes much of the filtering capacity of soil and rapidly channels precipitation into watercourses …... Cities affect the atmosphere by increasing airborne pollutants and also creating 'heat islands' where temperatures are greater than the surrounding areas. Various urban activities produce huge volumes of waste products that require complex disposal mechanisms" (Melosi, 2000).

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ABSTRACT

Various postulations have been put on the correlation between urban morphology and the urban environmental quality (UEQ). However, the studies have not quantitatively demonstrated the contributions of each morphological parameter in the determination of the UEQ. It is this gap in knowledge that this study sought to fill by modelling the relationship existing between the urban morphological variables of development density, land uses and vegetation density and the UEQ parameters of the surface temperatures and the air quality values of Nairobi City. The specific objectives of the study were to evaluate the impact of land use and land cover changes on the Land Consumption Rate and Land Absorption Coefficient for Nairobi City between the years 1988 to 2015, to determine the relationship existing between the urban morphology of Nairobi City and the surface temperature values using geospatial techniques, to establish the relationship existing between the urban morphology of Nairobi City and the variations in air quality, to establish a spatial and quantitative model depicting and explaining environmental quality variations in the city as well as to propose strategies for the achievement of sustainable environmental quality for the city. The study adopted both descriptive and quantitative research design. All the 30 development zones of the city as detailed out by the Nairobi City County Government constituted the target population. This study was aided by Digital Image Processing of Landsat 5 TM imageries of the years 1988 and 1995, Landsat ETM+ imageries of the years 2000, 2005, 2010 and 2015 as well as the IKONOS satellite imagery of the city for the year 2015. Together with the topographical and development zoning maps of the city, other secondary information such as the census reports for the city covering years under consideration were also utilised. Establishment of the air quality values involved *in-situ* measurements of the concentration of carbon dioxide, nitrogen dioxide, sulphur dioxide and suspended particulate matter. The Landsat imageries were further used in analysing the distribution of the surface temperatures within the city. The environmental implications of the above stated parameters were transformed into numerical values ranging from 1 to 10 of which lower values (1) were accorded to development zones whose morphological, thermal and air quality attributes have higher negative impacts on the city's environmental quality and *vice-versa.* The aggregate values for the development zones were arrived at through aggregation of the numerical values assigned to the parameters within a development zone. The above was superimposed with development zoning boundaries and converted into a spatial model depicting environmental quality variations within the city. Bivariate and multivariate statistical models of Pearson's correlation coefficients (r), coefficients of determination (R), *t*-tests and the Analysis of Variance (F-tests) with levels of significance decided at 95% were also used to determine the strengths, significances and consistencies of the relationships existing between and among the study variables. The study established that while urban built-up, open/transitional areas and forest covers within the city increased during the study period, rangelands, agricultural, grass, secondary growth and riparian vegetations declined. The study confirms that vegetation density is the most significant morphological variable influencing the distribution of the UEQ. This is followed by the development density and land uses in the order of significance. However, the significance of the error term in the model representing the relationship existing between the UEQ and the urban morphological variables implies that other factors such as topography, pedology, rainfall pattern and amount, slope, aspects and wind velocity which were not considered by the study are equally significant in determining the distribution of the same.

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LIST OF ACRONYMS

ANOVA	Analysis of Variance
CBD	Central Business District
DNs	Digital Numbers
EIA	Environmental Impact Assessment
EOSAT	Earth Observation Satellite
ERDAS	Earth Resource Data Analysis System
GIS	Geographical Information Systems
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GPS	Global Positioning System
ICT	Information and Communication Technology
ILWIS	Integrated Land and Water Information System
Landsat ETM	Landsat Enhanced Thematic Mapper
Landsat ETM+	Landsat Enhanced Thematic Mapper Plus
Landsat MSS	Landsat Multispectral Scanner
Landsat TM	Landsat Thematic Mapper
NDVI	Normalized Difference Vegetative Index
NEMA	National Environment Management Authority
NHDP	National Development Programme
NRSA	National Research Service Award
RCMRD	Regional Centre for Mapping of Resources for Development
SDGs	Sustainable Development Goals
SoK	Survey of Kenya
SPM	Suspended Particulate Matter
SPOT	Satellite Pour l'Observation de la Terre
UEQ	Urban Environmental Quality
UHI	Urban Heat Island
UNDP	The United Nations Development Programme
UNESCAP	The Economic and Social Commission for Asia and the Pacific
USGS	United States Geological Survey
VD	Vegetation Density

OPERATIONAL DEFINITION OF TERMS USED IN THE REPORT

A greenhouse gas: An atmospheric gas that absorbs and emits radiation within the thermal infrared range. They include water-vapour, carbon dioxide, methane, nitrous oxide and ozone. Greenhouse gases cause atmospheric greenhouse effects which affects the temperature of the earth. Without the Greenhouse gases, the earth's surface would be on average 33°C which is colder than at present (Schroeder, 2000).

Air Pollution: An atmospheric condition in which certain substances are present in such concentrations and duration that they produce harmful effects on man and the environment.

Development Density: Aggregate acreage of land under development within a development zone as a ratio of total acreage of land constituting the development zone.

Development: Pursuant to Section 3 (a) of the Physical Planning Act (Cap 286), development is either making material change on buildings and land or land subdivision.

Geographic Information System: A computer assisted system for the acquisition, storage, analysis and display of geographic data to aid in planning and solution of human and environmental problems (Star and Estes, 1990).

In-Situ: A Latin phrase for 'in position'. It is the act of obtaining measurements on objects, area or phenomenon using instruments which are in contact with the same.

Land Absorption Coefficient: A measure of change in the conversion of urban land to built up, open and transitional land uses and land covers within a specified time period by each unit increase in urban population.

Land Consumption Rate: A measure of progressive spatial expansion of a city as evidenced by increase in the amount of land under urban built up, open and transitional areas for the successive years of study.

Land Cover: Man-made and natural features such as human structures, soil types, vegetation types and water present on the earth surface (Meyer, 1995).

Land Use and Land Cover Change: Temporal variations in terms of nature, magnitude, pattern and trends in land uses and land covers.

Land Use: The economic utility associated with a piece of land such as agriculture, industrialisation, residential, transportation, recreational and educational purposes.

Normalized Difference Vegetation Index (NDVI): A numerical ratio ranging from -1 to 1 derived from red and near-infrared bands of the electromagnetic spectrum. NDVI is used to assess whether the land surface being observed through satellite remote sensing contain vegetation or not.

Remote Sensing: The art, science and technology of gathering information about a phenomenon, object or area using devices called sensors mounted on platforms such as the satellites, balloons and aeroplanes without physically coming into contact with the phenomenon, object or area under investigation as occasioned by differences in interactions between earth's surface materials and electromagnetic energy (Lillesand *et al.* 2004).

Scientific Model: Conceptual, spatial, mathematical and visual representation of a real-world phenomenon, objects and systems. They are often used in the construction of scientific theories to describe, explain, predict and visualize the behaviour and the relationship existing between phenomenon, objects or systems. Examples of models used in Earth Sciences and Ecology include the maps, biogeochemical and hydrological cycles as well as the general circulations. Models aid in weather forecasting, in projecting health outcomes of disease epidemics and in the development of early warning systems for epidemics and large-scale disasters. Conceptual models are used to enhance understanding of a relationship existing between variables influencing occurrence of a phenomenon, mathematical models to quantify and graphical models to visualize the subject (Ritchey, 2012; Johannes *et al.* 2006).

Scientific Modelling: An activity aimed at making a particular part, system or feature of the earth easier to understand, define, quantify, visualize or simulate. Models are developed through a scientist's combination of insight, data and observations about similar scenarios (Rainer *et al.* 1996).

Sustainable Development: The concept was popularised by the Brundtland Report through the publication of '*Our Common Future*' which defines the term as development that meets the needs of the present generation without compromising the ability of future generations to meet their needs (WCED, 1987).

Sustainable Urban Development: Urbanisation accompanied with environmental conservation. It is characterised by environmental, social and economically self sustained urban societies.

Urban Heat Island (UHI): A phenomenon of pockets of higher temperatures occurring in some urban neighbourhoods relative to the surrounding environment.

Urban morphology: A study which seeks to understand the attributes of a city such as the development densities, spatial structure (land uses), building pattern and configuration, vegetation density, streets and lots pattern as well as land tenure and occupation. It involves examination of the city's components, the process of its formation, transformation and how physical forms produces or reproduces various social forms.

Urban Sprawl: Unplanned urban expansion to the periphery which is often associated with consumption of forest and agricultural lands by low density suburban residential and commercial development (Galster *et al.* 2001; Yang and Lo, 2002; Hayden, 2004).

Urbanisation: Population increase in a built-up area over time (Grant, 2008).

CHAPTER ONE

INTRODUCTION

1.1 Background

Cities are development hubs as corroborated by the agglomeration of land uses within them. The agglomeration leads to both urban sprawl and internal densification of the cities to accommodate the increasing population and competition among the land uses for strategic sites. To accommodate this competition and to achieve sustainable urban development, there is need for clear understanding of the drivers of urban land use differentiations (Misra, 1990). The significant indicator of urban sustainability is the urban environmental quality which is a measure of the condition of an environment as presented by air and water quality and the potential effects which such conditions may have on human health and urban ecosystem.

Urban environmental quality is a spatially variable phenomenon of concern in densely populated cities of the tropics where urban infrastructure, morphology, topography and climate interact to produce uncomfortable thermal and hazardous air quality effects. The magnitude and pattern of urban environmental quality correlates to urbanization level of a city. This is because cities influence greenhouse gases (GHGs) production and sinks both directly and indirectly (Sánchez-Rodríguez *et al.* 2005). For instance, carbon dioxide which is a major component of the GHGs is a by-product of urban anthropogenic activities such as industrial and transportation activities. Clearance of land for urban expansion and infrastructure development are drivers of regional land cover changes which reduces the global carbon sinks. Cities generate approximately 90% of anthropogenic carbon emissions (Svirejeva-Hopkins *et al*. 2004).

Changes associated with urban developments have profound effects on urban surface temperatures and air quality which consequently have effect of inducing climate change. New surface materials associated with urban buildings, roads and other urban infrastructure alters the natural surface which consequently alters energy balance, water exchanges and airflow. The above combined with heat, carbon dioxide and other GHGs emitted by anthropogenic activities result in distinct urban climates (Landsberg, 1981; Oke, 1997). One of the best-known effects of such development is urban warming of which globally cities are warmer than the surrounding rural areas but with internal urban spatio-temporal variations (Oke, 1973). On average, urban temperatures may be 1^0C to 3°C warmer than rural environs, but in calm and cloudless nights, air temperatures can be more than 10°C warmer than surrounding rural environments (Oke, 1981; Grimmond *et al.* 1993).

At the urban scale, the spatio-temporal variations in urban temperatures is accentuated by the neighbourhoods' attributes such as the amount of vegetation on site, density of development and the nature of the construction materials used in the neighbourhood. This manifests in form of pockets of sites within the urban landscape with higher temperatures than the rest of the urban spaces, a phenomenon called the urban heat island. The urban heat island effects are exacerbated by the anthropogenic activities such as vehicular traffic, industrial production and domestic buildings which produce heat, sulphur dioxide, nitrous oxide, suspended particulate matter and carbon dioxide, gases known to contribute to global warming and climate change (Voogt and Oke, 2003; Owen *et al.* 1998). These gases interact with the city's compact mass to affect energy exchange and levels of thermal conductivity. However, factors such as topography in relation to the sun's angle and aspect are as influential as the surface type in controlling the amount of radiation received and absorbed. Thus a low-vegetated area incidence to direct solar radiation is much warmer as compared to vegetated areas (Fung *et al.* 2003).

Land uses and the distribution of development densities within an urban area define its form. This influences the transportation mode used in the city as well as the city's energy consumption and greenhouse gas (GHG) emissions. Urban morphology, particularly development densities, building configuration and land uses has implications on a city’s GHG emissions. This is because proximity of homes and concentration of services coupled with provision of efficient public transportation accentuated by compact (high density) urban development encourages walking, cycling and the use of mass transport instead of private motor vehicles. This consequently leads to decline in fossil fuel consumption per capita (Gottdiener and Budd, 2005; Newman and Kenworthy, 1989). However, this is complicated by the fact that urban centres are industrial hubs and GHG emissions coming from industries outstrip those from the transportation sector. Overall, empirical evidence shows that cities are responsible for 75% of global energy consumption and 80% of GHG emissions (Satterthwaite, 2008). Compact developments induce usage of less energy for heating. For example, households in the United States of America living in single-family detached housing consume 35% more energy for heating and 21% more energy for cooling as compared to households living in other forms of housing due to urban heat island effect (Quattrochi *et al.* 2000). This corroborates that urban density which is an aspect of urban morphology affects household energy consumption.

The urban spatial structure (spatial organisation of land uses) equally influences the GHG emissions. This is demonstrated by energy usage differentials in four urban spatial structures notably mono-centric, poly-centric, composite (multiple-nuclei) and urban village models. In the mono-centric cities, most economic activities and amenities are concentrated in the Central Business District (CBD). In this situation, the authorities focus on promoting public transport as the most convenient mode of transport, for most commuters travel from the suburbs to the CBD while in the poly-centric cities, few jobs and amenities are located in the centre and most trips are from suburb to suburb. In this regard, a large number of possible travel routes exists, but with few passengers per route. Therefore public transportation is difficult and expensive to operate and private means of transportation becomes convenient option for users.

The composite (multiple-nuclei) model is the most common type of urban spatial structure. This model manifests a dominant centre with a large number of jobs located in the suburb’s minor centres. Under the composite model, most trips from the suburbs to the CBD are made using public transport, while trips from suburb to suburb are made using private means of transportation. This necessitates the need for both public and private modes of transportation. The urban village model is utopian and is a creation of the urban master plans. In this model, urban areas contain many business centres, commuters travel only to the centre which is the closest to their residence and have more opportunities to walk or cycle to work. This model is ideal for it requires less transportation due to the reduced distances travelled to work. This lowers the energy usage and the GHGs emission. The more the urban spatial structure encourages public transportation, the more it leads to less emission of GHGs and other air pollutants and *vice versa*.

The above annunciations corroborate the correlation existing between urban morphology, GHGs emission, air quality, urban surface temperatures and the urban environmental quality. However, the relationship is moderated by the amount of vegetation within the urban landscape as they act as carbon sinks. According to Klaus *et al.* (1999), stale and polluted air accumulates in the highly built up areas due to convergence of air into the areas during the day for they are warm and acts as urban heat islands. These areas thus experiences warm rising air during the day but this may be replaced at night by cool fresh air from adjacent cold neighbourhoods. It is therefore evident that the urban environmental quality which is embodied by urban air quality and surface temperature values is determined by both anthropogenic and urban physical process.

The assessment of urban environmental quality is crucial in developing strategies for achieving sustainable urban development. In order to objectively evaluate the urban environmental quality at a particular site and to make comparison with another site within the same urban landscape, there is need for up-to-date and accurate data derived from precise measurements. Towards this end, the geo-spatial techniques, notably the application of remote sensing data as well as its integration with Geographical Information Systems, provides decision-makers and urban development policy implementing agencies with timely spatial information for urban environmental quality monitoring, management and planning purposes. This is because the technology has capabilities of mapping the urban growth and environmental change faster as opposed to the conventional surveying techniques. For example, the repetitive and synoptic coverage nature of the satellite remote sensing is significant in the urban environmental studies focusing on land use and land cover change detection and urban environmental impact assessment. However, remote sensing technology can be put to best use if it is combined with Geographical Information Systems which facilitate automation of information extraction, map compilation and revision as well as change detection due to its ability to superimpose various layers of geo-referenced data (Longley *et al.*1999). It is imperative that multi-criteria approaches be used in the study of spatial variations of urban surface temperature and air quality values and their correlation to urban morphology. Towards this end, this study aimed at establishing the correlation between urban morphology, surface temperature values and air quality variations within Nairobi City, noting that urban morphology is a significant determinant of urban environmental quality while surface temperature and air quality are imperative indicators of urban environmental quality.

1.2 Problem Statement

Various scholars have postulated the relationship existing between the urban morphological variables and the urban environmental quality. However, the studies have not quantitatively demonstrated the contributions of each morphological parameter in the determination of the urban environmental quality. It is this gap in knowledge that this study sought to fill by quantitatively modelling the relationship existing between the urban morphological variables of development density, land uses, vegetation density and the environmental quality parameters of the surface temperature and the air quality values of Nairobi City. This is significant in explaining the effects of urbanisation, expanding industrialization and problems associated with high-density urban developments on global warming and climate change. Since the existing body of knowledge on the correlation between urban morphology and the environmental quality are descriptive rather than quantitative, it is imperative that theories and models explaining the same be quantitative for it is the quantitative models (aided by geospatial techniques) which are most appropriate in the advancement of the knowledge. Quantitative models for analysing urban environmental quality are instrumental in the formulation of sustainable urban environmental policies, taking into account that the current urban management paradigms operational in the city are inadequate in mitigating the ravages of global warming and climate change.

Implementation of sustainable urban development policies is still a challenge to the African cities such as Nairobi yet urbanization rate in Africa is approximated at 3.5% per annum (United Nations, 2014). If environmental deterioration being experienced in most African cities is not addressed through adoption of proactive environmental quality management strategies, then the cities will continue facing plethora of environmental problems. This complicates the solution of the wider environmental quality issues constituting the urban brown agenda (collective term for environmental problems such as inadequate water supply, poor sanitation and drainage, solid waste management, air pollution, global warming and climate change) which is a threat to human health and urban productivity.

Cities being engines of national development due to myriad capital and human resource investments they attract, their environmental quality needs to be managed. Experience in the industrialized countries proves that an effective approach to addressing urban environmental quality issues is the formulation of city specific environmental management strategies and action plans. However, the capacity to plan and implement the same is hampered by insufficient data. According to Ford Foundation (1993), review of urban research in the developing countries revealed that even though research proposals in the 1990s prioritised urban environmental topics, there is scanty evidence of the researches having been completed and disseminated. While in Africa, environmental data for urban areas are inadequate, so are the analytical frameworks for understanding the magnitude and the trends of the problems and how they relate to global warming and climate change. For example, most urban authorities are not aware of the magnitude of the ongoing environmental damage caused by the increased development densities in the cities. This has arisen due to inadequate spatial information which can be bridged through enactment of geospatial information systems in the urban environmental monitoring and management. This approach enables modelling of the relationship existing between urban morphological parameters and the environmental quality conditions. However, some of the remote sensing techniques depending on the type of platform and sensor used have short-comings in terms of spatial and spectral resolutions required for the analysis of urban morphological parameters necessary for urban environmental quality studies.

This study utilised multi-spectral remote sensing technique namely Landsat 5 TM, Landsat ETM + and IKONOS satellite sensors. The Landsat 5 TM and Landsat ETM + satellite imageries were utilised in this study due to their broad spectral bands which comprise of visible and thermal bands which are useful in mapping urban growth and surface temperature variations. The IKONOS imagery was crucial in mapping the urban morphological variations due to its higher spatial resolution. In this study, urban morphological parameters of development density, land uses and biomass index were correlated to environmental quality parameters of surface temperature and air quality values. This was intended to establish the relationship existing between urban morphology, surface temperature and air quality values. This gives credence to urbanisation as an integral factor in global warming and climate change. Therefore, this study provides a spatial and quantitative model depicting and explaining the correlation between the urban morphological and environmental quality parameters of surface temperature and air quality values. The focus here was on the likely effects on the environmental quality of the city with adjustments to development densities, land uses and biomass indexes as occasioned by urbanisation.

1.3 Objectives of the Study

1.3.1 General Objective of the Study

The aim of this study was to establish the strength of the relationship existing between the urban morphological parameters of development density, land uses and biomass index and the environmental quality parameters of air quality and the surface temperature values of Nairobi City as derived from geospatial and *in-situ* measurements. The study culminates into spatial and quantitative models depicting and explaining environmental quality variations in the city.

1.3.2 Specific Objectives of the Study

This study sought to fulfil the following stated objectives: -

i. To evaluate the impact of land use and land cover changes on the Land Consumption Rate and Land Absorption Coefficient for Nairobi City between the years 1988 to 2015

ii. To determine the relationship existing between the urban morphology of Nairobi City and the surface temperature values using geospatial techniques,

iii. To establish the relationship existing between the urban morphology of Nairobi City and the variations in air quality,

iv. To establish a spatial and quantitative model depicting and explaining environmental quality variations in the city

v. To propose strategies for the achievement of sustainable environmental quality for the city.

1.4 Hypothesis of the Study

This study was guided by the hypothesis that there is a significant relationship existing between urban morphology and the urban environmental quality.

1.5 Research Assumptions

The following assumptions were made to guide the study: -

i. As the national urbanisation rate rises, Nairobi City bears the burden of absorbing the urban population in higher proportion relative to other towns in the country.

ii. The absorption of the increased population in Nairobi is undertaken through increment of the development densities.

iii. The evolution of land uses in the city has been guided by the principles of rational thinking, which postulates that the developer's decisions are driven by profit maximization. This necessitates perfect knowledge of development opportunities and market frontiers for their products. Therefore, the city shall continue experiencing environmental deterioration if the current development trend is not controlled to take cognisance of environmental quality.

iv. The wind velocity (speed and direction) in the city is uniform throughout the year. Therefore, the distribution and the concentrations of the air pollutants within the city are only influenced by the amounts of the pollutants emitted by the point and mobile sources.

1.6 Significance (Rationale) of the Study

The effect of urbanisation on global warming and climate change has raised challenges to urbanization theory and efforts have been made to postulate models explaining the correlation between the two. Majority of the models offering an explanation on the same are descriptive rather than quantitative. However, it is quantitative models facilitated by the geospatial techniques as demonstrated by this study which have a niche in aiding the validation of the correlation. The use of geospatial techniques in quantifying and analysing the spatial variation of a city's environmental quality as influenced by morphology further aids in the formulation of environmental policies. Since the current urban management paradigms operational in the city are inadequate in promoting sustainability, the environmental quality of Nairobi City has continued to deteriorate as a result of increasing urbanization, expanding industrialization and problems associated with high-density and unplanned urban developments. This sets scenario for global warming and climate change. Indeed, analysis of the city's morphology is essential in understanding the contribution of urbanization to urban environmental quality, global warming and climate change.

Nairobi City has witnessed high urbanisation rate as the city's population has grown from 270,000 to 3,138,369 between the years 1963 and 2009, respectively. This represents approximately 4.5% annual growth rate (Government of Kenya, 2012). Since urbanization has been recognised as a major factor in global warming and climate modification, cities with high urbanisation rates such as Nairobi are associated with the same. Urbanisation exacerbates climatic modifications by replacing natural surfaces with man-made materials such as buildings and asphalt road surfaces. These surfaces have high thermal properties due to their ability to store more solar energy and convert the same to sensible heat. The removal of the vegetation cover due to urbanisation reduces evapo-transpiration and shading effects to the ecosystem (Pickett *et al.* 2001). Further, urban topographical features such as the surface roughness, building configuration as well as anthropogenic activities contribute to higher urban surface temperature values by generating and reducing outgoing long wave radiation. This consequently hinders sensible heat loss and distribution of the same (Bonan, 2002; Ifatimehin, 2007). The above stated interactions alter the surface energy balance with a consequent increase in urban surface temperature values. The heat dynamics leads to accumulation of air pollutants and alteration of the precipitation pattern in the urban metropolis as well as the frequencies of urban flood disasters and changes in urban biodiversity (Zhao and Wang, 2002; Nowak *et al.* 2002).

The urban environmental problems of the African cities necessitate an enactment of urban environmental management strategies supported by multi-criteria environmental quality monitoring approaches. This encompasses an understanding of the causative factors to the environmental deterioration and manifestations of the same. In this study, the relationship existing between the urban morphology and environmental quality was established by correlating morphological parameters (biomass index, land uses and development density) with the environmental quality variables (surface temperatures and air quality). Whereas some satellite-based studies have demonstrated strong relationships existing between urban morphology and environmental quality, these studies have been at a generalized level and are only bivariate. To overcome the problems of generalisation, this study utilised both satellite imageries and *in-situ* measurements for surface temperatures and air quality, respectively as indicators of environmental quality. Studies on urban environmental quality and microclimates of the African cities are often conducted using *in-situ* measurements with mean monthly climatological data of 2 to 3 hourly intervals as opposed to multi-spectral and multivariate approach adopted by this study. The *in- situ* measurement approach has limitation in the spatial coverage of the environmental quality attributes requiring instantaneous data capture (Balogun *et al.* 2009).

As occasioned by constraints posed by imprecise information arising from *in-situ* measurements in urban analysis, the multi-spectral remote sensing technique and the Geographical Information Systems adopted by this study provides framework for assessing the relationship existing between urban morphology and urban environmental quality in an affective and efficient manner for it enables the integration of spatial data. Studies based on *in- situ* measurements use relatively expensive instruments in comparison to the satellite imageries having higher spatial and frequent temporal coverages of a scene. The above advantages combined with the higher spectral resolutions provided by the imageries enables the same to provide an efficient and effective approach to the analysis of the urban environmental quality attributes and the morphological variations within the city. This facilitates forecasting of changes in environmental quality with variations in morphology which is significant in building an understanding of the implications of the variations on global warming and climate change.

The urban environmental quality challenges facing developing countries such as Kenya stems from poor land use policies which promote incompatible land uses. This requires an enactment of an integrated urban land use policy responsive to the principles of balanced land use and environmental quality (Burra, 2005; Munda and Zeleza, 2007; Barnsley and Barr, 1996). Nairobi's spatial structure has been planned and executed with little appreciation to the implications of the morphology on the environmental quality. This partially occurred due to inadequate quantitative information to facilitate postulation of the environmental consequences of such decisions (Karuga, 1993). Although the evaluation of the consequences of such developments can be done using methods such as environmental impact assessment and post project analysis, by the time the impacts of such developments are appreciated, it would be late to make significant alterations. The advancements in the geospatial technology have made it possible for the acquisition of the past and current urban morphological information in a consistent manner. This enables the integration of multi-source and multi-date data for the generation and prediction of the trend, nature, pattern, magnitude and the impact of urban morphology on the environmental quality.

1.7 The Scope of the Study

This study covered the entire Nairobi City County bounded by longitude coordinates 36^0 40' and 37^0 10'E and latitudes coordinates 1^0 09' and 1^0 28'S covering an area of approximately 716 km^2. The variables scope for this study focussed on urban morphology and the environmental quality attributes. While the urban morphological parameters that were taken into consideration by this study are development density, land uses and vegetation density (biomass index), the environmental quality parameters considered by the study are surface temperature and air quality (concentrations of carbon dioxide, sulphur dioxide, nitrogen dioxide and the suspended particulate matter) values.

Biomass Index was considered in this study as a morphological parameter because vegetation influences urban environmental quality through evapo-transpiration, shading effects, filtration and recycling of air pollutants which ultimately influence the surface temperature and air pollutants distribution within the city (Wagrowski and Hites, 1997; Dwyer *et al.* 1992; Oke, 1982). Since paved and open surfaces constituting the largest percentage of urban surface have minimal evapo-transpiration and shading effects, they have maximum heat energy. Even individual street trees and small grassy parks have a cooling effect on the surroundings, thus this study considered biomass index as a significant morphological element. Despite building configuration not being one of the morphological attributes considered by this study, the significant role it plays in determining urban micro-climate through attenuation of wind flow and thermal energy which have effects on air pollutants' dispersal and surface temperature distribution is acknowledged.

As earlier stated, this study considered the concentrations of carbon dioxide, sulphur dioxide, nitrogen dioxide and the suspended particulate matter (SPM) as elements of urban air quality. The study did not take into account water vapour, methane and ozone gases (drivers of global warming and climate change emanating from urbanisation) which are integral aspects of GHGs and air quality. This is because the concentration of water vapour in the city is presumed to be uniform and determined by precipitation levels and not the anthropogenic activities. The ozone and methane gases are stratospheric layer gases thus could not be considered in this study which relied on instruments whose validity and reliability are only guaranteed in the troposphere. Sulphur dioxide is considered in this study for it is a significant by-product of transportation and industrial fossil fuel combustion. As urbanisation rises in Nairobi, the need for fossil fuel for transportation and industrialisation will increase resulting in increased sulphur dioxide concentration levels in the city. Apart from sulphur dioxide having noxious venom effect on human, animals and plants' health, the ability of the gas to form acid rain makes it destructive to vegetation, soil, construction materials and water bodies which are integral aspects of urban environmental quality.

1.8 Limitations of the Study

This study utilised satellite remote sensing data which is mainly two-dimensional in which only horizontal surface temperatures can be measured. This is considerably smaller than the complete surface noting that all urban surfaces contribute to the thermal levels of a city either by providing shading effects, thermal absorption or reflectance (Voogt and Oke, 1998; Nichol, 1998; Weng, 2001; Voogt and Oke, 2003). For example, Nichol and Wong (2007) argue that in high-rise areas of Hong Kong, where building density is 45% with average building height of 50m, the active radiating surface is 2.67 times the planimetric surfaces captured by the satellite. This constitutes an error of +1.5ºC for the satellite surface. The urban vertical facets are cooler when they face away from the sun's azimuth. However for the tropical cities such as Nairobi which are situated closer to the equator where the sun's angle is low throughout the year, the difference is marginal.

Traditionally, thermal satellite sensors are of low spatial resolution, such as 30m for Landsat ETM+ (the thermal band used to be 60m but products processed after 25th February 2010 are re-sampled to 30m resolution), 90m for ASTER and 1km for the AVHRR. In this study, Landsat 5 TM and ETM+ thermal bands were corrected for thermal emissivity differences in the conversion of the data to surface temperature values. In deriving urban surface temperature values from thermal images, emissivity difference is the main source of error. Therefore, the correction using Planck’s constant is necessary.

Another limitation to the study was lack of the air quality measuring stations in the city whose data could be utilised for the establishment of the relationship existing between the morphological attributes and the air quality. This necessitated the use of *in-situ* approach for data capture which is time consuming and expensive in terms of human resource involved, laboratory analysis and the cost of hiring the air samplers, yet studies of this nature require more point data to support meaningful interpolation of the air quality parameters in the city.

Building configuration has influence on urban environmental quality. For example, higher building densities coupled with skyscrapers leads to loss of urban natural vegetation alongside attenuation of wind velocity. Urban skyscrapers provide multiple sources for the reflection and absorption of electromagnetic energy which increases the efficiency with which urban areas are heated. The skyscrapers trap the reflected terrestrial energy within the urban environment consequently increasing the urban air temperature. Skyscrapers attenuate wind velocity and consequently restrict air pollutants to urban canyons thus impeding pollution dispersal. The building configuration negatively affects urban environmental quality by increasing population congestion and reducing citizens’ access to fresh air and sunlight. This corroborates the relationship existing between urban morphology, loss of natural vegetation, increased surface temperature values and low air quality which are all indicators of declining urban environmental quality. Despite the significant role the building configuration plays in the determination of the urban environmental quality, it was not included in this study. This is because the analysis of the building configuration requires up-to-date aerial photographs as opposed to satellite remote sensing which this study utilised. The constraint was on the acquisition of up-to-date aerial photographs of the city as the existing photographs are out-dated and provides incomplete spatial coverage of the city.

1.9 The Study Area

The successful achievement of sustainable urban environmental quality is dependent on balancing the socio-economic, political, legal and physiographical factors supporting the city. As such, a profile of factors which should be taken into consideration when formulating strategies for the achievement of the same is undertaken in this section. Nairobi which is the capital city of Kenya has continued to exhibit primacy in Eastern and Central Africa for it is a commercial, industrial, financial and communication hub in the region. As illustrated by Figure 1.1, the city’s location is bounded by the longitudes 36^0 40’ and 37^0 10’E and latitudes $1^0$09’ and 1^0 28’S covering an area of approximately 716 km^2. The city is one of the 47 autonomous county governments forming the devolved governance units of the Republic of Kenya. The primacy attributes of the city has continued to influence land use and land cover dynamics within the city. Currently, the city has large outlay of high density industrial, commercial and residential developments. This has reduced the vegetation cover which would otherwise act as carbon sinks and moderators of surface temperatures. Therefore, the city has continued to experience reduced environmental quality.

1.9.1 Historical Background of the City

Nairobi city owes its origin to the construction of Kenya-Uganda Railway, for which it acted as a construction depot and administrative camp. The railway line was meant to connect Uganda with the Kenyan coast as a commitment of the British Government to the colonization of East Africa. The site on which the city has grown from was chosen for its suitability as a railway depot as it is roughly located halfway between Mombasa and Port Florence (*now Kisumu*) which was part of Uganda. The railway company moved its headquarters from Mombasa to Nairobi in 1899 and was joined in the same year by the Government Administration of Ukamba province, which until then had its headquarter in Machakos. The depot was sited on the flat black cotton soil, which covered the southern and eastern parts of the city while the European housing and coffee estates occupied the fertile red volcanic soils to the northern and western ridges. Separate housing for the Indian railway workers *(coolies),* the washer men *(dhobie)* and the Indian businesses (*Bazaar)* emerged at the same time. There were relatively few Africans working on the construction of the railway and there is no mention of their accommodation in the town at that time (Obudho, 1988).

The city was first gazetted as a township in April 1900 covering an area of 18km^2 which grew to 1,813 hectares by the year 1906 (Obudho, 1988). As a result of rapid urbanisation, the year 1927 witnessed an extension of the township's boundary to cover an area of 2,537 hectares. The population of the city reached 118, 976 by the year 1948 within an area of 78 km^2 and by the year 1963, the city's population had reached 270,000 within an area of 684 km^2. The city's boundary was further extended to cover an area of 696km^2 and 716 km^2 in the years 1979 and 1999, respectively. Since then, there has not been any boundary change. Today, the city's population is estimated at 3.6 million with an average population density of

5980/km^2. The densities widely vary as high-income zones' average densities are approximately 350/km^2 while low-income areas' average densities are 63,000/km^2. This has implications on the environmental quality of the city.

Plague broke out twice in the bazaar area prompting setting up of a commission comprising of Engineers and Medical Experts in the year 1906 to investigate the sanitary conditions of the town. The investigations revealed that the site where the town was located was unsuitable for development as a capital city and the possibility of the town's removal was debated for 5 years until it was agreed that the proposal was not backed by political reality. In the year 1912, another plague occurred which occasioned the formation of another commission which recommended separation of European, Asian and African quarters. This became the harbinger of racial segregation, development density and the urban spatial structure differentials whose footprints persist to date. In the year 1927, a Commission led by Justice Feedham proposed boundary change by amalgamating the municipality with its environs to form the Nairobi Extra Provincial District which was subsequently declared a colonial capital city in the year 1928. This led to the preparation of a master plan by a team of South African Planners in the year 1948. The plan neither altered the municipal boundary nor did away with the established residential segregations and the development densities. It further placed accommodations for the African's in closer proximity to the industrial zone because the Africans were expected to provide unskilled labour force for the industrial plants.

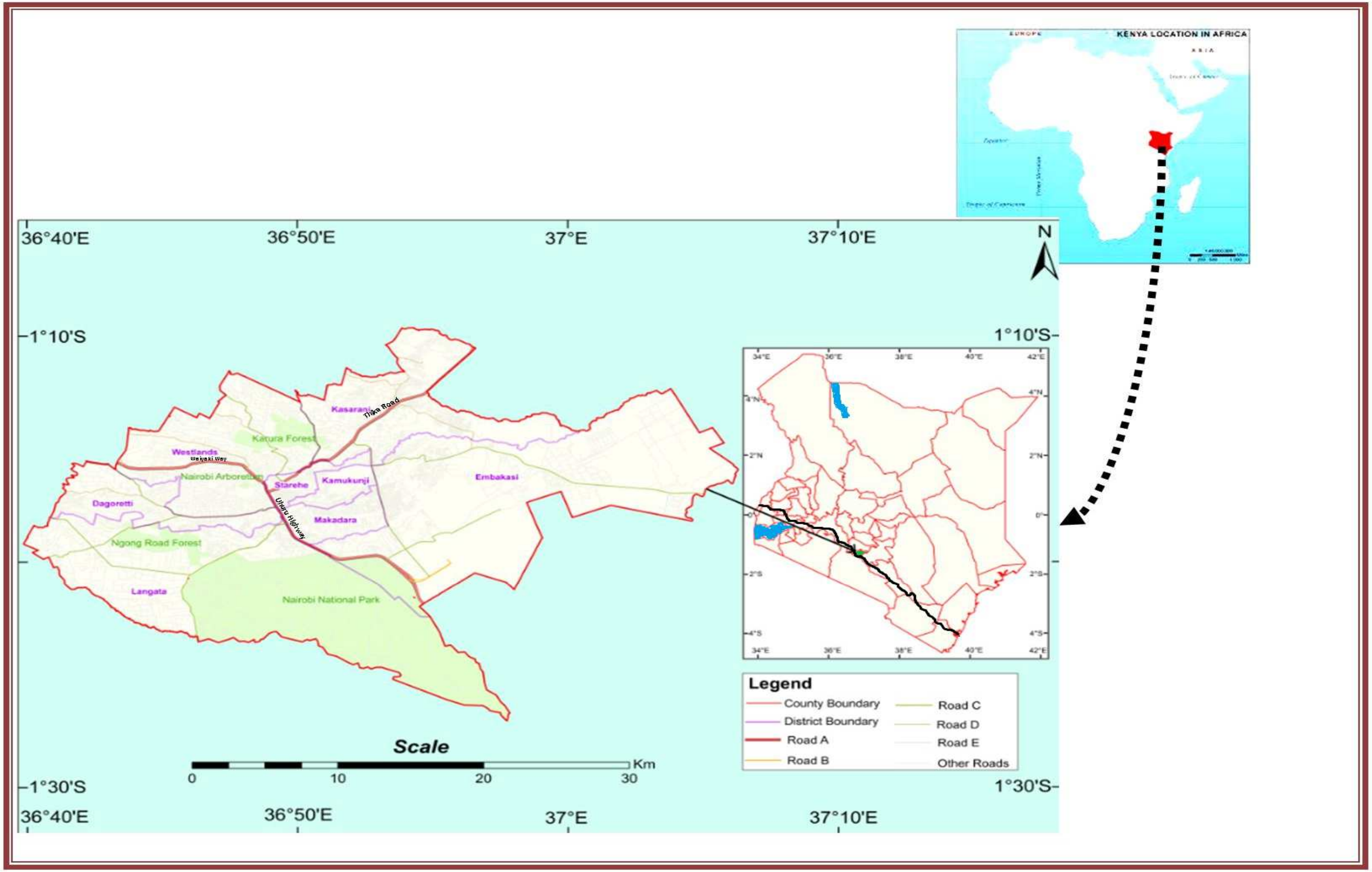

Figure 1.1. Location of the Study Area.

The 1948 master plan proposed the development of extensive road networks and roundabouts, public open spaces, neighbourhood units, civil centres and the replacement of the railway line with the current dual carriage Uhuru highway. At the time of the plan, the city’s population was 118, 976 and was projected to stabilise at 250,000 (the desirable population for the city) by the year 1975. The city developed along the lines postulated by the master plan up to the year 1963. However, the employment opportunities and freedom of movements occasioned by independence in 1963 raised the population above the target. This has continued to alter the morphology of the city as much land is continually being sought to accommodate the ever increasing population and employment centres.

By the year 1967, the Nairobi’s urbanisation rate was at climax causing shortages in water supply, shelter and traffic congestion. This has persisted to date subsequently lowering the environmental quality of the city. This necessitated commissioning of the Nairobi urban study group to comprehensively study the economic, social and physical aspects of the city as a basis for the preparation of a new development plan. The group produced a document called the *Nairobi Metropolitan Development Strategy 1973-2000* which proposed the directions across which the city was to expand. The document further provided guidelines for future city boundary extensions to the year 2000. It further considered the physical layout of the city through various stages of development and proposed infrastructural adjustments needed for the accomplishment of the vision. Other recommendations contained in the document included creation in a decentralised manner an additional seven secondary industrial zones next to residential neighbourhoods to the eastern and north-eastern parts of the city. This was meant to enhance employment opportunities as well as reduce transportation cost on journey to work.

To limit employments within the CBD to 100,000 people, the plan recommended the creation of other seven satellite commercial centres next to the industrial zones. To support the proposed commercial centres, new comprehensive housing schemes were also proposed. The plan further proposed the creation of three bypasses, the desired socio-economic aspects of the city and policy measures for the plan's implementation. To preserve the rich agricultural land, development control measures were proposed prohibiting urban developments to the northern and western parts of the city. To avoid the Nairobi National Park, Jomo Kenyatta International Airport and its flight corridor, the plan recommended urban growth across the Athi plains towards Thika town. Owing to poor articulation of the statutory rules and regulations governing the plan's implementation as well as over reliance on foreign and government funding for the plan's implementation, the plan achieved little when the promised financial and technical supports were not forthcoming. However, it provided a foundation upon which the alteration of the urban morphology was anchored.

The shortcomings of the *Nairobi Metropolitan Development Strategy 1973-2000* prompted the *Rezoning Policy* of 1979 which went against fundamental recommendations of the initial strategies by increasing plot ratios, coverage and development densities within the city. This was done without attempts at improving the infrastructure and utilities such as water supply, parking and recreational facilities. Since then, planning has been done on an *ad hoc* basis, dealing with single issues not linked to a structure plan. Over the years, the re-densification has lowered the city's environmental quality through increased population, traffic snarl and the clearance of vegetation cover. Consequently, the city has continued to experience increased surface temperature and air pollution values.

Despite the efforts, weak institutional framework and inadequate stakeholders' involvement in the plan preparation and implementation, failure to link the plans to the city's financial resource base and development trends, inadequate political goodwill and unfavourable socio-economic conditions have led to poor development of the city. Today, Nairobi is characterised by high unemployment rate estimated at 40% as well as increased poverty levels represented by 55% of the population living below the poverty line (Government of Kenya, 2012). The city's development is further constrained by inequitable access to serviced land which is partially attributed to the existing land administration instruments operational in the city. Statistics indicate that approximately 80% of Nairobi's inhabitants have no access to land at a time when approximately 60% of Nairobi's population are accommodated in less than 5% of the urban land (Matrix Development Consultants, 1993; Lee-Smith and Lamba, 1998). This has resulted in proliferation of slum and squatter settlements, high density developments, low productivity and environmental degradation.

1.9.2 Population Dynamics

Nairobi's early growth was exuberated by rural-urban migration which peaked between the years 1979 and 1989 when approximately 772,624 people migrated into the city (NEMA, 2003). Since then, Nairobi has continued to experience high population growth rates and the city is currently home to nearly 3.6 million people, representing approximately 25% of Kenya's urban population. As illustrated by Table 1.1, the average inter-censual population growth rate of the city being 4.5%, the city's population is projected at 4,852,736 by the year 2020. Currently, a significant number of commuters from satellite towns such as Thika, Naivasha, Ngong and Machakos travel to Nairobi daily which contributes an additional

500,000 people to the city's daytime population. This underscores an increased demand for services and employment facilities at a time when the urban infrastructure is already constrained. This has necessitated an increase in development densities to accommodate the population, consequently leading to environmental degradation, reduced vegetation cover, increased urban surface temperatures and air pollution.

Table 1.1. Population Census and Projections for the City between the Years 1969 to 2049

Year	Demographic Attributes		
	Total Population	**Population Density**	**Area (Km^2)**
1969	509,286	893	684
1979	827775	1452	696
1989	1324570	2323	696
1999	2143254	2993	716
2009	3138369	4383	716
2019*	4690415	6550	716
2029*	7010008	9790	716
2039*	10476732	14632	716
2049*	15657887	21868	716

***Projected Figures – The densities exclude 114km^2 constituting the Nairobi National Park.**
Source: (Government of Kenya 1969, 1979, 1989, 1999, 2009(a) and 2012)

1.9.3 Physiographical Background of the City

Physiographical base of a city provides anchorage to its developments which in turn influences the morphology and the environmental quality of the same.

1.9.3.1 Topography

Nairobi lies at the edge of the Rift Valley with elevations ranging between 1,500m and 2,300m above the sea level. The city's topography and geology have been influenced by tectonic forces associated with the formation of the Rift Valley. The lava flows from the fault lines of the Rift Valley gave rise to Kikuyu escarpments, Ngong Hills, Athi and Kapiti plains which are the major physiographic units of the city (Morgan, 1967). The Lari-Ondiri fault west of Kikuyu town is a significant source of groundwater flowing towards Nairobi and was at one time the only source of water supply for the city. The Ngong Hill ranges to the western part of the city are dissected by scarps representing the end of individual lava flow. Nairobi's topography is also characterised by deep valleys dissected by constellation of rivers and streams flowing from the foothills of Aberdare Mountains. Athi and Kapiti plains which are lava plains overlying the city are relatively flat right through the Nairobi National Park, City Centre, Jomo Kenyatta International Airport and Dandora areas. This has encouraged real estate developments and urban sprawl as the nature of the topography (flat to gentle slope) reduces construction costs. Therefore, plains to the eastern and southern parts of the city has continued to experience increased developments, multiplicity of land uses, vegetation degradation, low air quality and higher surface temperatures relative to the higher topographical areas to the northern and western parts of the city.

1.9.3.2 The Hydrogeology and Drainage

As illustrated by Figure 1.2, Nairobi's geological base is dominated by volcanic rocks which have influenced its landforms and the drainage pattern. The volcanic rocks within the city have undergone extensive faulting and sub-aerial weathering particularly the ones near the flanks of the Rift Valley. As such, the rock outcrops are closer to the surface and are covered by thin layers of overburden soils (Saggerson, 1991). The city has three basic geological structures namely; the Mbagathi phonolitic trachyte, the Nairobi trachyte (pliocene) and the Kirichwa valley tuff. The Mbagathi phonolitic trachyte which occurs across the Nairobi National Park and parts of Athi plains contain numerous closely spaced feldspar phenocrysts which often display sub-parallel alignments indicating the direction of lava flow they originated from. The second geological structure is the Nairobi trachyte which dominates northern and western parts of the city. It originates from pale grey mottled lava having a glittering appearance due to numerous tiny feldspar crystals it contains. Finally, the Kirichwa valley tuff which is an agglomeration of rocks significant of which is the devitrified welded tuffs (the Nairobi stone) used for construction (Morgan, 1967). Nairobi is situated within seismic intensity zone of between 6 to 7 on the Richter's scale and is prone to occasional tremors. This predisposes developments to seismic risk which requires consideration of the same in the design of structures. Basement rocks characterising larger parts of the city are covered by thin layer of soil. Therefore, foundations do not require extensive excavation thus reduces development costs. Further, the geological structure of the eastern parts of the city is a source of construction materials. This encourages high development rate in the zone, consequently lowering the environmental quality.

Nairobi’s hydrogeology is influenced by the basement rock configurations. While groundwater occurs in fluviatile aquifers and lacustrine deposits intercalated with weathered tuffs and sediments, the trachytes and phonolites being hard, un-fractured, impervious rocks with poor transmisivity experiences low water yields. Therefore, shallow aquifers occur within the Kirichwa Valley Tuffs and sediments deposited in the interface between Nairobi and Athi-Kapiti phonolite series, while deep aquifers are encountered within the Nairobi trachytes (Saggerson, 1991; Morgan, 1967). In this regard, developments to the eastern and southern parts of the city have minimal recourse of harnessing underground water. This necessitates implementation of proactive development control measures in these zones if the developments are expected to match the water supply and to preserve the environmental qualities of the neighbourhoods. The aquifers to the northern and western parts of the city have relatively high water yielding capacity because they are underlain by porous rocks and they also receive higher amounts of annual rainfall. Therefore, underground water supply presents an alternative source of domestic water supply in these zones.

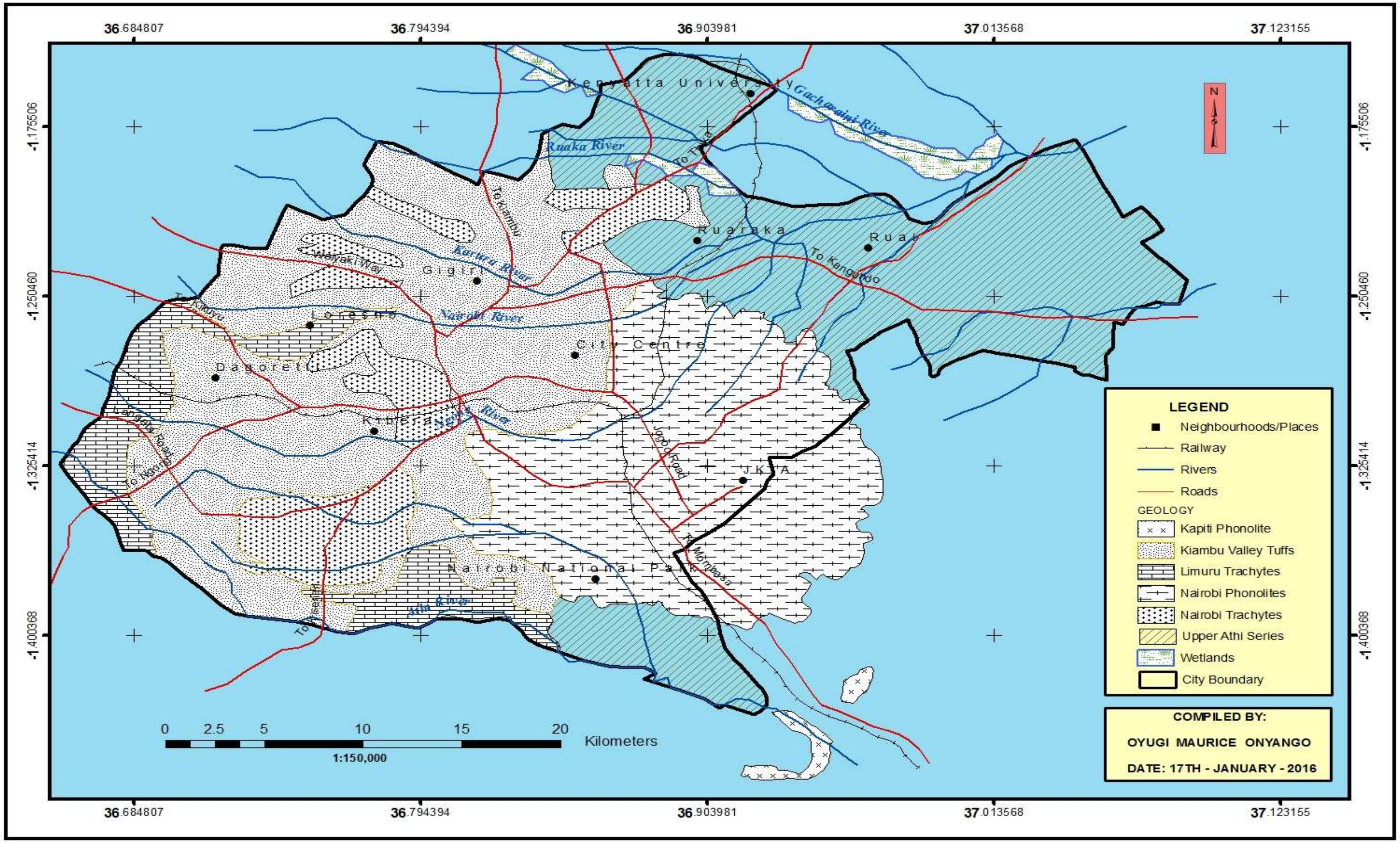

Figure 1.2. The Geology and Drainage of Nairobi City.

Source: (Morgan, 1967)

Nairobi lies within the Upper Athi-River Basin and is traversed by rivers such as Nairobi, Ngong, Mathari, Kirichwa-Kubwa, Masongari, Getathuru and Parklands. Nairobi River originates from Kikuyu Springs while Mbagathi River which is joined by other streams to form Ngong River originates from Mbagathi Springs in Oololua Forest. Since majority of the streams in the city emanate from the forests in the northern and western parts of the city, encroachment of anthropogenic activities into such ecologies impedes the rivers' flow leading to sedimentation and loss of biodiversity.

1.9.3.3 Pedological Base

The soils to the northern and western parts of Nairobi consist of red volcanic soils with high humus content. These types of soils develop from volcanic tuff under humid conditions (rainfall of more than 1000mm per annum). The southern and eastern parts of the city consists of black cotton clay which develops from similar rock types as the above but in areas where annual rainfall is slightly low ranging between 762mm to 1000mm per annum (Saggerson, 1991; Dumbleton, 1967; Sherwood, 1967). The soils within Nairobi range in depths from a few centimetres to several meters depending on the physiographic conditions of the area. The red volcanic soils in the highlands to the northern and western parts of the city are deep with well-developed profiles while those in the plains to the eastern and southern parts of the city vary in depth depending on their position within the plain. Poorly drained swampy peat soils rich in organic matter and characterised by grey colour occur in the plains, along the river courses and valleys.

The pedological base of the city has over the years influenced the city's morphological attributes and the environmental quality pattern. The red volcanic soils of the northern and western parts of the city are well drained while the black cotton clay soils to the eastern and southern plains are poorly drained, sticky, get waterlogged, has tendency of drying up during dry spells and are also susceptible to flooding and swellings which cracks the walls and the foundations. The red volcanic soils have higher load bearing capacity as compared to the black-cotton clay soils. The expansion of the city towards the plains has experienced constraints due to the swell, shrinkages and low load bearing properties of the black cotton soils. The red volcanic soils to the northern and western parts of the city being rich in nutrients do support vibrant vegetation growth and biodiversity relative to the southern and eastern black clay soils which have low nutrient contents and can only support perennial vegetations. The eastern and southern parts of the city are characterised by high density developments coupled with poor sanitation. This is because majority of the developments in these neighbourhoods are either on pit latrines or septic tanks which often get filled up due to poor seepage, consequently compromising the environmental quality of the city.

1.9.4 The Climate and Vegetation

Nairobi experiences Tropical Savannah type of climate which has been moderated by the city’s location closer to the Equator and the Indian Ocean. The East African weather is influenced by movement of the sun between the Tropics of Capricorn and Cancer across the Equator. During Equinoxes, low pressure belt or the Inter Tropical Convergence Zone (ITCZ) develops across the region. The Northeast and Southeast trade winds which are the prevalent trade winds in the region meet at the ITCZ and raise the air to form clouds which in turn intensifies the day to day weather activities. This makes places near the Equator such as Nairobi to experience bimodal rainy seasons notably March to June (long rains) and October to December (short rains) as illustrated by Figure 1.3.

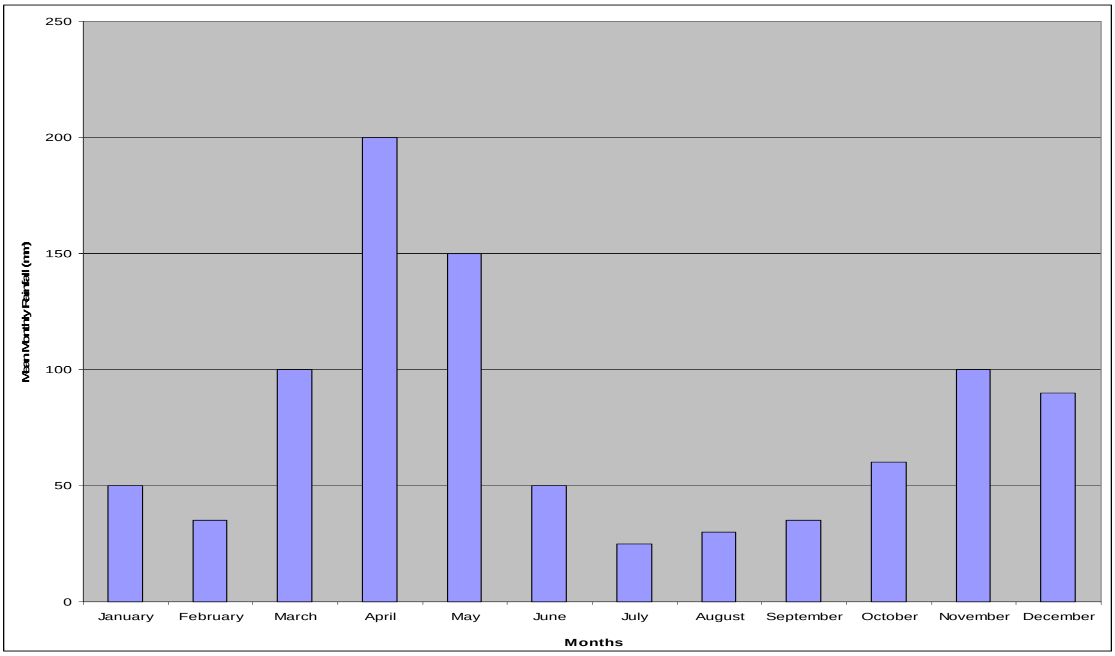

Figure 1.3. Mean Monthly Rainfall.

The rainfall regime of the city is characterised by unreliable annual amounts varying from 500mm to 1500mm with an average of 875mm. Northern and western parts of the city receive relatively higher rainfall amounts in comparison to the eastern and southern parts of the city. This has accentuated vegetation growth and establishment of agricultural activities in the northern and western parts of the city as compared to the shrubs, rangeland and grasses which dominates the southern and eastern plains. However, the population influx currently being experienced in the city has led to land fragmentations to acreages which are no longer viable for agricultural production. The subdivided parcels are often converted into real estate developments leading to urban sprawl. Forests which characterises the northern and western parts of the city are better carbon sinks and moderators of surface temperatures as compared to the shrubs and grasses which dominates the southern and eastern plains. This predisposes the northern and western parts of the city to relatively better environmental quality as compared to the southern and eastern plains.

The absence of forests coupled with higher surface temperature values predisposes the southern and eastern plains to low pressure belt and strong geotrophic winds. This contrasts with the northern and western parts of the city which are relatively cool due to high topography exuberated by the Kikuyu escarpments and abundance of vegetation cover. As illustrated by Figure 1.4, daytime temperatures in Nairobi during the months of July and August often remains below 20^0C while night temperatures of the same months can fall as low as 10^0C. The hottest periods in the city falls between January to March and October to November when the temperatures averages 28^0C.

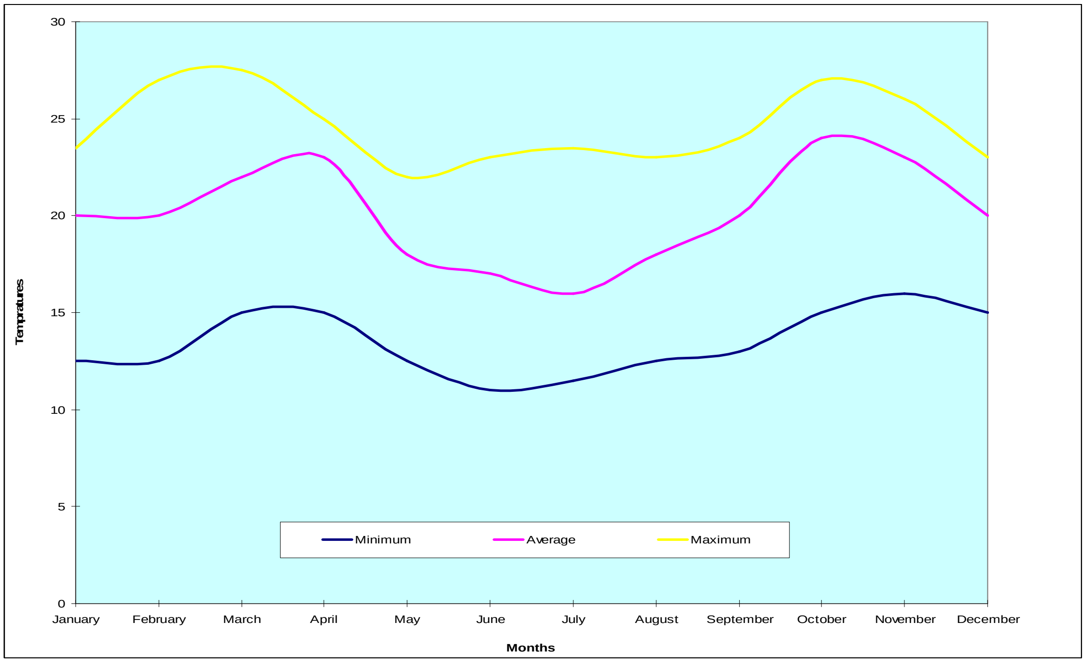

Figure 1.4. Monthly Diurnal Temperature (^{0}C).

Figure 1.5 shows that Nairobi experience approximately 2,500 hours of bright sunshine per annum, which is equivalent to 6.8 hours of sunshine per day. However, the eastern and southern parts of the city receive more solar radiation than western and northern parts of the city due to slope effects of Kikuyu escarpments. The sunshine inversely corresponds to rainfall regime and as such is at the peak between the months of January to March.

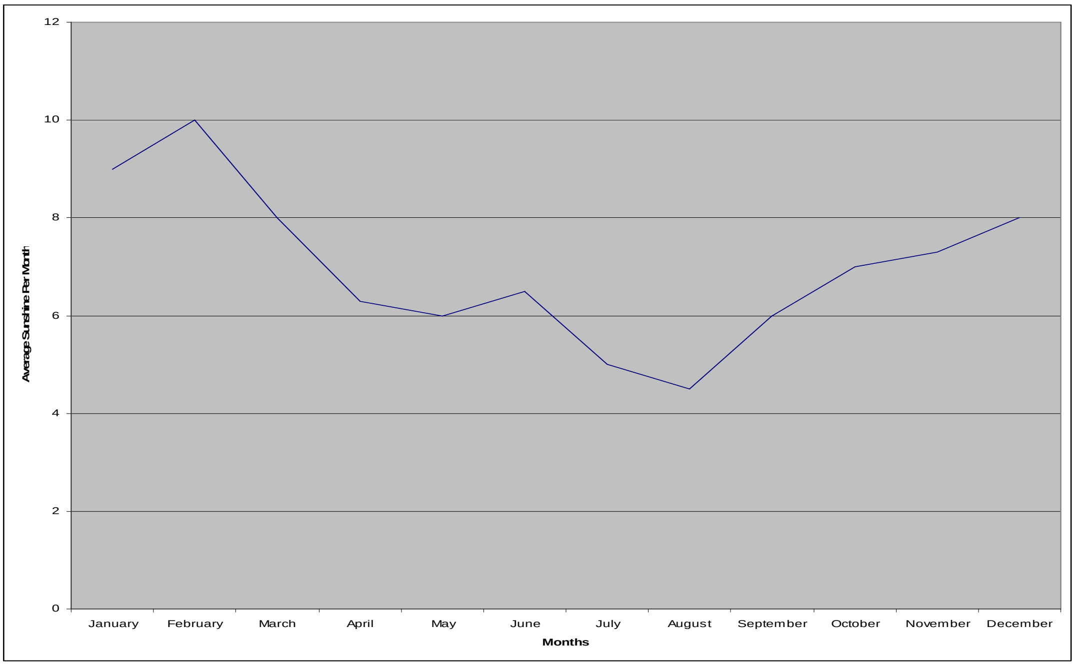

Figure 1.5. Average Number of Hours of Sunshine per Month.

As illustrated by Figure 1.6, Nairobi's maximum relative humidity occurs near dawn, the time of minimum temperature when the air is close to saturation. The minimum relative humidity occurs during the rainy seasons. This has been modified by the city's development density, topography and the vegetation cover as areas closer to the forests and Kikuyu escarpments experiences higher humidity relative to the southern and eastern plains characterised by disturbed bushes, shrubs, grasses and acacia vegetations. High development densities in the CBD, eastern and southern neighbourhoods decrease the albedo which subsequently raises the terrestrial radiation in comparison to the western and northern neighbourhoods where the development densities are relatively low. The maximum evaporation value in Nairobi occurs in the month of March, followed by February, October and January. The mean annual evaporation value of the city is 1735mm with the maximum and minimum values being 1951mm and 1519mm respectively.

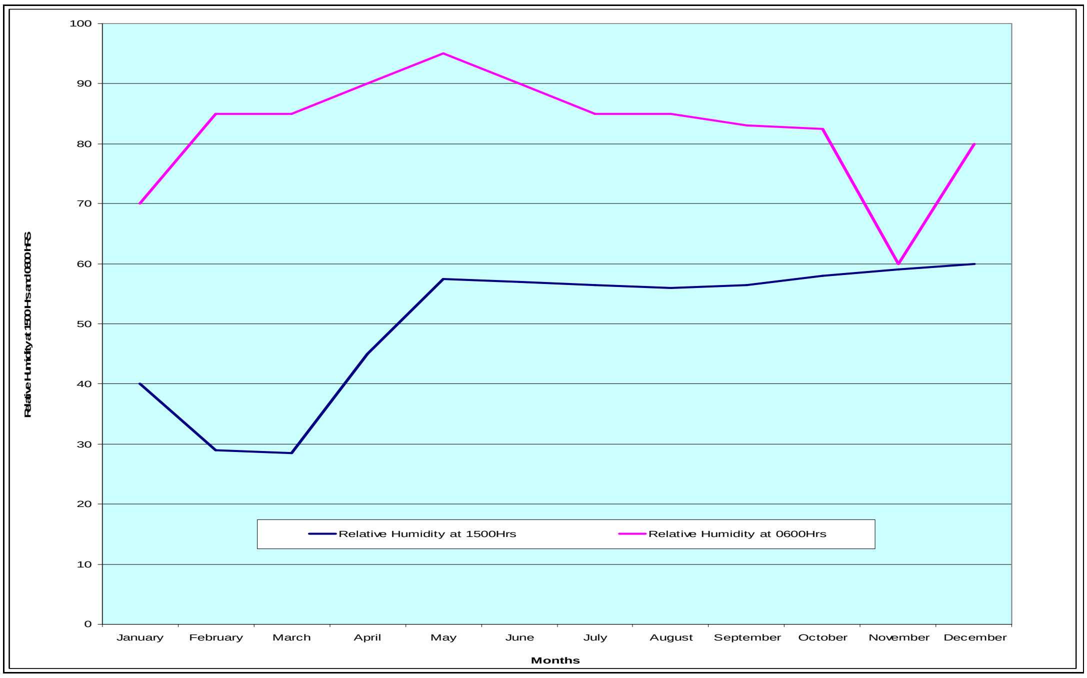

Figure 1.6. Relative Humidity in Percentage at 1500 Hours and 00600 Hours.

Healthy natural and exotic vegetation cover characterizes higher topographies to the western and northern parts of the city while the plains to the eastern and southern underlain by vertisol soils are characterised by sparse vegetation such as Acacia *mellifera*, Lawsonia *inermis*, A. *reficiens* and Salvadora *dendroides* with either bare ground or annual grasses which are only suitable for livestock grazing. Other vegetation covers in the city consist of gazetted forests and riparian vegetations. Ngong and Karura forests are the main gazetted forests while the riparian vegetations are concentrated along the rivers. However, encroachment of human settlements into the riparian reserves is steadily depleting the vegetation cover. In the plains, the vegetation density is low to effectively moderate the micro-climate as compared to the western and northern forests. Further, the presence of industrial developments and quarries characterising the eastern and southern parts of the city has worsened the environmental quality of the neighbourhoods for the above stated land uses lowers the albedo, consequently raising the surface temperature values and the concentration of air pollutants.

1.9.5 Infrastructure

Infrastructure is a prerequisite for urban growth, improvement of livelihoods and national development. It is a major determinant of land use and land cover dynamics as well as urban environmental quality and sustainability. It is therefore significant to understand the urban infrastructural base and/or capacity when discussing land use differentiations, land cover dynamics and the environmental quality of any urban setup.

1.9.5.1 Water and Sanitation

Population pressure in Nairobi has accentuated frequent water shortages which have continued to be mitigate through the construction of extra dams and boreholes. As illustrated by Figure 1.7, the major sources of water supply to the city are Ndakaini, Ruiru, Thika and Sasumua dams via the Kabete Water Works and Hill Tank Reservoirs. The first sewer works was implemented in 1945 while the second one took place between October 1978 and March 1983. Since then, there has not been major upgrade despite the system continuing to serve an increasing population. This poses a challenge to sustainability of the system which is already experiencing lapses in maintenance. Even though investment in water and sewerage infrastructure is expensive, the city agency has to expand the infrastructure for urban sustainability and to continue attracting investments.

The city's waste-water treatment facilities have not been expanded enough to keep up with the increasing population. Currently, the facilities are inadequate in treating the industrial and municipal effluents. As such, much of the industrial, municipal and petro-chemical effluents flow into the rivers and other water bodies. In addition to locally generated water pollutants, effluents enter the rivers from further a field where these rivers originate. Water pollution is a health risk to communities within the city, especially the poor who uses waste-water for gardening. This exposes both the farmers and consumers of such produce to health problems granted that almost 50% of the vegetables consumed in the city are grown on the banks of the polluted rivers (Ayaga *et al.* 2004).

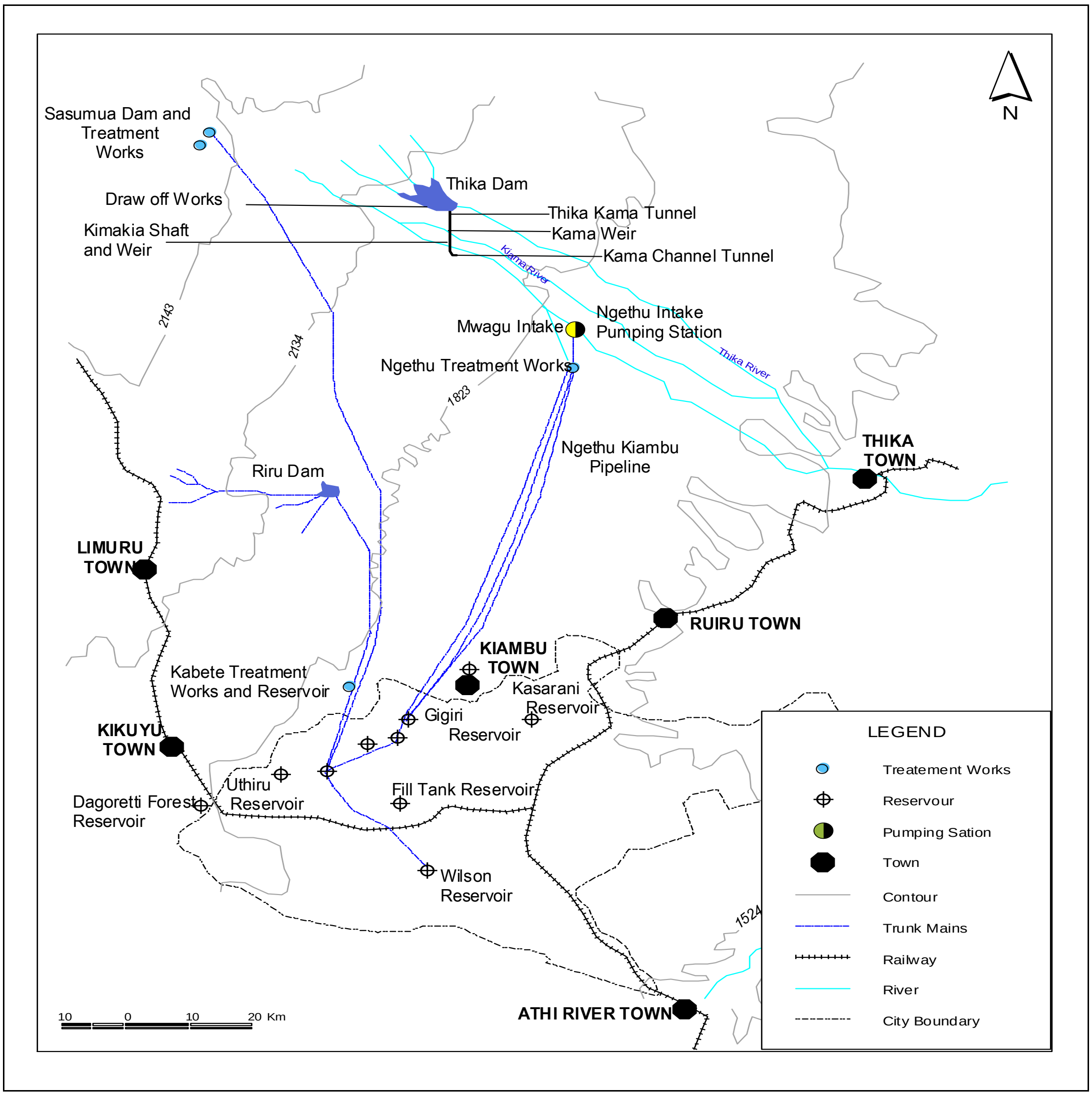

Figure 1.7. The Regional Water Resources.

1.9.5.2 Road Network

Motorised mode of transportation is the most preferred mode of transportation in the city. With the exception of the dual carriage Waiyaki way, Uhuru highway, Thika super-highway and Mombasa road, most of the roads within the city were designed to serve low-density residential neighbourhoods. Over the years, increased traffic volume in the city has lowered the functionality of these roads; making traffic snarls a permanent feature on roads. The traffic snarls contribute to rising concentration of air pollutants as occasioned by poor engine combustion when the vehicles are in low gears.

1.9.6 Environmental Issues

Nairobi once had a reputation for healthy living environment and was known as the *"Green City in the Sun"*. Its landscape was characterized by abundant wildlife, natural forests, labyrinthine riverine and wetland ecosystems. However, the city's expansion has occasioned loss of forests and other natural habitats. The city has managed to retain a number of green spaces as recreation and biodiversity conservation areas, water catchments and micro-climate moderators. The Nairobi National Park which is the country's most successful rhino sanctuary is 7.0kms from the city centre and is also the only protected area in the world with a variety of animals and birds so close to a city. However, as the city expands, the wildlife habitat is increasingly being exposed to air pollution and is threatened by encroachment of human settlements. The park which covers an area of approximately 114 km^2 is a dry season refuge for wildlife migrating from the Maasai-Amboseli ecosystem to Athi-Kapiti plains. Other major protected green spaces in the city include the Uhuru Park, Ngong and Karura Forests which collectively occupies approximately 2,180 hectares.

Land speculations, unemployment, poverty and inadequate planning have encouraged the proliferation of informal settlements in the city (Mitullah, 2003). The informal settlements and other low income residential neighbourhoods are overcrowded, venerable to flood and fire disasters and are experiencing poor sanitary conditions and inadequate water supplies. Since most of these settlements are illegal, they face insecurity of tenure which exposes the inhabitants to constant harassments and evictions. The Dandora dumping site, which receives most of the city's solid wastes is only 8.0kms from the city centre and is surrounded by low-income residential developments, a situation which exposes the inhabitants to health risks.

The main sources of atmospheric pollution in the city are the motor vehicle and industrial fumes, open burning of wastes and emissions from charcoal and wood fuels. The increasing number of motor vehicles in the city over the years has intensified air pollution problems for the vehicles emit significant levels of air pollutants including greenhouse gases. The use of charcoal fuel in the low income residential neighbourhoods emits methane, carbon monoxide and suspended particulate matter into the atmosphere. These pollutants are associated with respiratory and eye diseases such as asthma, lung cancer and conjunctivitis. They are also a major contributor to acid rain which adversely affects the soils, aquatic resources, artefacts and vegetation.

Increasing urbanization and rising standards of living have increased solid waste generation within the city. However, the increase has not been accompanied by an equivalent growth in the capacity to address the problem. For example, in the year 1992 approximately 900 tonnes of solid waste was being generated everyday in the city, of which less than 10% was being collected. By the year 2007, the amount had grown to 1,845 tonnes per day of which 40%

was uncollected (City Council of Nairobi, 2007). Food, plastic and paper wastes are the dominant forms of solid wastes in Nairobi, with plastics having far reaching environmental consequences. Once released into the environment, they choke wildlife, pollute the soil and serve as breeding grounds for mosquitoes (NEMA, 2008).

1.10 Organization of the Report

This study is organized into five chapters of which chapter one introduces the study by presenting the research problem, objectives, hypothesis, research assumptions and the study justification. The chapter further details out the scope and limitations of the study as well as the background information of the study area. Chapter two focuses on the literature review where scholarly arguments on what constitute urban environmental quality, morphology, the role of geospatial techniques in studying the same as well as how various environmental quality parameters are correlated to the urban morphology are discussed. Chapter three presents the methods and tools employed for data collection, analysis and the presentation of the findings. While chapter four presents the study findings and justification for the evolution of an alternative urban development policy and environmental quality enhancement strategies for the city, chapter five is the study summary, conclusions and recommendations. References and appendixes are included at the end of the report.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Despite cities being engines of national development, they are continuously under threat occasioned by pollution, congestion and environmental hazards arising from high urbanisation rates. High urbanisation rates in Africa have been perpetuated by inherent demographic processes characterized by high natural urban population increase and rural-urban migration, notwithstanding poor economic performance of these nations. Apart from rendering obsolete attempts of replicating northern models for controlling urbanisation, the scenario has continued to complicate the provision of urban services (Smith, 1996). Despite all the problems associated with urbanization, economic development in Africa shall continue largely being dependent on urbanization. Therefore, urban management and allied body of knowledge are crucial in combating urban exclusion, environmental degradation and decadences in human dignity which characterizes urbanization in Africa.

According to Van der Ryn and Cowan (2007), unsustainable urban design practices not grounded in ecological principles has made urbanisation come at the expense of natural ecosystems. Van der Ryn and Cowan (2007) further posits that this has distanced man away from nature and today, cities are characterised by traffic snarl, urban sprawl, wastes and hazardous emissions which defies pollution prevention and control efforts. Therefore to bridge this gap and to link man with nature, there is need for ecological consideration in the planning and management of cities.

Urban morphology emanating from planning decisions has implications on urban environmental quality. For example, high development densities enable Planners to achieve economies of scale in infrastructure provision, but can also impose high costs associated with congestion, thermal discomforts and air quality degradation. On the other hand, low development densities in a city means reduced congestion, but urban sprawl, loss of agricultural land and higher costs of infrastructure provision. It is therefore important to understand the interconnection among factors that shapes the urban environmental quality. This chapter therefore presents literature on urban environmental quality, factors influencing the same and the role of geospatial techniques in understanding the relationship existing between urban morphology and the environmental quality parameters.

2.2 The Concept of Urban Morphology

The concept of urban morphology was first expressed in the writings of the Poet and Philosopher Johann Wolfgang von Goethe in 1790. Since then, the term has extensively been used in Biological Sciences, Geography, Urban Planning, Architecture and other related disciplines. These scholars have defined the concept depending on the focus of their studies. For example, Gilliland and Gauthier (2006) defines urban morphology as the study of a city's physical form which consist of development density, land use, street patterns, building configuration and population density while Moudon (1997) defines urban morphology as the study of a city as a human habitat. Despite diverse definitions of urban morphology by various scholars, an area of convergence is that an analysis of a city's morphology should begin with dissection of how the city has evolved over time and space, identification of the urban elements and subsequent transformations which have taken place on the elements as well as how the physical form produces various social forms.

Urban morphology has since evolved to discern the physical approach into a body of knowledge analysing the urban fabric as a means of understanding the urban structure (Moudon, 1994). This approach challenges the perception of urban centres as chaotic organic (unplanned) environments. According to Moudon (1997), Urban Morphologists focus on socio-economic forces moulding cities through constant transformation of elements notably the buildings, gardens, streets, parks and monuments. This portrays cities as unconscious products that emerge over a long period of time through accrual of successive generations of developments which leaves traces that restructures the urban elements by either providing opportunities or constraints to successive developments. This has led many to prefer the term *Urban Morphogenesis* to describe the field of study and the logic of these traces.

Three schools of thought exist in the study of urban morphology namely; the Italian, British and the French. The Italian school of thought dates from 1940s and is centred on the works of Saverio Muratori who attempted to develop an operational history for the cities he studied. This was meant to provide rationale for the integration of new architectural works in the syntax of the urban tissue (Emmanuel, 2005). Muratori’s views were further advanced by Gianfranco Caniggia who conceptualised a city as a dynamic procedural typology of buildings, gardens, streets, parks and monuments shaped by political and economic forces. The British school of thought is centred on the works of M.R.G Conzen, who developed a technique called town-plan analysis (Moudon, 1997). For Conzen, understanding the urban building fabric and land use through history is imperative in comprehending the urban morphology. This approach has been applied by his followers such as J.W.R Whitehand and Peter Hall in the management of historic and contemporary townscapes. The realisation that the relationship existing between the built spaces and the social world is dialectical made the French school of thought based at the Versailles School of Architecture to place emphasis on the importance of built spaces in sustaining social practices. In America, urban morphology as a field of study owes its origins to Lewis Mumford, James Vance and Sam Bass Warner (Moudon, 1994).

2.3 Determinants of Urban Land-Use and Land Cover Differentiations

Various postulations have been made on the determinants of urban morphology. Miller (1994) posits that human behaviour impacts on urban morphology through city design. This view is shared by Hall (1977) who argues that the management interventions adopted by cities have destroyed the innovative entrepreneurship that was once the significant determinant of urban morphology. As a reaction to the sentiments expressed by Hall (1977), urban planning as a practice has adopted the development corridor concept which entails the transformation of urban thoroughfares into linear business hubs. This concept works well if augmented with the concept of the city of towers which advocates for vertical densification of cities as was advanced by *Le Corbusier* in the 1920s. Therefore, the entrepreneurial endeavour of the urban community is a core determinant of urban land use and land cover differentiation.

Alonzo (1964) gives an account of urban land use differentiation based on land values by detailing out how individual households faced with the desire to buy land is equally faced with the dilemma of deciding on the size of land to purchase and how close it should be to the city centre. Alonzo’s theory assumes a city of single employment and shopping zone with equal transportation costs and opportunities in all directions, making the cost of commuting to the city centre a function of the distance. The theory also assumes that the households and/or firms have perfect knowledge of the prices of land within different locations of the city and that the cost of land drops as one moves away from the city centre. Therefore, household's locational equilibrium is achieved through selective combination of the desired quantity of land and distance from the city centre. He further uses the concept of bid rent curve to arrive at distances from the city centre at which deferent land uses will viably locate. The theory observes that the most accessible sites in the city goes to the users with the steepest bid rent-curve notably the high order commercial activities with the second steepest bid rent-curve locating on the next ring outward from the city centre. The theory explains the urban expansion of Nairobi by observing that land use competitions for strategic locations within the city compels land uses such as residential developments whose bid-rent curves are gentle to migrate to the periphery.

Wingo (1961) postulated *Transportation-Oriented Theory* to explain the distribution of urban residential development densities. The theory posits that higher residential development densities within cities positively correlate with accessibility. Webber (1929) posits that spatial interactions as aided by transportation network (the flow of people, goods and services) are significant determinants of urban activities and spatial structure. Guttenberg (1960) advances the concept further by acknowledging that accessibility influences urban spatial structure by promoting interactions and land use clustering. However, Firey (1974), in his study of Boston City observes that socially rooted values and ethnicity exert causative influence on urban land use patterns and that infrastructure and market forces are only secondary factors. Therefore, failure to recognize the role of cultural values in determining urban land use and land cover differentiation by Wingo (1961), Alonzo (1964), Webber (1929) and Guttenberg (1960) was an omission. Indeed, Firey (1974) explains residential choices in cities such as Nairobi whose origin is dominated by colonial legacies such as racial segregation.

The *Concentric-Model, Sector Model* and *Multi-Nucleic Model* illustrated by Figure 2.1 are the urban land use and land cover models commonly used to explain the differentiations of the same within a city. The *Concentric-Model* which was postulated by Burgess (1925) consists of five series of concentric zones namely; the CBD, Zone of Transition, Working Men's Homes, Residential Zone and the Commuters’ Zone. Burgess notes that while the CBD has facilities such as shopping areas, theatres, hotels, offices and banks among others, the zone of transition is characterised by mixed land uses such as the co-existence of high-rise residential developments with commercial developments. The zone of working men’s homes is home to factory workers while the residential zone is where the white-collar workers and middle-income families reside. The fifth ring being the commuters’ zone is a suburban community where the upper-income group having private modes of transport reside. Burgess (1925) further observes that with increased urbanisation, inner zones invade the next outer zones similar to ecological succession. In contrast, when urban decay occurs, the outer zones remains stationary while inner fringe of the transitional zone recedes into the

CBD. While the model provides a useful explanation to urban land use patterns, it is an oversimplification of urban morphological reality.

Hoyt (1939) postulated *Sector Model* which posits that different urban land uses locate in distinct neighbourhoods in a star-shaped manner centred on a single CBD which is the most accessible part of a city. Rents then graduate downwards from the CBD as determined by transportation network. In this case, high-income residential areas developing along the highways pull high order commercial activities to the neighbourhoods to form an agglomeration of compatible land uses. Despite the simplicity of the model and its emphasis on residential developments, it provides a profound explanation to urban land use differentiations than the concentric model.

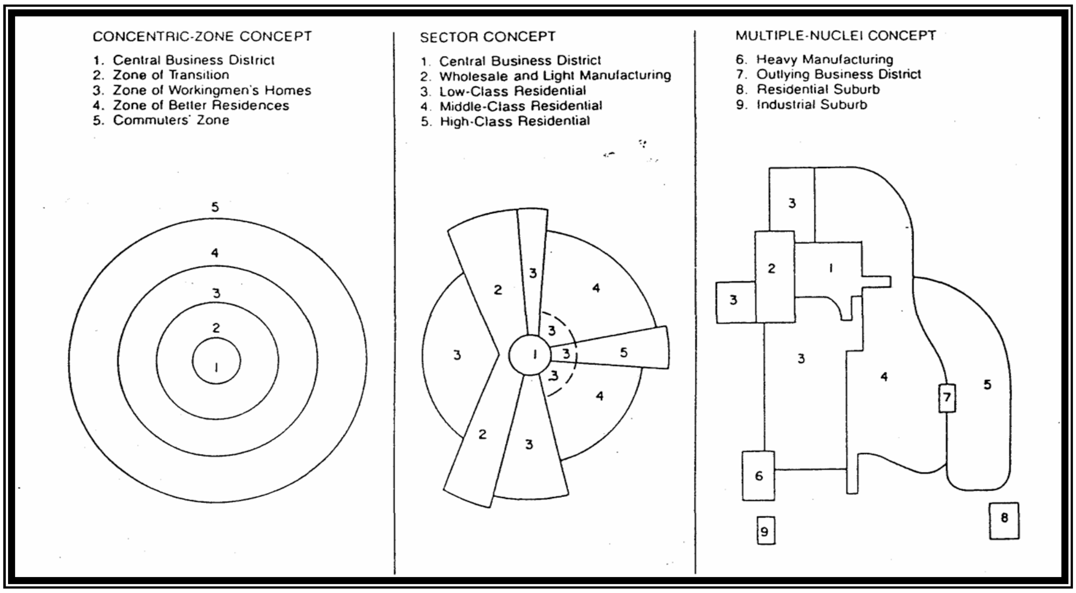

Figure 2.1. Urban Land Use Models.

Source: (Hartshon, 1980)

Harris and Ullman (1945) formulated *Multi-Nucleic Model* which posits that rather than a single CBD as postulated by the other models, there exist series of nuclei patterning urban land uses. The nuclei may take the form of industrial or wholesaling centres where specialized complementary economic activities have gravitated over the years. Harris and Ullman (1945) further notes that factors responsible for multi-nucleic patterning of urban land uses are inter-dependence of certain activities that find it mutually profitable to cluster, some activities have specific site requirements which must be fulfilled for them to locate, presence of activities which are offensive to other users and rents which either attract or repelling users. Despite the model satisfactorily explaining the metropolitan land use differentiations, it needs modification before it can be utilised in explaining land use and land cover differentiations in cities with colonial legacies such as Nairobi.

As noted by the 19th century Scholars such as Ruskin, Geddes, Carlyle, Dickens, Engels and Disraeli, urban land use differentiations is occasioned by land value speculations and environmental considerations (Gallion, 1963). This informed Howard (1898) to envisage a town with communal land ownership where residential facilities and civic buildings are distributed along a large central court with shopping centres and industrial land uses located on the edges. As illustrated by Figure 2.2, Howard's utopian city envisaged a population of 58,000 people within 1,000 acres surrounded by 5,000 acres of agricultural land.

Bicik *et al.* (2001) postulates that urban land use and land cover dynamics is a by-product of the interactions between nature and the society's socio-economic developments. While Bibby and Shepherd (1990) posits that the rate of land use and land cover change is determined by the demand and supply of houses, population growth, political ideology and the national economic performance, Bourne (1976) posits that the main processes controlling urban land use and land cover dynamics are the expansion of urban infrastructure especially transportation and the migration of industrial, institutional, commercial and recreational land uses to the suburbs. Bourne (1976) further postulates that population increase alone is no longer the main stimulus of urban land use and land cover dynamics. This debate has metamorphosed into sustainable urban development agenda of the 21st century which incorporates multiple-variables such as natural ecology, socio-economic, political and legal factors in explaining land use and land cover differentiations within a city.

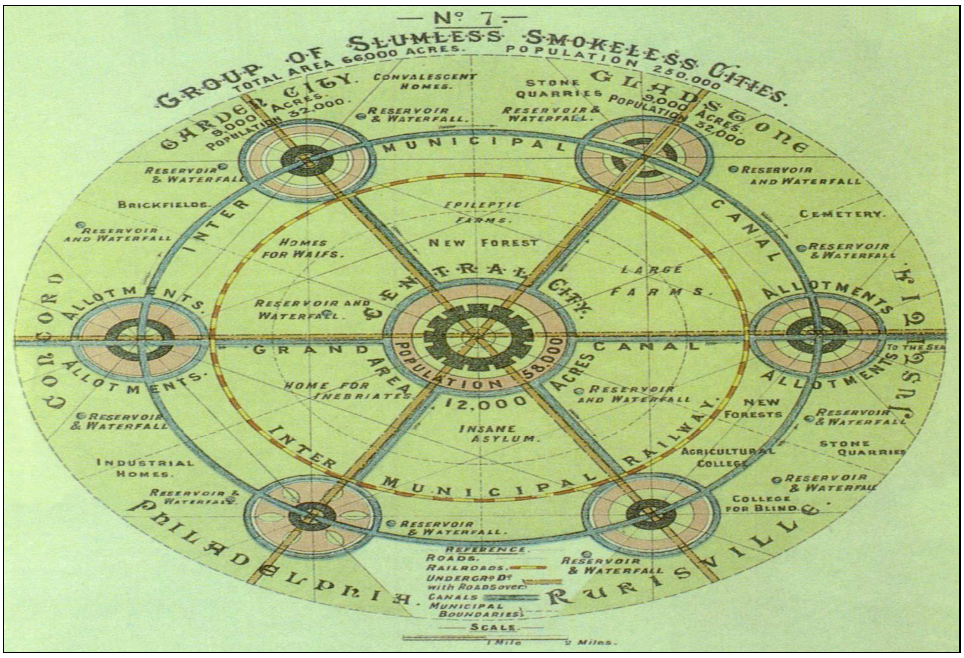

Figure 2.2. Ebenezer Howard’s Model.

Source: (Gallion, 1963)

De Groot *et al.* (2002) advances the debate on sustainable urban development by noting that urban land use and land cover equilibrium is achieved through perceptions among the urban residents as to whether an urban neighbourhood provides a healthy environment for interactions and establishment of economic activities. If the perception is negative, then there is likelihood of migration and establishment of the activities in other neighbourhoods which are positively perceived. This ultimately lead to urban land use and land cover changes. De Groot *et al.* (2002) further states that urban vibrancy depends on its ability to provide goods and services to its inhabitants which ultimately triggers land use and land cover changes. Other sentiments expressed by De Groot *et al.* (2002) on the same is that legal, statutory regulations, political decisions on land use and technological advancements in the society accelerate urban land use and land cover changes. Together with the above, globalisation which facilitates movement of people, goods and services between nations also determines the urban morphological changes depending on a city's location, internal site opportunities and the stage of national economic development (Martin, 1986).

According to Mengistu and Salami (2007), physiographic, geo-processes such as climatic and pedological variations, tectonic forces, drainage regime and the socio-economic drivers comprising of technological and demographic changes, social values, economic growth, political and public policies related to land use are the main agents of land use and land cover change. In support of the above, Arvind and Nathawat (2006) in their study of land use and land cover mapping of Panchkula (India) using multi-date satellite imageries observes that heterogeneous climate and physiographic conditions in the district has resulted in the development of different land use and land cover categories such that hilly regions and the plains are characterised by forests and grasslands respectively.

2.4 Theoretical Basis of the Relationship Existing between Urban Morphology and the Urban Environmental Quality

This study is anchored on *Urban Boundary Layer Dynamics Theory* which explains how urbanization determines the *Urban Energy Balance, Surface Temperature Variations, Heat*

Islands Effects, *Air Pollution Concentration and Dispersal*, *Global Warming* and *Climate Change.* Further to building configuration attenuating wind velocity to subsequently influence the distribution and concentration of air pollutants, the waterproofing and thermal properties of the materials used in the constructions influence the concentration of anthropogenic heat and the distribution of surface temperatures. However, this relationship is moderated by the geographic setting (relief, elevation and regional climate), size of a city, population density and proximity to water body (Mills, 2007; Grimmond, 2006).

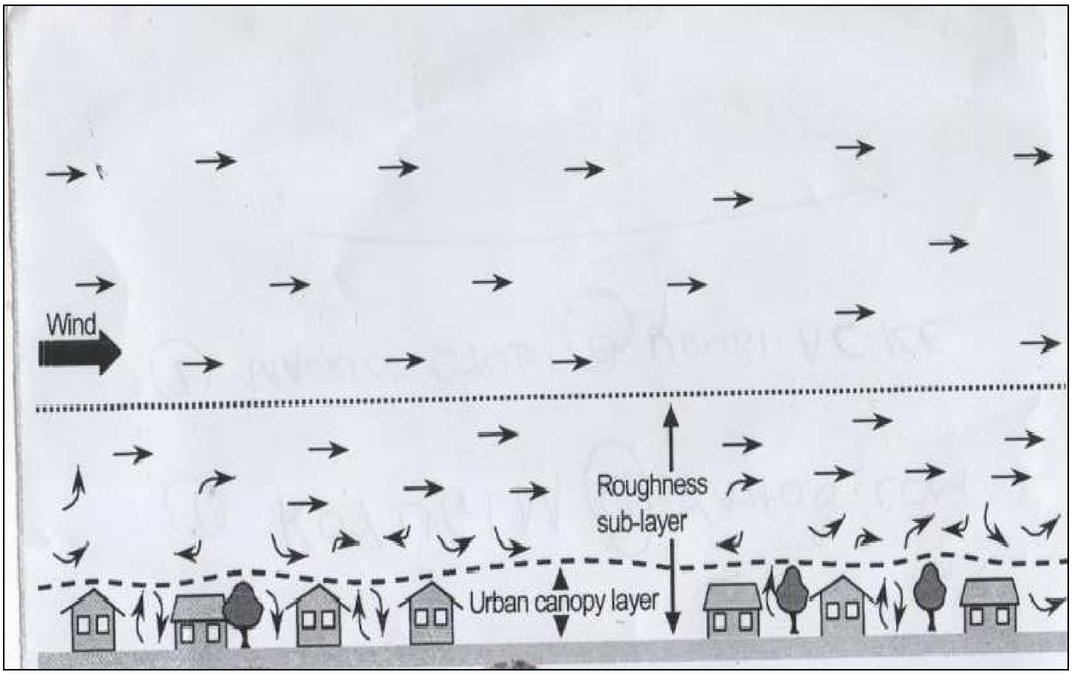

Figure 2.3. The Urban Boundary Layer Dynamics.

Source: Grimmond and Oke (1999a).

The Urban Boundary Layer Dynamics Theory posits that the urban atmosphere consists of two sub-layers namely the urban roughness and canopy sub-layers. The climatic conditions in the urban roughness sub-layer are defined by heat and moisture exchanges between the city's overlying air and the urban surface elements such as the roofs, trees, lawns and roads among others (Schmid, 1994). On the other hand, the climatic conditions of the urban canopy sub-layer which is the lower part of the urban atmosphere, extending from the ground to the average height of urban buildings is influenced by energy fluxes from the urban elements. Since heat fluxes, mass and momentum change with height, the roughness and the canopy sub-layers are not in equilibrium (Grimmond and Oke, 2002; Grimmond and Oke, 1999a).

As illustrated by Figure 2.3, the urban boundary layer dynamics as influenced by the urban morphology determines the dispersal and the concentration of the air pollutants, humidity and wind velocity. The boundary layer dynamics is also responsible for the urban energy balance which states that the available radiated energy at a surface is balanced by attenuated heat and vapour fluxes into the atmosphere. According to Grimmond and Oke (1999b), the energy balance for a single surface element is represented by function 2.1.

$$\mathbf{Q = E + H + G} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{2.1}$$

Where: -

Q = Net radiation

H = The sum of the turbulent transport of sensible heat between the surface and the atmosphere

E = The sum of the turbulent transport of latent heat between the surface and the atmosphere

G = The heat transport between the surface and the material below

According to Oke (1988), for a volume of air extending to the top of the roughness sub-layer, the energy balance is presented as equation 2.2.

$$\mathbf{Q_{local} + F = H_{local} + E_{local} + G_{local} + A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{2.2}$$

Where:-

$\mathbf{Q}_{\mathbf{local}}$ = The area's average net radiation,

F = Energy released or consumed by anthropogenic activities within the volume,

$\mathbf{H}_{\mathbf{local}}$ = The turbulent fluxes of sensible heat across the top of the volume,

$\mathbf{E}_{\mathbf{local}}$ = The turbulent fluxes of latent heat across the top of the volume,

$\mathbf{G}_{\mathbf{local}}$ = Change in storage within the volume (including air, structures and the ground)

A = The net advection of heat in the horizontal direction.

Urban energy balance is a complex process of shading and reflection of short-wave radiation as well as absorption and emission of long-wave radiation, all taking place within the urban three-dimensional structures. In densely built-up urban areas, heat storage can amount to at least 50% of daily net radiation, which is larger than most natural ecosystems. However, there is a tendency for more energy to be stored in the morning and within the city centres. This consequently leads to large amount of stored energy being released during the evening and night, resulting in upward directed sensible heat (Arnfield, 1982; Schmid *et al.*1991).

The urban heat island effect which makes cities generally warmer relative to the rural surroundings is explained by the differences in energy storage and cooling rates between the urban surfaces and rural environments. Urban surfaces store thermal energy during the day and release the same during the night, making urban heat island affect a nocturnal phenomenon. In return, the urban heat island effect influences thermal turbulences, atmospheric stability, nocturnal inversions and local circulation systems among others which collectively have impact on urban air pollutants' dispersion and concentration. The urban heat island effect and the increased production of GHGs and other air pollutants arising from anthropogenic activities notably the urban transportation and industrialisation has since been linked to global warming and climate change (United Nations, 2014).

Despite the urban heat island effects being associated with thermal discomforts and increased energy consumption for air conditioning, its impact vary depending on a city's setting, morphology and the regional weather conditions and does not necessarily have to be negative. For example, urban heat island effects contribute to reduced energy consumption in high latitude cities (Taha, 1997; Santamouris *et al.* 2001; Svensson and Eliasson, 2002). Apart from urbanisation and industrialisation impacting on urban energy balance to create urban heat island effects, the two phenomena further impact on local winds and convection patterns to heighten surface roughness which exacerbate the concentration of air pollutants and precipitations (Han, 2014).

2.4.1 Effects of Urban Morphology (Development Density and Building Configuration) on Environmental Quality

High rates of urbanisation have exacerbated increased development densities in the cities. This is beneficial for the conservation of open spaces and natural resources, enhancement of social relationships as well as enabling urban authorities to deliver more housing stock, services and employment stations within walking distances. However, high development densities exacerbate noise, air pollution and overcrowding (The Jerusalem Institute for Israel Studies, 2005). Lowry (1977), notes that as urban centres grow towards mega cities, their natural vegetation get replaced by skyscrapers which provide multiple surfaces for the reflection and absorption of terrestrial energy. This increases the efficiency with which urban areas are heated to raise the urban air temperatures. Moreover, concrete materials used in urban constructions have thermal retention capacity which limits rapid cooling after evening transition. The building configuration attenuates wind velocity and cause turbulences which restrict the air pollutants to narrow building canyons within the neighbourhoods. This allows the pollutants to settle and increase in concentration (Vougt, 2002). Therefore, development density and building configuration is today known to adversely affect the urban environmental quality (Wagrowski and Hites, 1997; Dwyer *et al.* 1992).

Development density is the best tool for shaping urban morphology, yet agreements on whether to adopt low or high urban development density is often emotive. Based on the lessons learnt from the European and North American cities, it is imperative to find a middle ground between the two models. High density development is viewed as anti-suburbanisation and an indicative of claustrophobic squalor, poverty and deprivation. On the other hand, low-density urbanism is equated with selfish gated communities and the environmentally disastrous car-orientated suburbs. However, it grants individuals freedom to spacious living and can be presented as a model of freedom and sturdy individual choice (Dodman, 2009; Sudjic, 2008). Views on the impacts of urban development densities have tended to be polarising as noted by the works of Howard (1898) and Jacobs (1996). Howard (1898) argues that it is universally agreed by men of all parties that it is deeply deploring that people are still streaming in already overcrowded cities. On the other hand, Jacobs (1996) whose work, *The Death and Life of Great American Cities* is taken as a mantra for new urbanism movement (those opposed to the suburban sprawl and restrictive residential enclaves) is passionate in the defence of high development densities. According to Burton (2000), a study of medium-sized English cities suggests that while high urban development densities lead to reduced living spaces, it has the ability to improve public transportation, reduce social segregation and enhance access to utilities and amenities.

Low development densities are viewed as the main causes of urban sprawl. However, the definition and the effects of urban sprawl on environmental quality are widely debated. Frenkel and Ashkenazi (2008) states five parameters for detecting urban sprawl as growth rates, development density, spatial geometry, accessibility and aesthetics. Urban sprawl is often associated with problems such as social isolation, obesity and asthma, global warming, climate change, the demise of farmlands and extinction of wildlife. However, some scholars argue that urban sprawl is inevitable for it is an outcome of free-market mechanism (Gottdiener and Budd, 2005). In low and middle-income countries, peri-urbanization is increasingly taking place and the boundaries between urban and rural areas are continually being re-negotiated. The interfaces between the two are often afflicted by slums, inadequate urban services and degradation of farmlands. This is because planning regulations are inadequately enforced in the peri-urban neighbourhoods for such neighbourhoods are outside the legal and administrative boundaries of the cities (McGregor *et al.* 2006; Tacoli, 2006; Wackernagel *et al.* 2006).

Cities constituting 2% of the earth surface are responsible for 75% of global energy consumption and 80% of GHG emissions. Therefore, cities significantly contribute to global warming and climate change (Angel *et al.* 2005; Satterthwaite, 2008). A study of GHG emission in Toronto City concludes that low density suburban developments consumes between 2.0 to 2.5 times more energy annually than densely developed neighbourhoods. This is because high development density encourages low car ownership and requires less energy for heating, cooling and to power the buildings (VandeWeghe and Kennedy, 2007; Baldasano *et al.* 1999; Dubeux and La Rovere 2007; Norman *et al.* 2006). A study of 16 variables in 45 Chinese cities concludes that there is a positive relationship existing between urban development density and environmental quality up to a certain level as other variables such as income levels, urban spatial structure, transportation network, surface temperatures and population size explains why cities in Southern Asia are densely settled than cities in North America yet they generate high levels of GHGs (Chen *et al.* 2008; Glaeser and Kahn, 2008; Mindali *et al.* 2004).

In as much as high urban development density encourages compact urban form which reduces GHG emissions, high development densities cause localised climatic effects such as increased surface temperatures, urban heat-island effects as well as increased outdoor and indoor air pollution (Coutts *et al.* 2007). As noted by Neumann (2005), compact urban form is not singly sufficient for the improvement of urban sustainability. Therefore, other strategies such as enactment of policies related to public transportation, building regulations and reduction of household energy consumptions must be entrenched in the urban development agenda if sustainability has to be realised (Campbell-Lendrum and Corvalán, 2007).

Jabareen (2006) identifies seven pillars of urban sustainability as urban form, public transportation, development density, mixed land uses, diversity, passive solar design and greening. He used the concepts to compose a sustainable urban form matrix and concludes that compact city model is the most sustainable, followed by the eco-city, neo-traditional development and urban containment. Indeed doubling a neighbourhood's density combined with green buildings and smart-growth technologies decreases automobile usage by 30%, with a corresponding decline in gasoline consumption and GHG emissions (Walker and King, 2008; Brown and Southworth, 2008).

Sea-level rise exacerbated by increased GHG emissions, global warming, climate change and increased precipitation provides the linkage between urban development density and environmental quality. Climate change induced by GHG emissions and global warming is likely to increase the intensity of natural hazards such as storms, cyclones, tsunamis, flooding and erosion in the coastal cities (Satterthwaite *et al.* 2007; Pelling, 2003). According to IPCC (2007), a rise in global average temperatures by 2°C or more will exacerbate coastal flooding while a temperature rise of more than 3°C may result in loss of about 30% of global coastal wetlands and agricultural land as occasioned by water logging and salt stress. Other likely effects of temperature rise are inadequate freshwater supplies, destruction of property, loss of human lives and increased prevalence of environmental, malnutrition and cardio-respiratory diseases. Further to temperature variations associated with global warming and climate change inducing frequent and intense heat waves, it also results in additional cost of environmental control within buildings as well as increased concentration of air pollutants (Kovats and Akhtar, 2008; Awuor *et al.* 2008; Dodman and Satterthwaite, 2008).

It has been established that the urban heat island intensity rises with increasing urban population (Mihalakakou *et al.* 2004; Philandras *et al.* 1999; Torok *et al.* 2001; Hinkel *et al.* 2003). Towards this end, Oke (1973) developed a regression model for the North American and European cities which successfully explained 97% of the variability in urban heat island intensity and concludes that urban population is the single most significant variable influencing the intensity. The model further posits that for every increment of 100,000 people within a city, there is a corresponding 1°C temperature increase.

2.4.2 Effect of Urban Morphology (Land Cover and Land Use) on Environmental Quality

Oke (1987) notes that as urban areas evolve, buildings, roads and other infrastructure replaces open land and vegetation cover, making surfaces that were once permeable and moist become impermeable and dry with a corresponding increase in average temperatures above the hinterland. This is accentuated by materials used in the urban areas as roads, pavements and roofs. These materials have higher thermal energy absorption and retention capacity than the open spaces and vegetation cover which characterises the hinterlands. Since the materials and vegetation cover are not evenly distributed across the urban space, neighbourhoods often experience variations in surface temperatures, of which some neighbourhoods experience pockets of higher thermal values than others – a phenomenon known as the urban heat islands (Lemonsu and Masson, 2002). Further, anthropogenic heat emanating from residential, industrial and transportation land uses also contributes to urban heat island whose net effect is increased concentration of air pollutants (Givoni, 1998).

Alterations of urban land uses and land cover indirectly modify the urban climate (Chandler, 1976). For example, in America, surface temperature increases have been observed where extensive forests and other natural vegetations have been cleared (Skinner and Majorowicz, 1999). Accordingly, Kalnay and Cai (2003) estimates that over the past fifty years in the United States of America, land-cover changes have resulted in 0.27°C mean annual surface warming. Narisma and Pitman (2003) having observed the impacts of land cover change on temperatures in Australia, supported the postulations of Kalnay and Cai (2003). Other studies such as Sailor and Fan (2002) and Unger *et al.* (2001) concludes that for large urban areas, depletion of vegetation cover increases surface temperatures by between 1.67°C to 2.22°C during summer and by 5.6°C during winter.

It is now evident that as man continues to alter the natural ecology of cities through urban development processes; the long-term energy exchanges taking place within the boundary layer are affected. This is because the surface properties influence the atmospheric energy budget and by altering the surface conditions, man has inadvertently affected the atmospheric properties which influences local, regional and global climate through the cascading linkages of the atmospheric, terrestrial and hydrological systems (Khan and Simpson, 2001; Dixon and Mote, 2003; Rozoff *et al.* 2003). Therefore, global warming and climate change may not be attributed to the effects of the GHGs alone but also to the effects of heat islands occasioned by urbanization (Arnfield, 2003; Quattrochi and Ridd, 1998).

Vegetation mitigates the heating and polluting effects generated by the urban developments through a combination of shading and evaporative cooling effects. This is because vegetation through photosynthesis sequences carbon dioxide gas in the atmosphere thereby mitigating the greenhouse effects (Kubota and Ossen, 2008; Weng *et al.* 2004; Brovkin, 2002; Grimmond *et al.* 1996; Spronken-Smith and Oke, 1998). Vegetation facilitates cooling of the urban temperatures through evapo-transpiration which involves the conversion of solar radiation into latent heat of vaporisation. The latent heat of vaporisation then escapes with the sensible heat to the atmosphere (Fan and Sailor, 2005; Comrie, 2000;

Fujibe, 2003; Giridharan *et al.* 2004; Chudnovsky *et al.* 2004). Therefore, vegetation density differentials within urban neighbourhoods explain the surface temperature variations among the same. Vegetation also impacts on urban storm water management. For example in Baltimore, it was determined that neighbourhoods with 40% tree cover reduce surface runoff by 60% more than neighbourhoods without trees. Further, vegetation has effect on wind velocity and precipitation regime of urban areas which in turn affects the environmental quality of the same (Moll, 1997; Artis and Carnahan, 1982).

2.5 The Role of Geospatial Techniques in Urban Environmental Quality Studies

Advancements in the geospatial technology have brought tremendous changes in the study of urban morphology. The efficiency and effectiveness of the technology has enhanced its utility in the urban morphological studies in comparison to conventional surveying methods of mapping which are labour intensive, time consuming and unreliable in capturing spatio-temporal aspects of rapidly changing urban environments (Kerry, 2003; Billah and Gazi, 2004). Shosheng and Kutiel (1994) did a comparative study on the utility of geospatial techniques and the conventional surveying techniques in deriving information on land use and land cover variations and concludes that geospatial techniques are cost effective and efficient due to the technology’s ability to instantaneously acquire data of large areas and inaccessible regions. The increased computer power over the years has further enabled digital image processing of the satellite imageries. This has made Landsat and SPOT imageries useful in gathering land use and land cover information (Ehlers *et al.* 1990; Martin, 1986; Kam, 1994).

Urban morphological studies notably land use and land cover change detection has extensively applied geospatial techniques due to the alterations of the spectral radiance occasioned by the changes (Ursula *et al.* 2004). Macleod and Congalton (1998) posit that aspects of change which are important when monitoring urban land use and land cover are the nature of change, quantification of the changes and the spatial pattern of the changes. The eleven change detection algorithms (techniques) commonly used are mono-temporal change delineation, delta or post classification comparisons, multidimensional temporal feature space analysis, composite analysis, image differencing, multi-temporal linear data transformation, change vector analysis, image regression, multi-temporal biomass index, background subtraction and image ratio, all of which requires augmentation with field surveys for increased accuracy (Singh, 1989; Coppin and Bauer, 1996).

Ever since the launch of Landsat-1 in 1972, land use and land cover studies have been carried out on different scales using the imagery. Researchers have utilized satellite imagery in providing accurate information for identifying, classifying, mapping and monitoring the urban environments (Gastellu-Etchegorry, 1988; UNESCAP/UNDP, 1985). For instance, in the year 1982 waste land mapping of India was carried out on 1:1 million scale by NRSA using Landsat MSS imagery. Mahavir and Galema (1991) used SPOT imagery to monitor land use and land cover dynamics of Chiangmai - Thailand by visually interpreting panchromatic print of the imagery and achieved 92.7% overall accuracy. The study concludes that for a rapid and quantitative assessment of urban land use and land cover dynamics, SPOT imageries are accurate. Dimyati and Kitamura (1990) separately used Landsat-MSS and SPOT-HRV imageries to analyze the growth of Samarinda city in

Indonesia for the years 1984 and 1987 and the study's high level of accuracy legitimized the utility of geospatial techniques.

Brouwer *et al.* (1990) further validate the utility of the technology through the assessment of the urban growth of Barranquilla-Colombia using SPOT imageries of the city for the years 1982 and 1986. The findings of the study enabled the policy makers to redirect the urban development resources equitably. In the year 1985, the U.S Geological Survey produced 1:250,000 scale land use and land cover maps of Alaska using Landsat MSS imagery while the State of Maryland Health Resources Planning Commission used Landsat TM imagery to create a land use and land cover dataset for inclusion in Maryland Geographic Information Database (Fitzpatric, 1987; EOSAT, 1992; Dimyati, 1995). In the year 1992, the Georgia Department of Natural Resources undertook land use and land cover mapping using Landsat TM imagery (ERDAS, 1992). Prior to this, Odenyo and Pettry (1977) undertook land use and land cover mapping of Virginia City using Landsat MSS imagery and achieved 88% overall accuracy.

Recent studies have increasingly utilized geospatial techniques to model the relationships existing between urban morphology and the environmental quality parameters of surface temperature and air quality. Such studies include Sundarakumar *et al*. (2011), Mahmood *et al.* (2010), Tan *et al*. (2010), Weng (2001), Streutker (2002), Nichol *et al.* (2006), Weng (2003), Lo and Quattrochi (2003), Hawkins *et al.* (2004), Weng and Yang (2004), Borghi *et al.*(2000) and Hirano *et al.*(2004) among others. Voogt and Oke (2003) notes that improvements in the spatial and spectral resolutions of satellite sensors will continue to enhance the utility of remote sensing in the study of urban morphology and climatology.

This view is supported by Arnis *et al.* (2003) who posit that urban morphological and environmental quality parameters such as land use, land cover and surface temperatures can efficiently and effectively be derived from satellite remote sensing imageries to corroborate the effects of anthropogenic activities on urban environmental quality.

Despite geospatial techniques being vital in rapid and detailed survey, mapping, modelling and monitoring of urban environmental quality parameters, the accuracy of such analysis depends on the quality of the imagery used, schema and the classification procedure used as well as the technical and indigenous knowledge of the analyst on the study area. Daniel (2002) undertook a comparative study on land use and land cover change detection methods and concludes that there are merits to each method and that no single approach can wholly solve the inaccuracies associated with geospatial techniques. Sentiments have also been expressed on classification schema; that no single classification schema can universally apply in all the study scenarios thus there is a need to device a schema which represents a study area under consideration (Nasreen, 1999). To date, the best attempt at developing a general purpose schema compatible with remote sensing data has been by Anderson *et al.* (1976) and majority of the studies are a modification of the same.

2.6 Conceptual Model for the Relationship Existing between Urban Morphology and Environmental Quality

This study which examines the correlation between urban morphology and environmental quality takes cognisance of the principles underpinning urban morphological changes such as transportation, planning regulations, socio-economic and environmental factors. Elements of urban morphology such as vegetation and development density, land use, land cover and building configurations have profound effects on urban air quality and surface temperatures (Sundarakumar *et al.* 2011; Mahmood *et al.* 2010). Development densities influence household’s mode of transportation and energy consumption, all of which have implications on a city's GHG emissions. Similarly, industrial land uses associated with fossil fuel combustions generates GHGs (Tan *et al.* 2010). Replacement of urban surfaces with impervious materials such as concretes, asphalt and steel creates urban heat island effects which cause thermal discomfort and increased energy demand in the buildings (Jusuf *et al.* 2007; Lo *et al.* 1997). Further, the replacement of urban vegetation with impervious materials reduces evapo-transpiration with net effect being increased surface temperatures (Przekurat *et al.* 2011; Takeuchi *et al.* 2010).

Poor air quality occasioned by increased number of automobiles and industries in the urban centres is a significant environmental problem facing cities. This is because automobiles and industries generate GHGs, suspended particulate matter and sulphur dioxide. This is further complicated by the urban skyscrapers which attenuate wind velocity to restrict air pollutants to narrow canyons, subsequently raising the concentrations of the same. This is best mitigated by the vegetation which acts as sinks to air pollutants (Mölders, 2012). Vegetation also provides shade, creates aesthetic appeal and sense of community. Therefore, a development which diminishes the vegetation cover lowers the ability of the environment to reduce air pollution and to cool (Tan *et al.* 2010; Sekovski *et al.* 2012).

Interactions between forces underpinning urban developments such as the infrastructure, land markets, planning regulations and people’s inclinations to environmental conservation present a web of constraints to the achievement of sustainable cities. As illustrated by

Figure 2.4, achievement of urban sustainability requires implementation of multiple innovative strategies entailing re-orientation of institutions and provision of adequate transportation and other urban infrastructure, enhancement of socio-economic developments, community, public and private sectors participation, civil society involvement, institutional capacity building for planning both at the national and county government levels. Other strategies should include the promotion of green infrastructure, innovative urban design as well as tightening legislations on protection of urban ecosystems such as the green belts, trees and river restoration. From the foregoing, it is evident that various factors act in concert to influence the urban environmental quality. These can be categorised as indirect, intervening and direct variables. Examples of these variables include: -

Indirect Variables or the Urbanisation Factors

- Economic perception and societal aspirations
- Urbanisation rate
- Effects of globalisation
- Development technology and planning regulations

Intervening Variables

- Urban population size and distribution
- Land costs and property sizes
- Climate of the region where the city is located

Direct Variables

- Urban development density and construction materials used
- Land uses (industrial and transportation)
- Building configuration
- Street orientation and configuration
- Land cover changes (vegetation depletion)
- Energy consumption levels

2.7 Conclusion

There exist many approaches for the improvement of the urban environmental quality. However their adoptions in the developing countries are weak due to subtle web of constraints operating through institutional arrangements, infrastructure, incentives and access to information. This can be mitigated through simultaneous actions across many fronts and by different actors. Towards this end, this study demonstrates the role of geospatial techniques in modelling the relationship existing between urban morphology and the environmental quality using five related parameters namely; development density, land uses, biomass index, air quality and surface temperature values.

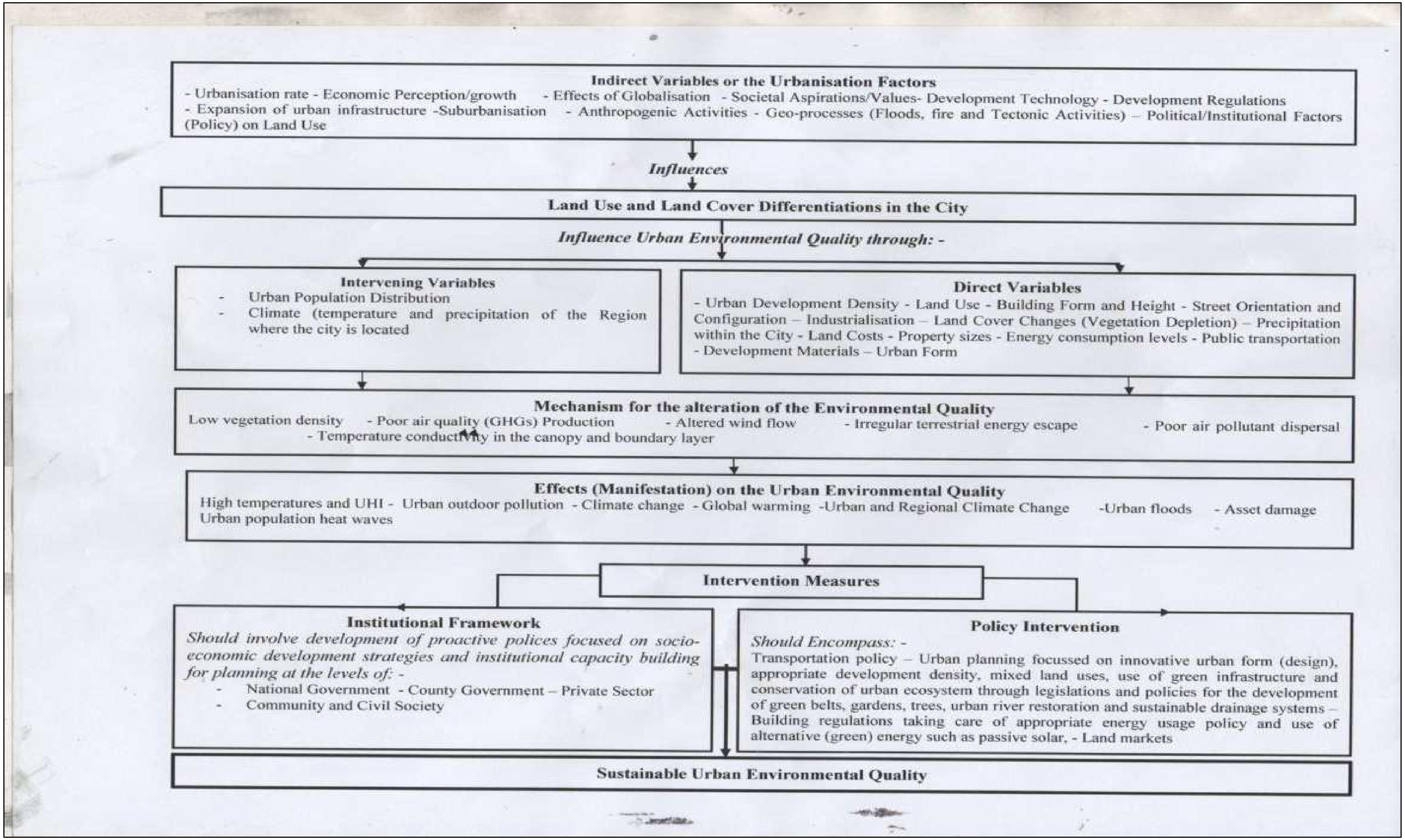

Figure 2.4. Conceptual Model for the Relationship Existing between Urban Morphology and Environmental Quality

CHAPTER THREE

STUDY METHODS AND MATERIALS

3.1 Introduction

This study adopted both descriptive and quantitative designs. While descriptive designs explain who, what, when and how a phenomenon occurs over space, quantitative designs explain how various factors affecting an occurrence of a phenomenon are related (Cooper *et al.* 2003). This chapter discusses the approaches and the materials utilised for the fulfilment of the study objectives. It entails discussions on the target population, sampling techniques, data needs and sources, techniques and tools of data capture and processing as well as measures undertaken to enhance validity and reliability of the data collected and information presented.

3.2 Target Population and Sampling Procedures

All the 30 development zones as detailed out by the Nairobi City County Government constituted the target population. Except for the air quality, sampling was not undertaken for the vegetation density, development density, land uses and surface temperatures.

3.3 Evaluating the Impact of Land Use and Land Cover Change on Land Consumption Rate and Land Absorption Coefficients

This study established the nature, magnitude, pattern and trends of land use and land cover changes in the city between the years 1988 and 2015. This was imperative in aiding the calculations of Land Consumption Rate (LCR) and Land Absorption Coefficients (LAC) for the city which are significant indicators of the effects of urbanisation on environmental quality, global warming and climate change.

3.3.1 Data Needs and Sources

This study utilised cloud-free satellite imageries of the city as follows: - Landsat 5 TM imageries - Band 2 (Green: 0.52 µm –0.60 µm), Band 3 (Red: 0.63 µm - 0.69 µm) and Band 4 (the NIR: 0.76 µm – 0.90 µm) for the years 1988 and 1995 while Landsat ETM+ imageries at the same bands were used for the years 2000, 2005, 2010 and 2015. In all the cases, band combinations comprising of Green, Red and Near Infra-Red were used due to the combination's appropriateness in discriminating built up areas, water bodies and vegetation categories as well the ease at which it enables land use and land cover change detections. The spatial resolutions of the bands under consideration are 30m. While the Landsat imageries used in this study were procured from the archives of the United States Geological Survey (USGS) through the Nairobi based Regional Centre for Mapping of Resources for Development (RCMRD), secondary information on the city's population for the years under consideration were extracted from the National Population Census Reports authored by the Kenya National Bureau of Statistics (KNBS). Other secondary information used in this study included 1: 50,000 scale topographical maps of the city obtained from the Survey of Kenya (SoK) as well as various planning reports obtained from the Planning Department of the Nairobi City County Government.

3.3.2 Data Processing and Accuracy Assessment

As illustrated by Figure 3.1, unsupervised digital image processing technique was used in land use and land cover classification and change detection. This procedure involved image pre-processing, design of classification schema, image classification, accuracy assessment and change detection. As illustrated by Table 3.1, the imageries were geo-referenced using

11 Ground Control Points whose coordinates were obtained from 1:50,000 scale topographical maps of the study area.

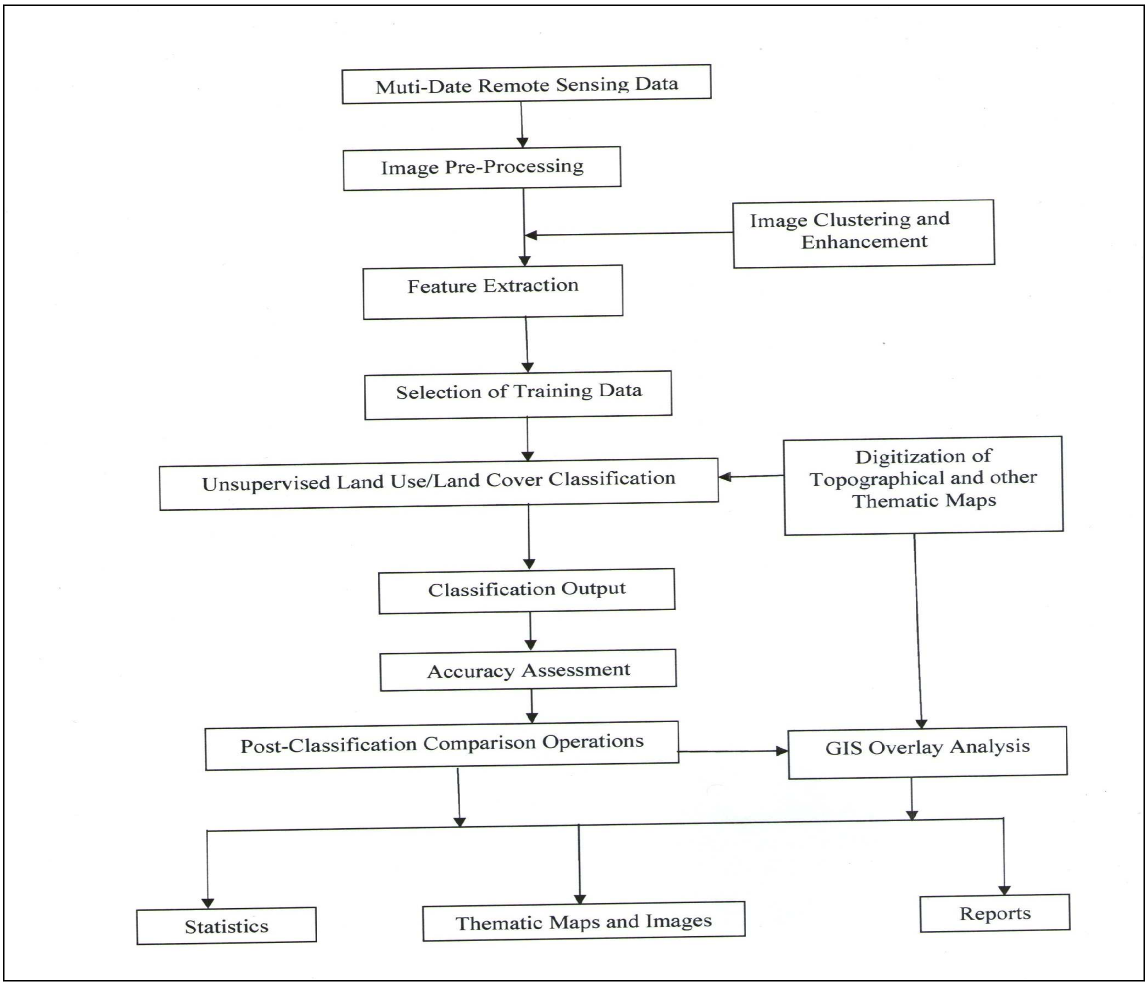

Figure 3.1. Procedures used in the Analysis of Land Cover and Land Use Change using Times Series Satellite Imageries.

The unsupervised method of imagery classification employed by this study relies on spectral and radiometric characteristics of land uses and land covers. Since the procured imageries covered the city and its environs, extractions of the study area from the imageries of the city for the years under consideration were undertaken using ArcGIS 10.3 Software. The extracted imageries were thereafter exported to ILWIS 3.6 Academic environment in TIFF Format.

Table 3.1. The Tie-Points Used for Geo-Referencing

Points	Coordinates	
	X (Longitude)	Y (Latitude)
A	36.719	-1.227
B	37.045	-1.181
C	36.991	-1.286
D	36.922	-1.435
E	36.657	-1.325
F	37.058	-1.287
G	36.683	-1.362
H	36.931	-1.158
I	36.778	-1.181
J	36.928	-1.321
K	36.891	-1.364

Upon launching the extracted imageries of the city in the ILWIS 3.6 Academic environment, colour separation operations were undertaken. This was followed by rebuilding of the colour composites using band combination 4-3-2 (Near Infra-red, Red and Green). Other operations undertaken to enable the assignment of pixels to various land use and land cover classes were creation of map list, sample set and classification domain. Upon assigning at least 2500 pixels per land use and land cover category, the classified imageries were assessed for accuracy through cross-tabulations of the same with sample sets. Maps generated from this analysis met the minimum USGS and Congalton (1991) accuracy requirement of at least 85%. The classified imageries were then exported back to ArcGIS 10.3 environment for polygonisation, area computations, layout designs and labelling.

Post-classification comparison approach which utilised cross matrix function of ILWIS 3.6 Academic Software was employed for the detection of land use and land cover changes. The main advantage of this method is its capability of providing simultaneous information on the nature, magnitude, trend, pattern and rate of changes. The procedures involved cross-tabulating the classified imageries of the years 1988 and 1995, 1995 and 2000, 2000 and 2005, 2005 and 2010 as well as the years 2010 and 2015. This culminated into three outputs namely; tables showing the nature of the changes, histogram transformation revealing magnitude (percentage) of the changes and the raster imageries depicting the spatial distributions of the same. The raster imageries of the detected changes were further exported to ArcGIS 10.3 environment for polygonisation and layout designs.

Table 3.2. Land Use and Land Cover Classification Schema

	Classes	Description
i.	Urban Built-Up Areas/Open/Transitional Areas	Residential, commercial and services, industrial, transportation, communication and utilities. Open or Transitional areas are bare-lands which are exposed areas and quarries
ii.	Agricultural/Grass/Secondary Growth and Riparian Vegetation	Cropland, coffee plantations, horticultural farms, greenhouses, other agricultural crops, well – kept grass as well as the riparian vegetation
iii.	Forests	Evergreen forests, mixed forests with higher density of trees, little or no under storey vegetation
iv.	Rangeland and Shrubs	Sparsely distributed scrub species. Ground layer covered by grass. Species include *Acacia mellifera* and *Lawsonia inermis.* The shrubs constitutes perennial grass under storey, trees rarely above 5m, impoverished woodlands near the forests. Other dichotomy entails very sparsely distributed, low-lying scrub species. Usually less than 1m, typical species include *A. reficiens, Salvadora dendroides,* ground usually bare or covered by annual grasses.
v.	Water Bodies	Rivers, natural dams, reservoirs and waste water lagoons

Source: (Modified from Anderson *et al*. 1976)

As illustrated by Table 3.2, a modified version of Anderson *et al.* (1976) land use and land cover classification schema was adopted by this study. The need to consistently discriminate the land uses and land covers irrespective of seasonal variations informed the decision on the five land use and land cover classes used in the schema. This is further supported by Yang and Lo (2002) who notes that when undertaking digital image processing for land use and land cover variations, there is need to limit the number of classes used in the schema so as to avoid the spectral confusion which may occur due to several land uses and land covers having closer spectral signatures.

3.3.3 Calculation of Land Consumption Rate and Land Absorption Coefficients

According to Yeates and Garner (1976), Land Consumption Rate (LCR) and Land Absorption Coefficient (LAC) functions are stated as 3.1 and 3.2 respectively.

$$\mathbf{LCR = A/P} \quad \text{(3.1)}$$

Where:-

A = Areal extent of the city under urban built up, open and transitional areas in hectares.

P = Population of the city at a particular date.

$$\mathbf{LAC = (A_2 - A_1)/\,(P_2 - P_1)} \quad \text{(3.2)}$$

Where:-

A_1 and **A_2**: The areal extents of the city under urban built up, open and transitional areas in hectares for the early and later years.

P_1 and **P_2**: Population of the city for the early and later years.

While LCR is a measure of progressive spatial expansion of a city (urban sprawl) as evidenced by increase in the amount of land under urban built up, open and transitional areas for the successive years of study, LAC is a measure of change in the conversion of urban land to built up, open and transitional land uses and land covers within a specified time period by each unit increase in urban population. The population growth rates used for the calculations of LCR and LAC were 4.7% per annum for the years between 1980 to 1989 and 4.5% per annum for the years between 1990 to 2015 (Government of Kenya, 2012). Function 3.3 was used for population projections.

$$\mathbf{P_n = P_o(1+r)^t} \quad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(3.3)}$$

Where: -

P_n = Estimated population at a given year

P_o = Base year population

r = Growth rate

t = Number of years projecting for

3.3.4 Presentation of Findings on Land Use and Land Cover Change, Land Consumption Rate and Land Absorption Coefficient

Classified land uses and land covers for the years 1988, 1995, 2000, 2005, 2010 and 2015 as well as the nature of the detected changes are presented inform of maps. While information on the magnitude of land uses and land covers for the years under consideration and the detected changes are summarized inform of tables, graphs are used to present the trends of land uses and land covers. The LCR and LAC trends are presented in tabular and graphical formats.

3.4 Assessment of Development Density and Land Use Variations

3.4.1 Data Needs and Sources

The Nairobi City County Government has divided the city into 30 development zones with varying development densities and land uses. Multi-Spectral IKONOS imagery (Bands 2, 3 and 4) together with the development zoning map procured from the Nairobi City County

Government were used for land use and development density analysis. The imagery was acquired on 19th July 2015 and procured from the European Space Agency through the Nairobi based Regional Centre for Mapping of Resources for Development.

3.4.2 Data Processing and Accuracy Assessment

The IKONOS imagery used in this study was procured when it had already been pre-processed and rectified. The study area had to be extracted from the imagery for the procured imagery covered the city and its environs. The analysis of development densities was undertaken through polygonisation of the developed surfaces from the extracted imagery and superimposing the same with the zoning boundaries. The development densities were computed through aggregating areas of developed surfaces within a development zone as a ratio of a development zone's area. The computed development densities for the 30 development zones were further transformed into numerical (nominal) values ranging from 1 to 10. Since high development densities compromises urban environmental quality as compared to low development densities, high development density zones were assigned low (1) numerical values while low development density zones were assigned high (10) numerical values. This information is presented in form of a map showing the spatial distribution of the city's environmental quality based on development densities.

Visual image interpretation technique utilising 9 elements notably the shape, size, shadows, site, tone, texture, pattern, height and association was used to analyse land use distribution within the city. The identified imagery elements which represent land uses were polygonised into a land use map. To assess the accuracy of the established land uses, random ground truthing aided by a hand-held GPS was undertaken. As informed by environmental quality implications of the land uses, the identified land uses were assigned nominal values ranging from 1 to 10. In this regard, land uses such as industrial users known to compromise the environmental quality were assigned the lowest nominal values while forests and parks were assigned the highest nominal values. To arrive at a nominal value for a development zone based on land uses, areas constituting different land uses within a development zone were multiplied by the assigned nominal values of the land uses. The products were further divided by the areas of the development zones and aggregation of the same undertaken. This information is spatially presented inform of a map.

3.4.3 The Relationship Existing between Urban Form and Environmental Quality

To arrive at nominal values for the development zones based on urban form (development densities and land uses), computation of averages based on the sums of the nominal values for the development densities and land uses per development zone was undertaken. This was further transformed into a map showing the city's environmental quality distribution based on the urban form. Similar procedures were followed by Nichol *et al.* (2006) when undertaking the assessment of urban environmental quality of Hong Kong City.

3.5 Determination of Biomass Index within the City

Vegetation influences urban environmental quality due to their ability to purify air and to moderate the surface temperatures. However, it has been established that the biomass component of the vegetation is the most significant determinant of the degree to which vegetation influences energy flow and ecosystem purification. This made biomass index or the vegetation density be the focus of this study.

3.5.1 Data Needs and Sources for Biomass Determination

Remote sensing techniques for mapping urban vegetation parameters such as the total green spaces and the percentage of tree canopy combines higher spatial resolution infrared imageries such as the IKONOS, GEO-EYE, QUICK-BIRD with photographs and fieldwork. Although such methods are expensive, they present the best option for the medium resolution satellite imageries such as SPOT and Landsat lacks spatial details to detect fragmented urban vegetations (Nowak *et al.* 1996). As noted by Fung and Siu (2001) who used Normalised Difference Vegetation Index (NDVI) for the assessment of Hong Kong city's vegetation change over time, Landsat imagery is only useful in conducting generalised surveys of green spaces and vegetation vigour, but fails to establish the vegetation type. The above being the case, IKONOS imagery as augmented by the development zoning map of the city was utilised to facilitate the computation of the biomass index.

3.5.2 Quantifying Biomass

Since the multi-spectral IKONOS imagery used in this study covered the city and its environs, it was imperative that extraction of the study area from the imagery be undertaken. Upon accomplishment of the above, classification and polygonisation of the vegetation types were undertaken. To facilitate the computation of the Biomass Index or the Vegetation Density (VD), the development zone boundaries were superimposed on the generated vegetation cover map. The VD for individual vegetation type was computed using equation 3.4 adopted from Nichol *et al.* (2006).

$$\%VD = 100 \frac{WvLv}{L} / \sum_{v} Wv \qquad \text{………………………………..} \ \mathbf{(3.4)}$$

Where: -

W_v : Weighting for each vegetation type *v;*

L_v : Area covered by a vegetation type *v* in a zone;

L: Total Area of a zone.

Vegetation classifications and weightings were undertaken as shown in Table 3.3. Plots with 100% short grass cover were assigned a VD value of 20% while forested plots were assigned a VD value of 90%. Others were as follows: small trees 70%, shrubs 60% and tall grass 40%. Average VD values for each development zone were calculated and converted into numerical values ranging from 1 to 10. In acknowledging that vegetation covers with higher VD values create better environmental quality, development zones with high average VD values were assigned higher (10) nominal values and *vice-versa.* This information was further transformed into a map showing the city's environmental quality distribution based on biomass index.

Table 3.3. Vegetation Weightings

Type	**Weighting**	**Description**
Short grass	0.2	Green grass lower than 0.5 m
Tall grass	0.4	Green grass higher than 0.5 m
Shrub	0.6	Short and woody plant with woody (non-green) stems from the base
Small Tree	0.7	Woody plant with trunk diameter < 0.3 m
Large Tree	0.9	Woody plant with trunk diameter > 0.3 m

Source: (Adopted from Nichol *et al.* 2006)

3.6 The Assessment of Temperature Variations within the City

3.6.1 Data Needs and Sources

To establish the relationship existing between urban surface temperatures, land uses and land covers, thermal information provided by Landsat 5 TM imageries of the years 1988 and 1995 as well as Landsat ETM+ imageries of the years 2000, 2005, 2010 and 2015 were used. In all the cases, the thermal band (*Band 6 -This band used to be 60m resolution but products processed after 25th February 2010 are re-sampled to 30m pixel sizes*) and the visible bands (Band 3 and Band 4) were utilised. This was augmented by land use and land cover information of the same years.

Table 3.4. The Spectral and Spatial Resolutions of the Procured Imageries

Band No	Wavelength (µm)	Spectral Region	Spatial Resolution (m)
2	0.52 – 0.60	Green	30
3	0.63 – 0.69	Red	30
4	0.76 – 0.90	Near Infra-Red	30
6	10.4 – 12.5	Thermal Infra-Red	30

3.6.2 Data Processing and Presentation of the Surface Temperature Models

The study adopted Radiative Transfer Method in estimating the urban surface temperatures from the satellite imageries under consideration. While the first step within Radiative Transfer Method involved the extraction of Digital Numbers (DNs) from the Thermal Infra-Red (TIR) imageries, the second step involved the conversion of DNs to spectral radiance using function 3.5.

$$\mathbf{L\lambda = 0.0370588 * DNs + 3.2} \quad \text{..} \quad \mathbf{(3.5)}$$

Where: -

Lλ:	The Spectral Radiance,
DNs	Digital Numbers
0.0370588:	The Gain Constant (the gradient of the satellite’s pre-launch radiance)
3.2:	The Bias Constant (the spectral radiance of the DN at zero)

The conversions of the DNs to spectral radiance values were undertaken to correct the effects of atmospheric attenuations such as reflectance, absorption and scattering which create haziness in the imagery to consequently reduce the contrast. For example, scattering creates adjacency effect in which radiance recorded for a given pixel partly incorporates the scattered radiance from the neighbouring pixels.

The third step involved the calculation of the satellite temperature values of the imageries used. This was done using function 3.6.

$$\mathbf{TEs = (K_2)/L_n \{(K_1/ L\lambda) +1\}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.6)}$$

Where: -

TEs	Satellite temperature values
Lλ:	The Spectral Radiance
L_n	Natural Logarithm
K_2 and K_1	The calibration constants whose values are

	Landsat TM	**Landsat ETM+**	
K_1	607.76	666.09	$mWcm^2$
K_2	1260.56	1282.71	K

The fourth step involved the calculation of the NDVIs using function 3.7.

$$\mathbf{NDVI= (R\ band\ 4-R\ band\ 3)/(R\ Band\ 4+R\ Band\ 3)} \quad \ldots\ldots\ldots\ldots\ldots \mathbf{(3.7)}$$

Where: -

NDVI	Normalised Difference Vegetative Index
R band 4:	Land Surface Reflectance in the Near Infra-Red Band
R band 3:	Land Surface Reflectance in the Visible Bands.

The fifth step involved the calculation of the Emissivity (ε) values from the NDVIs using function 3.8.

Emissivity (ε) =1.0094 + 0.047* L_n(NDVI) ……………………...…….(3.8)

Finally, surface temperature values (Ts) were computed using function 3.9.

$$\mathbf{Ts = (TEs)/ \{1+ [\lambda * (TEs/\rho)]\, L_n\varepsilon\}} \quad \text{………………………….. (3.9)}$$

Where:-

Ts: Surface Temperatures Values

TEs: Satellite temperature values

L_n: Natural Logarithm

ε: Emissivity Value

λ: The wavelength of the emitted radiance = 11.5µm (Markham and Baker, 1985);

ρ = hc/σ = 1.438×10^2 mK;

σ =Stefan Boltzmann’s constant ($5.67 \times 10^{-8} Wm^{-2}K^4$),

h = Planck’s constant (6.626×10^{-34}Js)

c =2.998×10^8 m/s

The information is presented in form of surface temperature maps for the years under consideration. For the year 2015, calculation of average surface temperature values per development zone was further undertaken. As informed by the implications of the surface temperature values on the environmental quality, the average surface temperatures for the development zones were further converted into nominal values ranging from 1 to 10. Development zones with low average surface temperature values were assigned higher (10) nominal values and *vice-versa*. This information was converted into a map showing the city’s environmental quality distribution based on surface temperature values.

The relationship existing between urbanisation, global warming and climate change was determined through the establishment of the strength of the relationship existing between surface temperatures, the size of land under built-up, open and transitional areas and the size of land under vegetation cover for the years under consideration. This was done through multivariate regression analysis, computation of correlation coefficient, *t*-test and the Analysis of Variance (ANOVA). While ILWIS Academic 3.6 Software was used for radiometric enhancement, ArcGIS 10.3 was used in the production of surface temperature maps. Microsoft Excel 2010 Software was used in calculating the spectral radiance, satellite brightness, emissivity and the surface temperatures while the Statistical Package for the Social Scientists (SPSS) Software was used in establishing the strength of the relationship existing between surface temperatures, built environment and the vegetation cover.

3.7 The Assessment of the Spatial Variations in Air Quality within the City

Air sampling was undertaken to ascertain the concentrations of SPM, carbon dioxide, sulphur dioxide and nitrogen dioxide gases within the city. For the purposes of collecting air samples, sample sites were established through regular systematic point technique which involves the subdivision of the city into regular square cells each measuring 2.0 kilometres. Systematic random sampling technique of three cell intervals in all the directions was thereafter utilised in deciding the grid cells from whose centres air samples were picked (Franzen, 2011). In this regard, the city's development zones were superimposed with square grid cells and coordinates of the centres of the targeted grid cells (sample sites) established per development zone using ArcGIS 10.3 Software. The identification of sample sites were done through hand held GPS. A total of 150 sample sites were established and air samples collected for laboratory analysis using Spectrex PAS-500 hand held air samplers. Granted that some development zones such zone 20A (Karura Forest), 20G (Nairobi National Park), 20F (Jomo Kenyatta International Airport) and 20J (Ngong Forest) among others are homogeneous in terms of development densities and land use types within them, few samples were taken from the zones despite them being larger in size. Therefore, apart from the sizes of a development zone, the decision on the number of sampling sites established per development zone was further influenced by development densities and the heterogeneity of the land uses within the zones.

Laboratory readings for the gaseous concentrations were made for each sampled cell and averages computed by gas type per development zone as illustrated by Table 3.5. The averages were further converted into nominal values ranging from 1 to 10 and aggregates of the same computed per development zone. This facilitated calculations of average air quality nominal values for the development zones. In acknowledging the implications of gaseous concentrations on environmental quality, low gaseous concentrations were assigned higher (10) nominal values and *vice-versa*. Therefore, development zones with low aggregate and average gaseous concentration nominal values correspond to better environmental quality.

This study adopted spatial interpolation technique which relies on Geographical Information System to generate continuous surfaces from point measurements. The technique is premised on *Tobler's First Law of Geography* which states that *"The closer together two points are in space the more likely the points are similar and influence each other"*. As informed by simplicity, accuracy and the need for outputs which are sensitive to clustering and presence of outliers, Inverse Distance Weighting (IDW) technique of spatial interpolation was used in modeling the distribution of the gaseous concentrations into continues surfaces. In this technique, the weights of the measurements diminish as a function of distance, hence the name Inverse Distance Weighted technique (Li and Heap, 2008). While the results of the computations are presented in tabular format, the various gaseous concentrations are spatially presented in form of maps using ArcGIS 10.3 Software.

Table 3.5. Sample of the Form Used for Recording Air Quality Values per Development Zone

Development Zones	Average Carbon Dioxide Values	Carbon Dioxide Nominal Values	Average Nitrogen Dioxide Values	Nitrogen Dioxide Nominal Values	Average Sulphur Dioxide Values	Sulphur Dioxide Nominal Values	Average Suspended Particulate Matter Values	Suspended Particulate Matter Nominal Values	Total Air Quality Nominal Values	Average Air Quality Nominal Value
1										
2										
3										
4										
. .										
20J										

3.8 An Integrated Urban Environmental Quality Model for the City

In acknowledging that urban environmental quality measurement requires integration of multiple parameters, this study integrated urban development density, land use, vegetation density, air quality and surface temperatures in modelling the environmental quality distribution of the city. This was done using numerical surrogates ranging from 1 to 10 as earlier stated. As illustrated by Table 3.6, the aggregate nominal values for the development zones were arrived at through aggregation of the nominal values of the variables under consideration. This is further presented in form of an integrated spatial model showing environmental quality variation within the city.

Table 3.6. The Form Used for Presenting Environmental Quality Values per Development Zone

Development Zones	Land Use (Urban Spatial Structure) Nominal Values	Development Density Nominal Values	Vegetation Density Nominal Values	Surface Temperature Nominal Values	Average Air Quality Nominal Values	Aggregate Urban Environmental Quality Nominal Values	Average Urban Environmental Quality Nominal Values
1 **2** **.** **.** **.** **.** **.** **.** **.** **.** **20J**							

Bivariate and multivariate models were used in establishing the relationships existing between the variables under consideration. This was done through the computations of the correlation coefficients of the relationships, which culminated into correlation matrix table. To determine the significance of the relationships and consistencies of the same, *t*-test and ANOVA were undertaken with levels of significance (α) and confidence being 5% and 95% respectively. In this endeavour, SPSS Software was used for statistical analysis. The correlation coefficients and the coefficients of determinations were calculated using *Pearson's Product Moment Correlation Coefficient Index* stated as function 3.10.

$$\mathbf{r} = \frac{\sum[X-\dot{x}][Y-\dot{y}]}{\sqrt{\sum[X-\dot{x}]^2}\,\sqrt{\sum[Y-\dot{y}]^2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.10)$$

Where: -

r = Correlation Coefficient

X = The Independent Variables

$\dot{x}$ = The Mean of the Independent Variables

Y = The Dependent Variables

$\dot{y}$ = The Mean of the Dependent Variables

Regression Models were established through equations 3.11, 3.12 and 3.13.

$$(\grave{Y}-\dot{y}) = \frac{(r)\delta Y}{\delta X}[X-\dot{x}] \quad \text{……………………………….……..(3.11)}$$

Where: -

$\grave{Y}$ = Estimated Dependent Variable

r = Correlation Coefficient value

X = The Independent Variables

$\dot{x}$ = The Mean of the Independent Variables

Y = The Dependent Variables

$\dot{y}$ = The Mean of the Dependent Variables

δY = The standard deviation of the dependent variables **(Y)**

δX = The standard deviation of the Independent variables **(X)**

The **δY** and **δX** are calculated as: **-**

$$\delta Y = \sqrt{\frac{\sum[Y-\dot{y}]^2}{n-1}} \quad \text{……………………….…..……….(3.12)}$$

$$\delta X = \sqrt{\frac{\sum[X-\dot{x}]^2}{n-1}} \quad \text{……………………..….……….(3.13)}$$

Hence the regression model is stated as function 3.14

$$\Upsilon = a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 \ldots\ldots + \acute{\varepsilon} \quad \text{…..……………………..…… (3.14)}$$

Where:-

Υ = The urban environmental quality

X_s= The independent variables

a_s **=** Coefficient of determinations of the independent variables

$\acute{\varepsilon}$ **=** The error term

The tests of significance of the established correlations were undertaken using *t*-test stated as either function 3.15a or 3.15b.

$$\mathbf{t} = \frac{r}{\sqrt{[1-r^2/n-2]}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.15a)}$$

Or

$$\mathbf{t} = \frac{(r)[\sqrt{n-2}]}{\sqrt{[1-r^2]}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.15b)}$$

Where: -

t = The calculated *t*-value

r = Correlation Coefficient Index

n = Sample Size

With level of significance (α) being 0.05 and the degree of freedom (df) being n-2, null (H_0) hypothesis was rejected if the calculated-t value was greater than the critical or the tabulated-t value. The ANOVA or the F-test whose procedures are shown in Table 3.7 facilitated the decisions as to whether the witnessed correlations occurred by chance (spurious) or not.

Table 3.7. The Analysis of Variance (ANOVA)

Source of Variation	Degree of Freedom	Sum of the Squares	Mean of the Squares
Accounted for by the Regression Line (SSR)	1	$SSR = \sum(\grave{Y}-\dot{y})^2$	SSR/1 $SSR = \sum(\grave{Y}-\dot{y})^2$
Accounted for by the Residuals (SSE)	n-2	$SSE = \sum(Y-\grave{Y})^2$	SSE/n-2 $SSE = \frac{\sum(Y-\grave{Y})^2}{n-2}$
Accounted for by the Mean (SST)	n-1	$SST = (Y-\dot{y})^2$	Nil

Source: (Hammond and McCullagh, 1978)

The F-values were calculated using either function 3.16a or 3.16b.

$$\mathbf{F} = \frac{\mathbf{SSR/1}}{\mathbf{SSE/n-2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.16a)}$$

Or

$$\mathbf{F} = \frac{\sum(\grave{Y}-\dot{y})^2}{\sum(Y-\grave{Y})^2/n-2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.16b)}$$

With level of significance (α) being 0.05 and degree of freedom being n-2, the null (H_0) hypothesis was rejected if the calculated F-value was greater than the critical F-value.

3.9 Quality Assessment – Validity and Reliability

Validity is the degree to which information presented by a study represents phenomenon under investigation. The main components of validity are accuracy (position, thematic and temporal accuracy), precision (spatial, thematic and temporal), resolutions, logical consistencies and completeness (coverage, classification and model completeness) of data used and information presented by the study. In this study, validity was safeguarded by pre-testing of data collection instruments, training of the Field Assistants on appropriate use of the instruments as well as proper data entry (particularly data obtained through *in-situ* measurements). On the same note, secondary information particularly the satellite imageries used in the study were procured from internationally accredited organisations notably the USGS and the European Space Agency while the development zoning map and other allied maps were sourced from Nairobi City County Government and the Survey of Kenya. Reliability on the other hand refers to a measure of the degree to which research instruments yield consistent results. In this study, instruments used for *in-situ* measurements were granted equal exposure time. This was further accentuated by training of Research Assistants on accurate data capture and entry.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

Land uses compete for locations within cities and in the process of accommodating the same, cities experience both urban sprawl and internal densification which adversely affects their environmental quality. For example, clearance of land for urban developments reduces vegetation covers which are carbon sinks and moderators of surface temperatures. This raises the concentration of air pollutants and surface temperatures as well as influencing global warming and climate change. This chapter presents findings on the relationship existing between the morphological attributes of the city and the environmental quality.

4.2 Land Use and Land Cover Change in Nairobi for the Period between 1988 to 2015

The land use and land covers of Nairobi for the years 1988, 1995, 2000, 2005, 2010 and 2015 are shown in Figures 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6 respectively. While quantification of land uses and land covers is summarized in Table 4.1, trends of the same are presented in Figure 4.7. The area of the city under built-up, open and transitional land cover increased from 73.08 km^2 in the year 1988 to 228.65 km^2 in the year 2015. While agricultural, grass, secondary growth and riparian vegetation which occupied 126.82 km^2 of the city in the year 1988 marginally increased to 189.73 km^2 in the year 2015; forests have shown mixed gains and loss. In the year 1988, the area of the city under forest cover was 59.63 km^2. This increased to 122.41 km^2 in the year 1995 and thereafter declined to 63.63 km^2 in the year 2000. The decline is attributed to the clearance of the forests for urban developments which characterised the periods between the years 1995 to 2002. This situation was reversed in the year 2003 when the new government re-energised strategies geared towards increasing the forest cover in the country. The strategies included the degazettements and clearance of illegal structures within the forest reserves. The forest cover has since increased from 63.63 km^2 in the year 2000 to 93.44 km^2 in the year 2015. Similarly, the area of the city under rangeland and shrub vegetation cover steadily declined from the year 1988 when it covered 453.99 km^2 of the city to 200.30 km^2 in the year 2015.

As illustrated by Figures 4.8 to 4.12 and Table 4.2, land use and land cover conversions took place in the city within the study period. Notably, there has been a marked decline in agricultural, grass, secondary growth, riparian, rangeland and shrubs as well as forest covers which is attributed to the expansion of the urban built-up, open and transitional areas. The steady decline in the ratio of the city under vegetation cover to the area under urban built-up, open and transitional lands has significant implications on urban air quality and surface temperatures.

The built-up, open and transitional areas have expanded with discontinuous patches along Thika, Kangundo and Mombasa Roads. This has been occasioned by the distribution of the transportation arterials and the *ad hoc* planning which has characterised the city over the years. The *ad hoc* planning has encouraged rapid revisions of land use zoning policies (minimum plot sizes, ratios and coverages), land speculations as well as land use and land cover changes. While the revisions have tended to favour increased development densities, conversions of productive agricultural lands to residential, industrial and commercial developments, the distribution of transportation arteries have significantly determined the rate of urban growth and the distribution of economic activities.

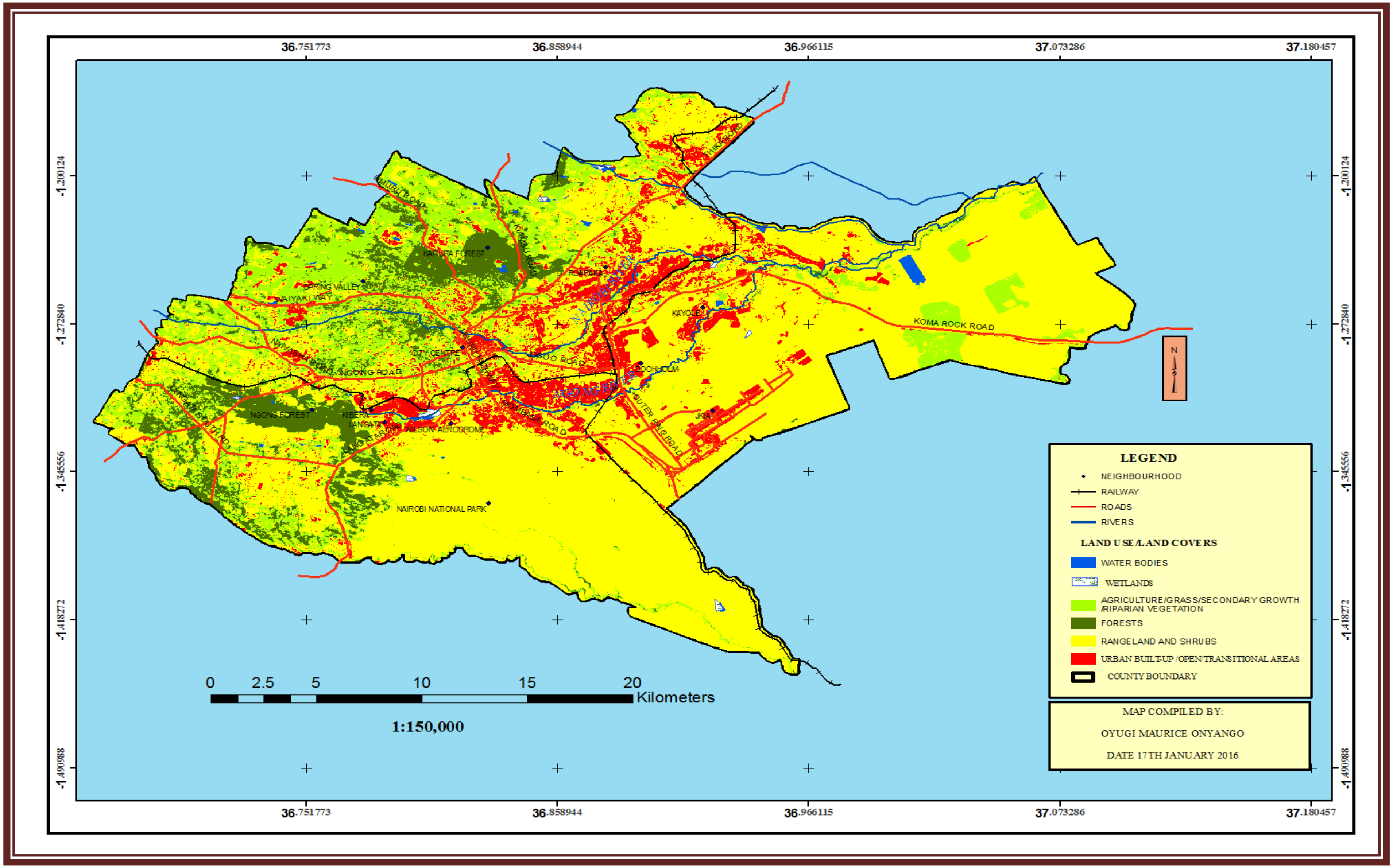

Figure 4.1. Classified Land Use and Land Cover Map of Nairobi for the Year 1988.

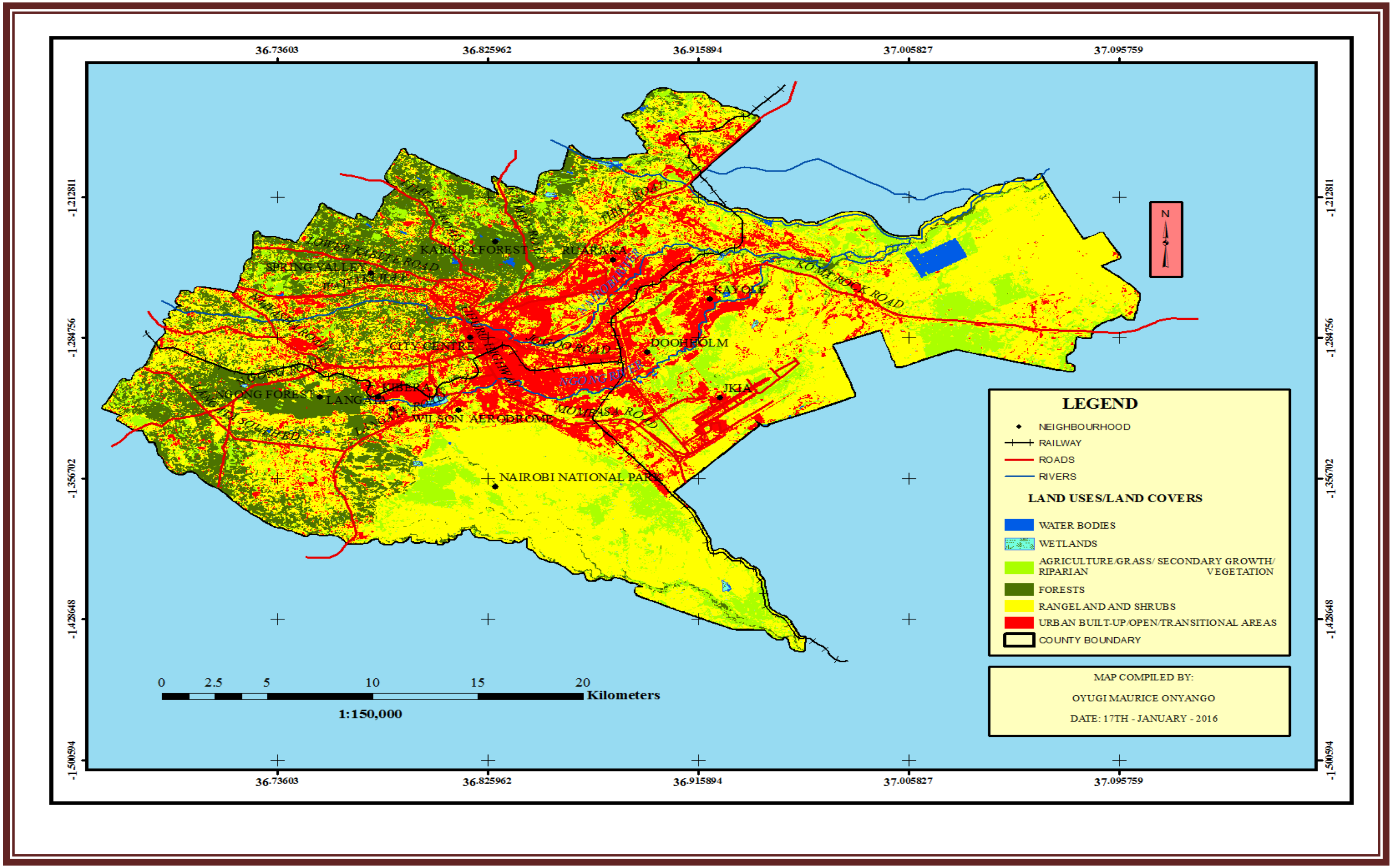

Figure 4.2. Classified Land Use and Land Cover Map of Nairobi for the Year 1995.

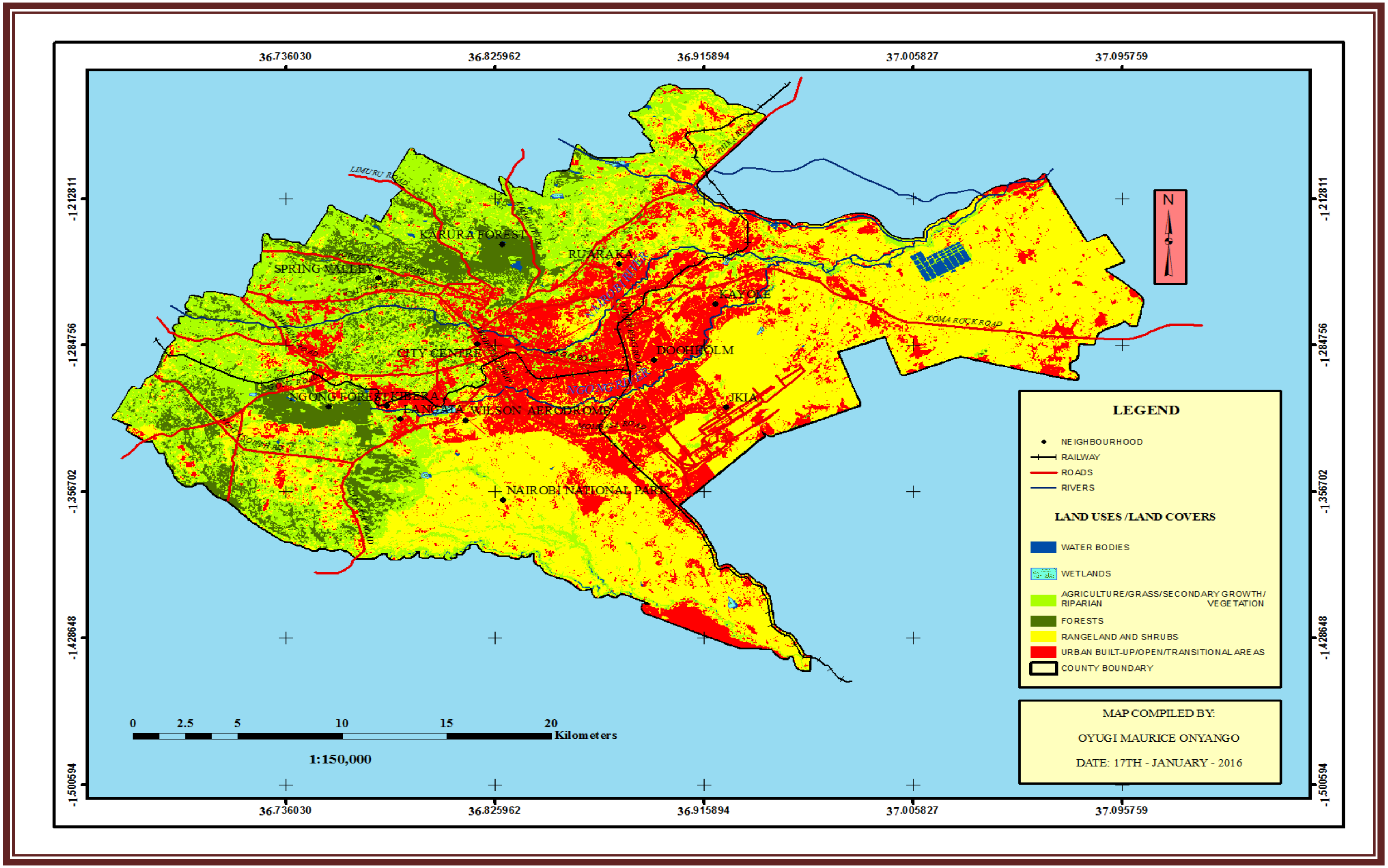

Figure 4.3. Classified Land Use and Land Cover Map of Nairobi for the Year 2000.

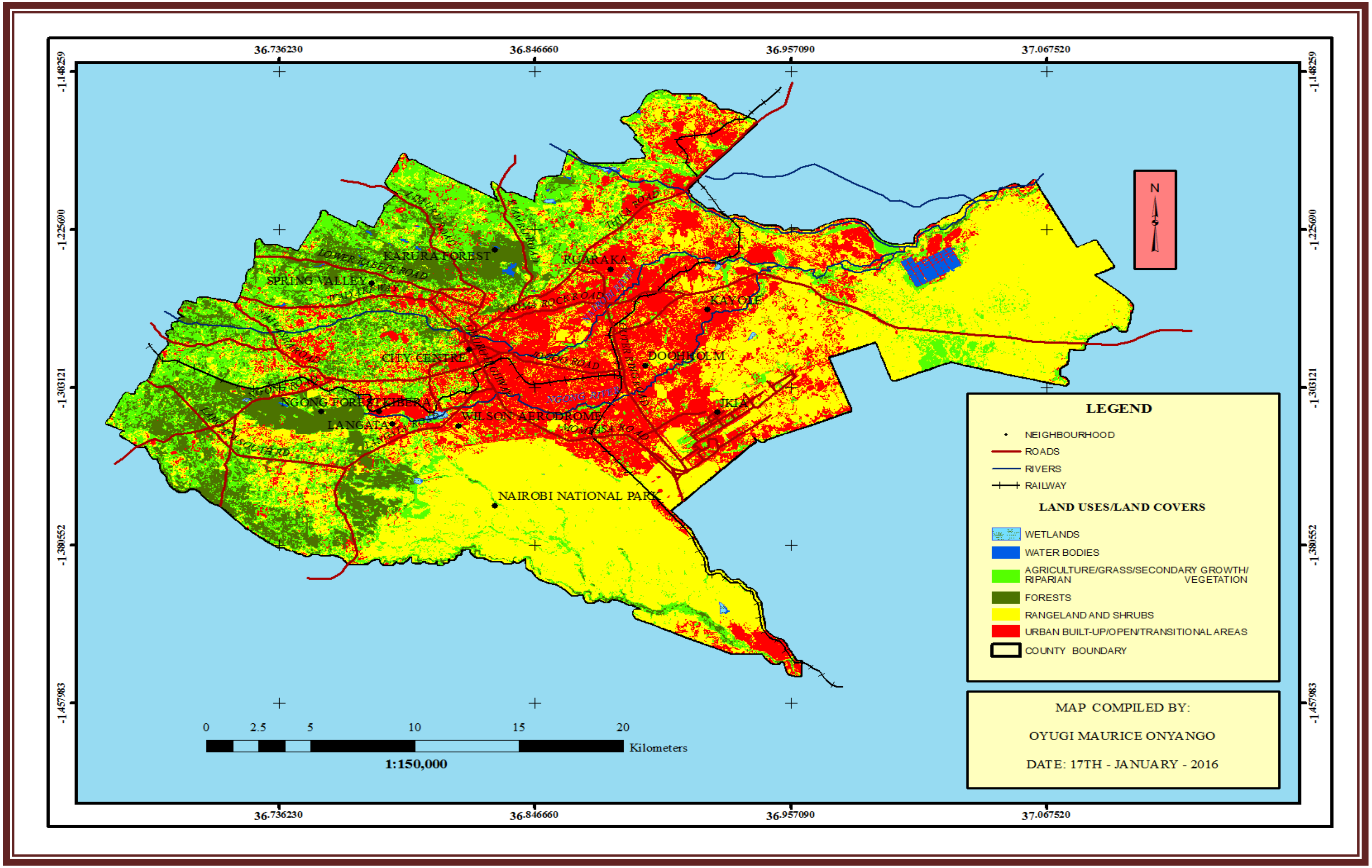

Figure 4.4. Classified Land Use and Land Cover Map of Nairobi for the Year 2005.

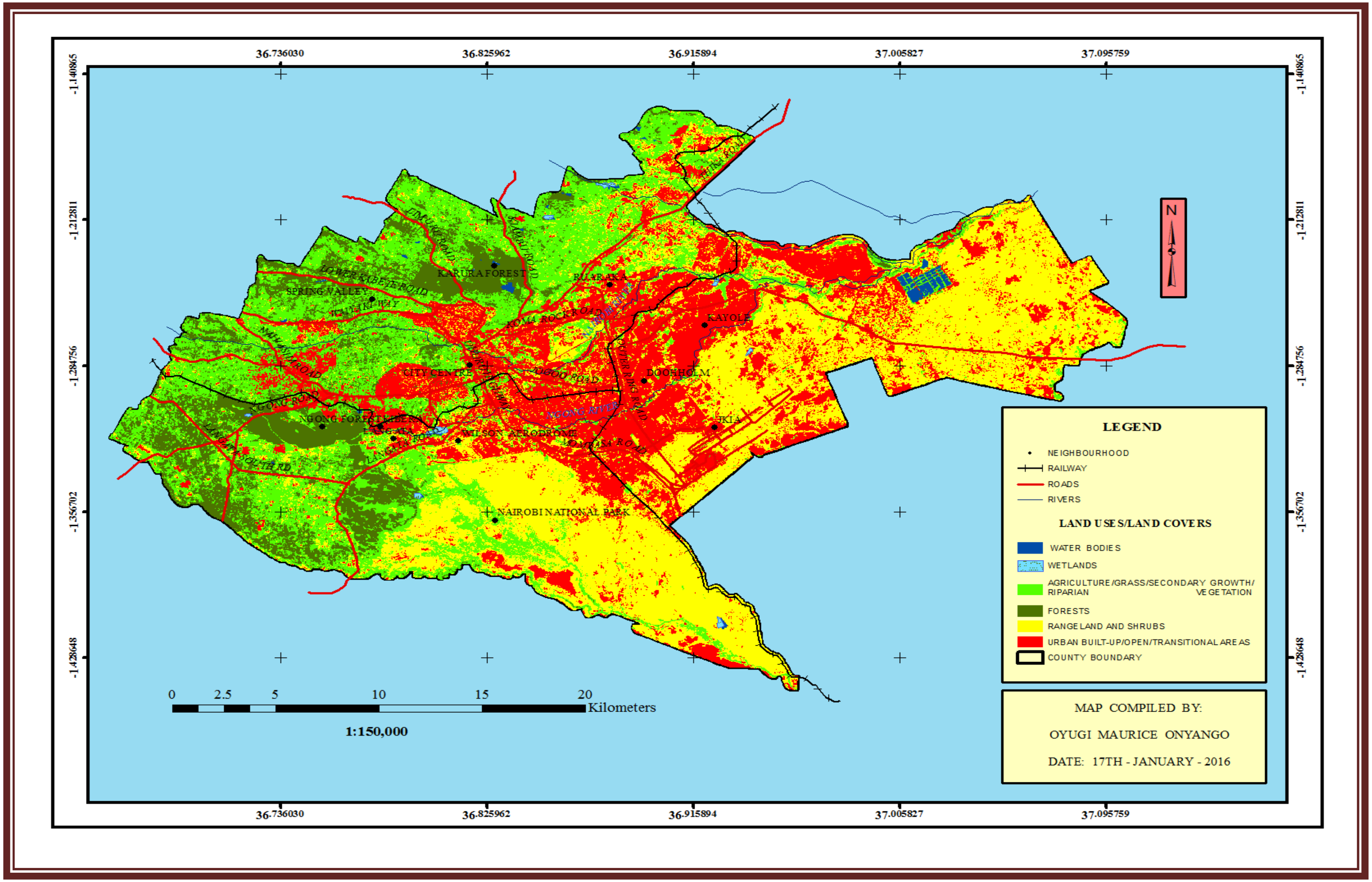

Figure 4.5. Classified Land Use and Land Cover Map of Nairobi for the Year 2010.

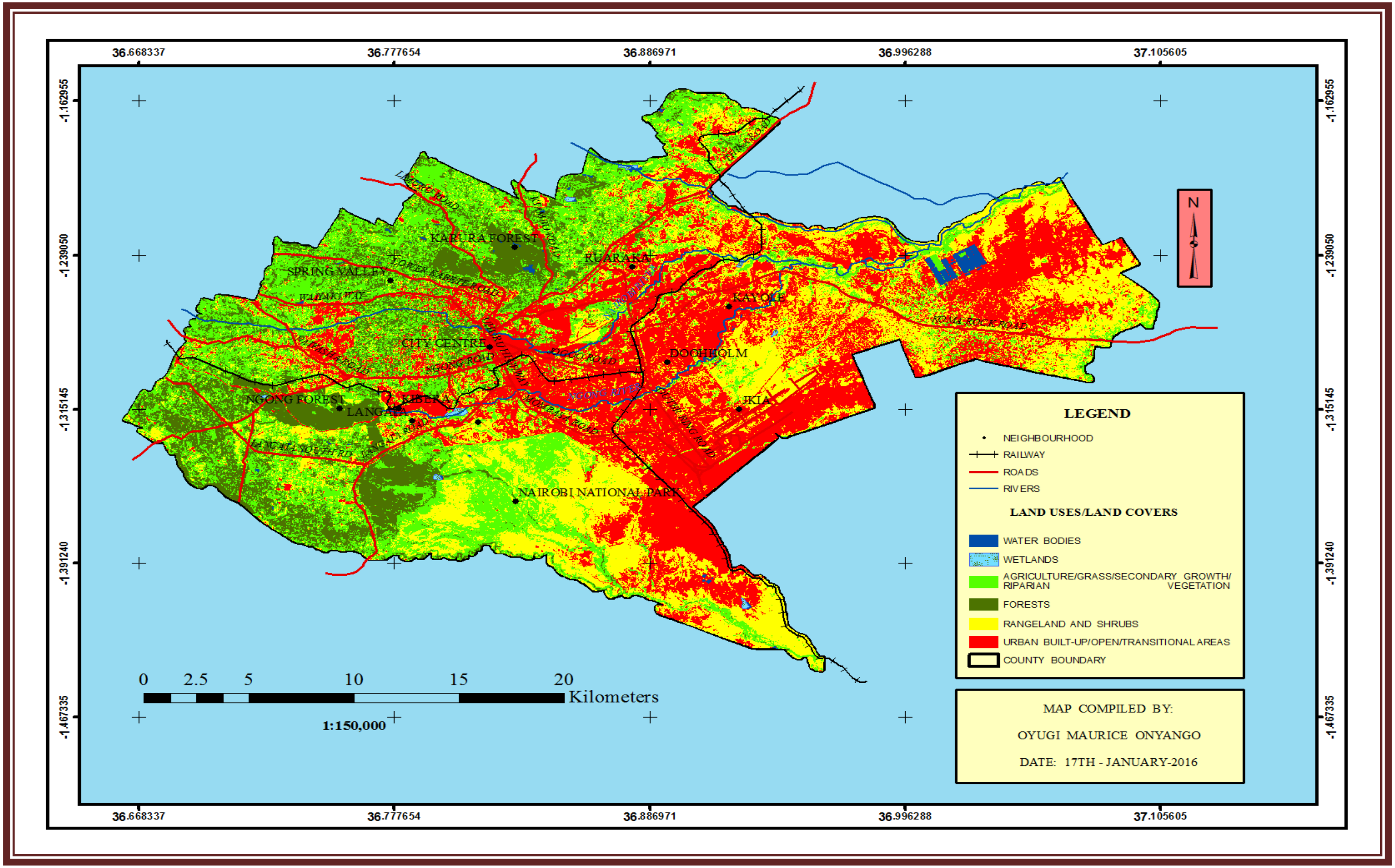

Figure 4.6. Classified Land Use and Land Cover Map of Nairobi for the Year 2015.

Table 4.1. Land Use and Land Cover Types in Nairobi City between the Years 1988 to 2015

Land Use and Land Cover Classes	**Years**											
	1988		**1995**		**2000**		**2005**		**2010**		**2015**	
	Area (km^2)	**Percentage**	**Area (km^2)**	**Percentage**	**Area (km^2)**	**Percentage**	**Area (km^2)**	**Percentage**	**Area (km^2)**	**Percentage**	**Area (km^2)**	**Percentage**
Agriculture/Grass/Secondary Growth/Riparian Vegetation	126.82	17.71	101.12	14.12	176.76	24.68	143.03	19.97	190.75	26.63	189.73	26.49
Water Bodies	2.70	0.38	4.72	0.66	4.84	0.68	3.62	0.51	3.04	0.42	4.09	0.57
Urban Built-Up/Open/Transitional Areas	73.08	10.20	124.36	17.36	155.20	21.67	175.19	24.46	183.97	25.69	228.65	31.93
Forests	59.63	8.33	122.41	17.09	63.63	8.88	79.14	11.05	83.19	11.62	93.44	13.05
Rangeland and Shrubs	453.99	63.39	363.61	50.77	315.79	44.09	315.23	44.01	255.25	35.64	200.30	27.97
TOTAL	**716.22**	**100.00**	**716.22**	**100.00**	**716.22**	**100.00**	**716.22**	**100.00**	**716.22**	**100.00**	**716.22**	**100.00**

The decline in the percentage of land under agriculture in the study period is partly attributed to the population growth in the peri-urban areas which has led to land fragmentation to acreages which are not agriculturally viable. This encourages conversions of the agricultural land to built-up users such as residential, industrial and commercial developments. The study further reveals marked encroachment and degradation of the gazetted and protected areas such as the forests and the Nairobi National Game Park by the urban built-up developments and other anthropogenic activities such as grazing. This has reduced the forest covers to either rangeland and shrubs or open and transitional areas. The anthropogenic encroachments have over the years affected water supply and the availability of wildlife. Further to the degradation of the natural habitats, encroachments into the natural ecosystems have also brought unprecedented fragmentation and isolation of the remaining natural ecosystems. For example, wildlife migration corridor towards Kitengela along the Nairobi National Park has been encroached into by the built-up developments (Lamba, 1994).

Since most of the informal settlements in the city are located in the urban marginal lands such as flood plains, abandoned quarries and river banks, the residents of such neighbourhoods are predisposed to disasters. Quarrying which is a major source of building materials within the city have played a significant role in altering the morphology of the city, particularly in the eastern and north-eastern parts of the city where they are scattered. With increased economic growth, the city has experienced increased demand for residential facilities subsequently up-scaling construction and quarrying activities. This has triggered rapid conversions of rangeland and shrubs, agricultural, grassland and riparian vegetations to built-up, open and transitional (quarry) lands in the eastern and north-eastern parts of the city.

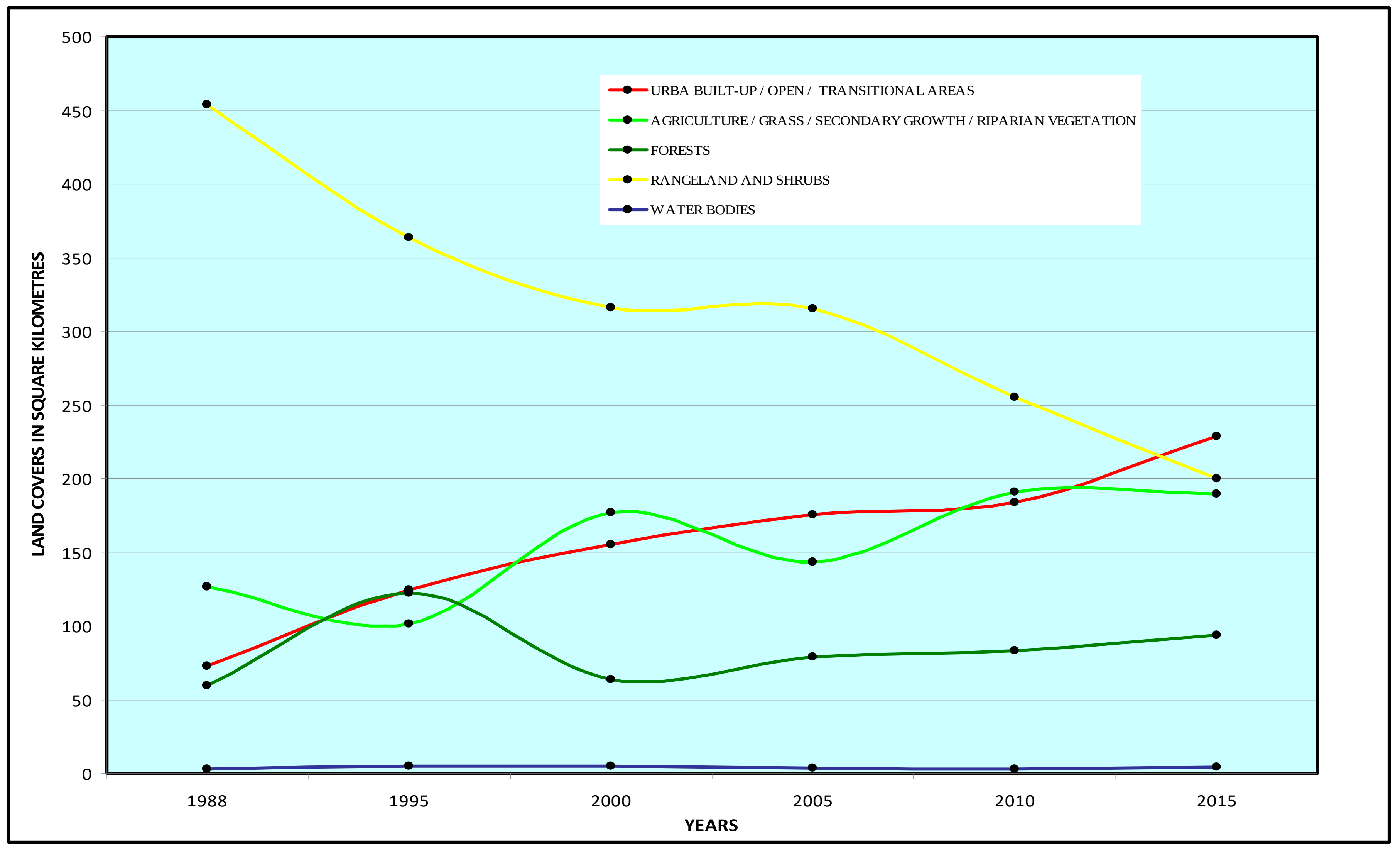

Figure 4.7. Land Use and Land Cover Change Trends in Nairobi City between the Years 1988 to 2015.

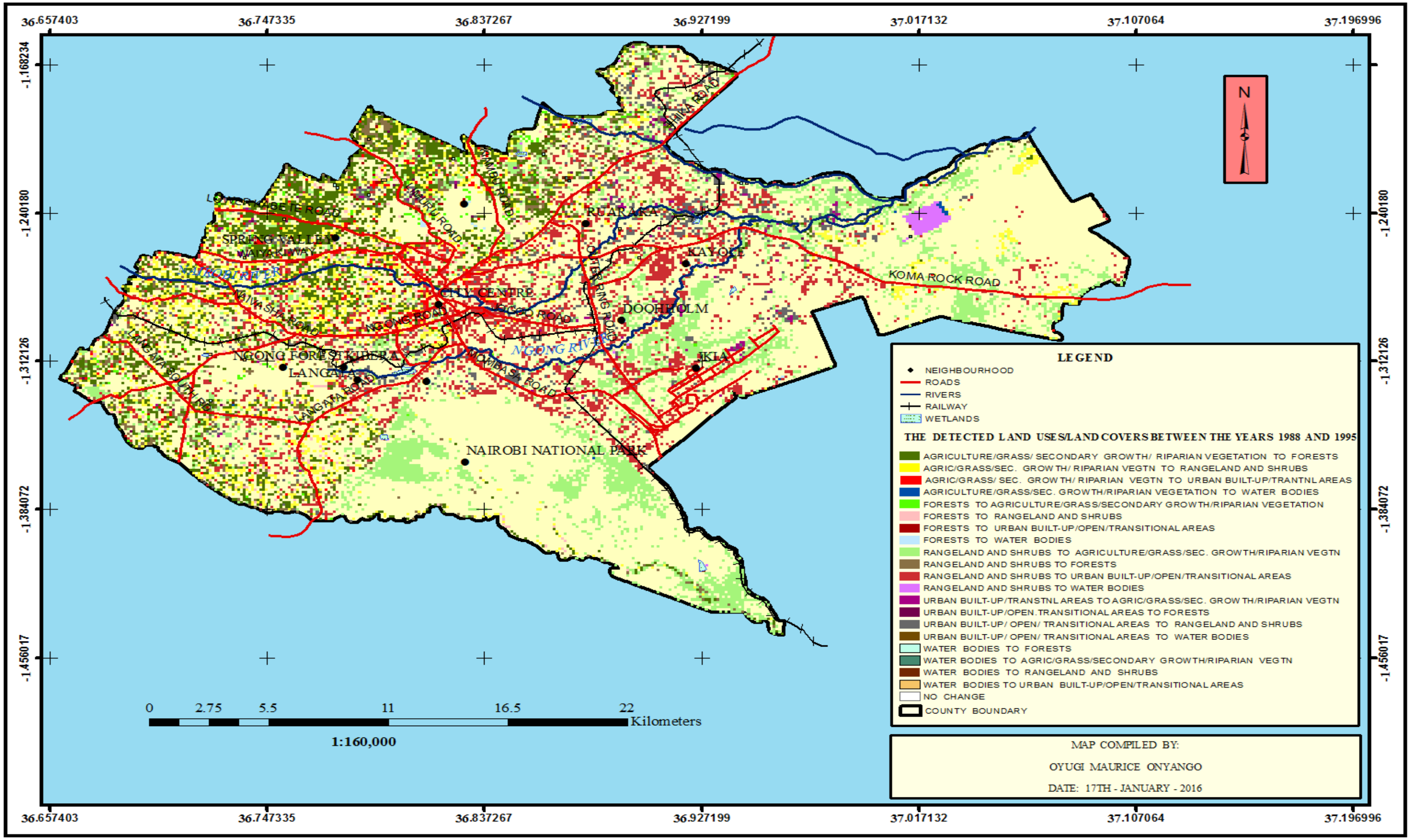

Figure 4.8. The Detected Land Use and Land Cover Changes between the Years 1988 and 1995.
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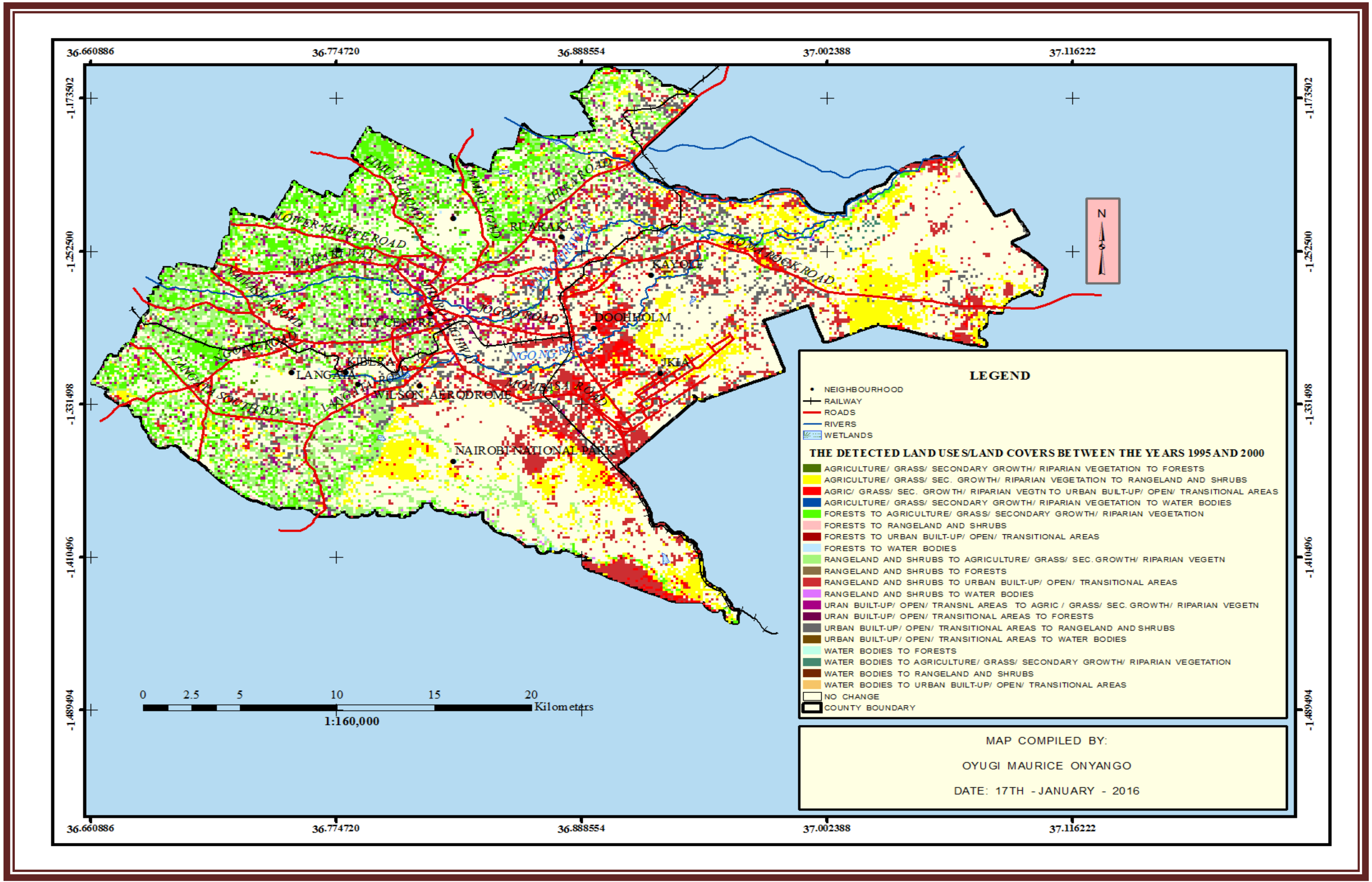

Figure 4.9. The Detected Land Use and Land Cover Changes between the Years 1995 and 2000.

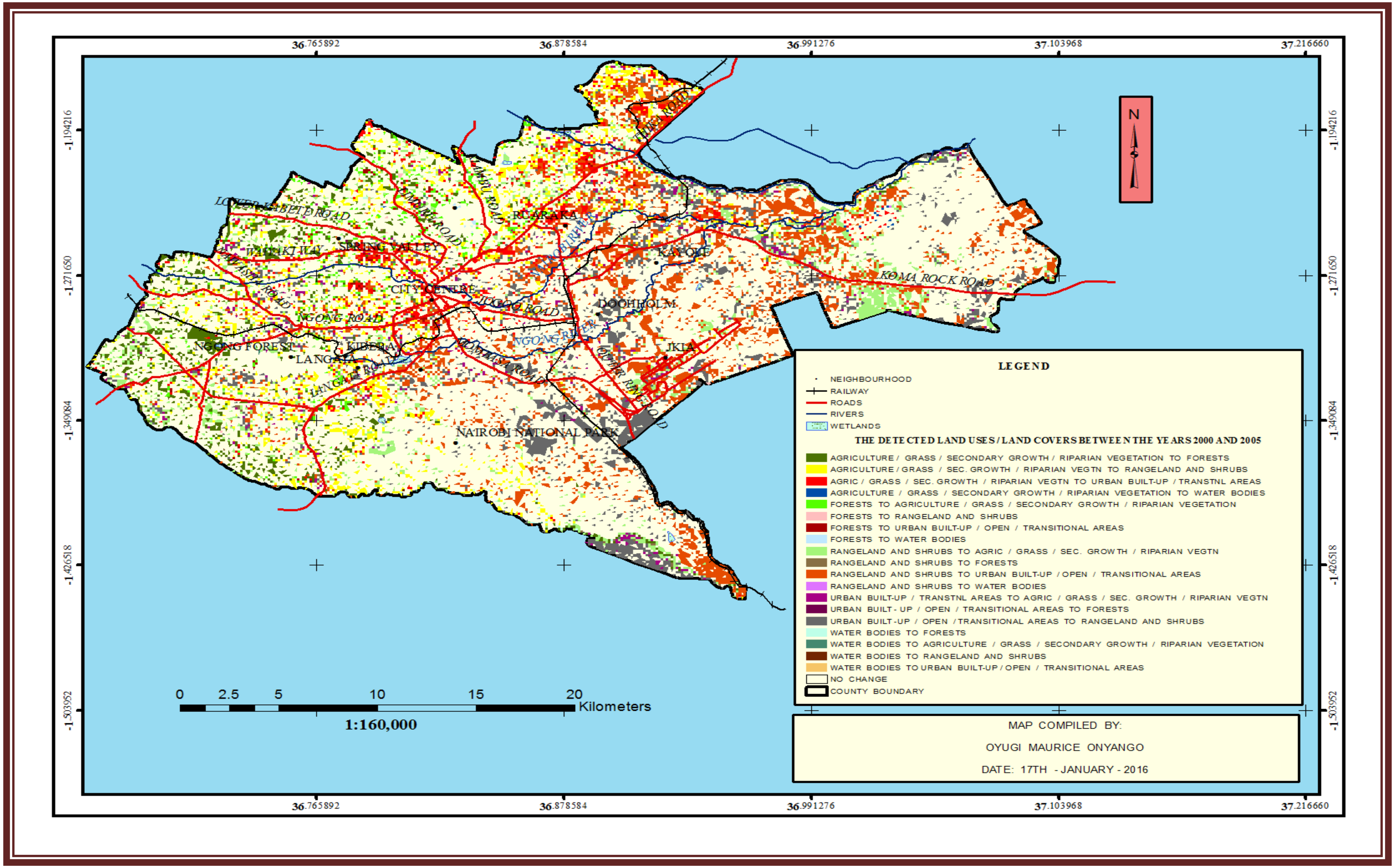

Figure 4.10. The Detected Land Use and Land Cover Changes between the Years 2000 and 2005.

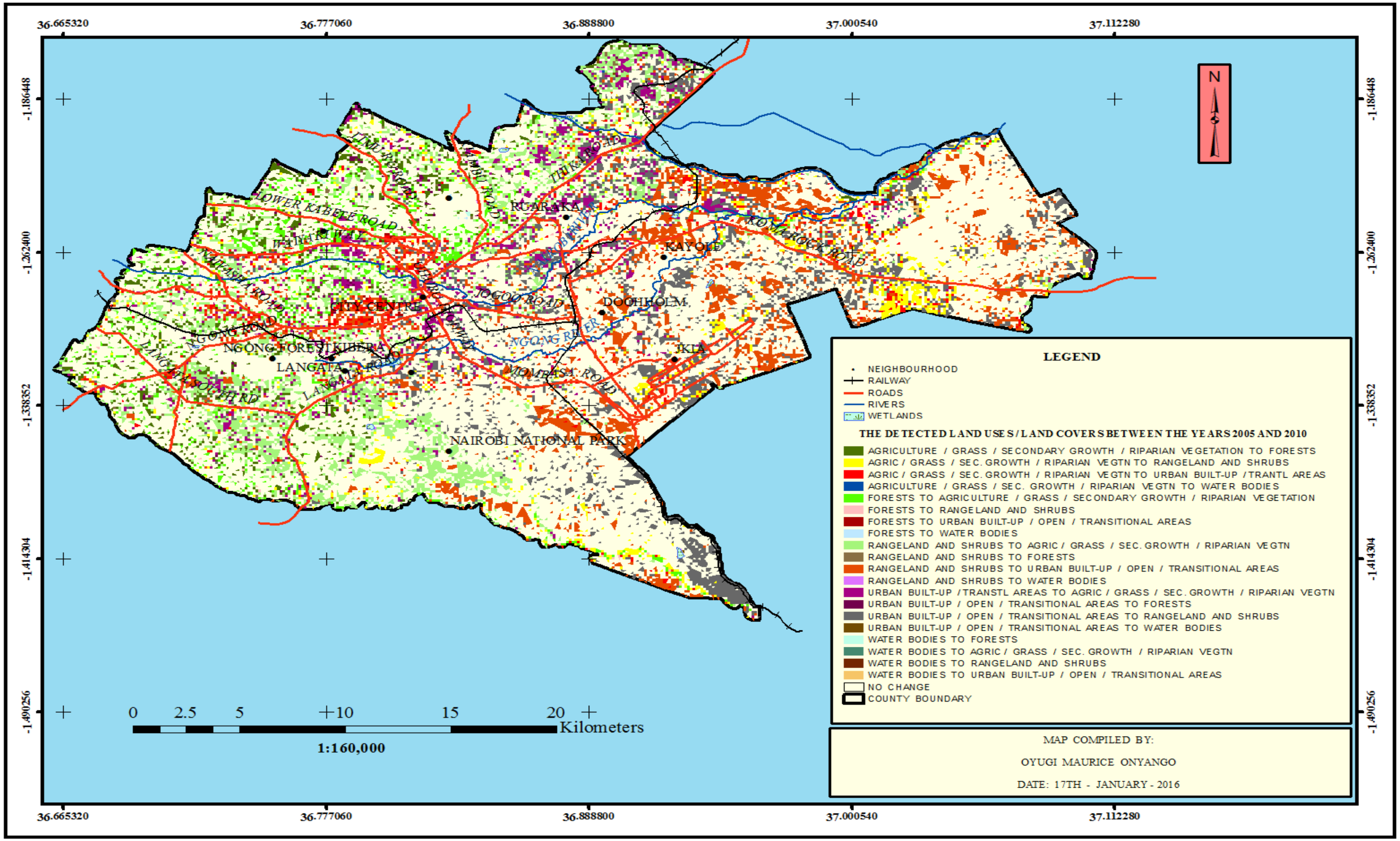

Figure 4.11. The Detected Land Use and Land Cover Changes between the Years 2005 and 2010.

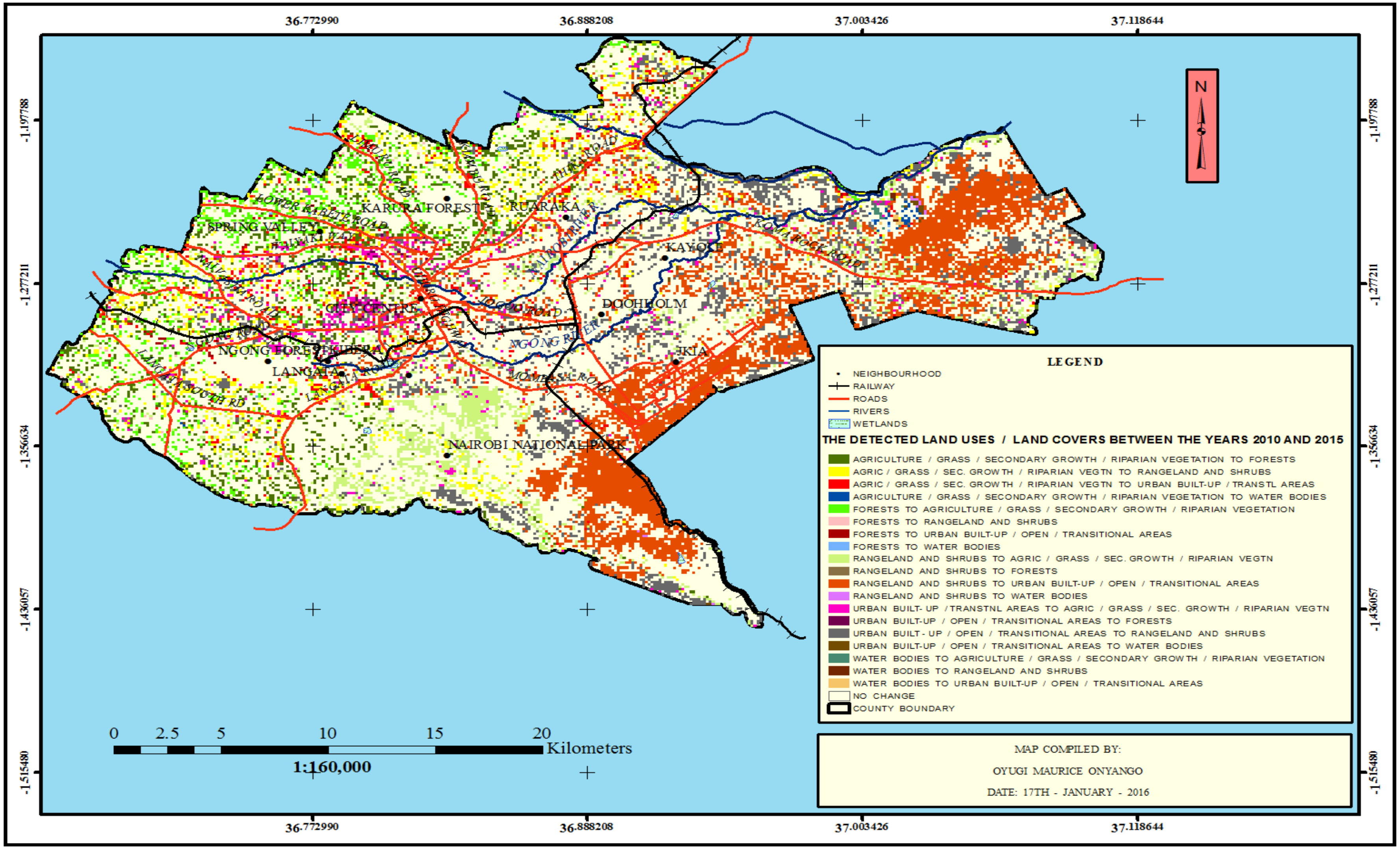

Figure 4.12. The Detected Land Use and Land Cover Changes between the Years 2010 and 2015.

Table 4.2. Major Land Use and Land Cover Changes in the City for Different Epochs

	Land Use/ Land Cover Changes	Years				
		1988 - 1995	1995 - 2000	2000 -2005	2005 - 2010	2010 – 2015
		Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)
1.	Agriculture/Grass/Secondary Growth/Riparian Vegetation to Forests	54.11	1.84	22.10	18.75	31.55
2.	Agriculture/Grass/Secondary Growth/Riparian Vegetation to Rangeland and Shrubs	38.46	62.39	35.06	20.04	28.46
3.	Agriculture/Grass/Secondary Growth/Riparian Vegetation to Urban Built-up/ Open/ Transitional Areas	9.26	16.48	17.27	11.72	12.34
4.	Agriculture/Grass/Secondary Growth/Riparian Vegetation to Water Bodies	0.24	0.22	0.19	0.08	0.66
5.	Forests to Agriculture/Grass/Secondary Growth/Riparian Vegetation	2.28	60.62	7.64	16.50	20.03
6.	Forests to Rangeland and Shrubs	5.29	4.66	0.71	0.75	1.10
7.	Forests to Urban Built-up / Open/ Transitional Areas	2.57	1.27	1.88	0.90	1.28
8.	Forests to Water Bodies	0.19	0.71	0.13	0.09	0.17
9.	Rangeland and Shrubs to Agriculture/Grass/Secondary Growth/Riparian Vegetation	73.38	78.35	30.36	56.93	39.19
10.	Rangeland and Shrubs to Forests	17.19	5.12	0.48	1.36	0.19
11.	Rangeland and Shrubs to Urban Built-up/ Open/ Transitional Areas	60.72	65.30	73.23	56.75	97.67
12.	Rangeland and Shrubs to Water Bodies	2.30	0.44	0.06	0.09	0.22

13.	Urban Built-up/ Open/ Transitional Areas to Agriculture/Grass/Secondary Growth/Riparian Vegetation	2.77	16.09	6.76	23.86	11.27
14.	Urban Built-up/ Open/ Transitional Areas to Forests	0.79	1.74	0.14	1.59	1.22
15.	Urban Built-up/ Open/ Transitional Areas to Rangeland and Shrubs	17.51	34.70	44.83	58.35	53.78
16.	Urban Built-up/ Open/ Transitional Areas to Water Bodies	0.02	0.29	0.00	0.27	0.51
17.	Water Bodies to Forests	0.12	0.08	0.62	0.20	0.00
18.	Water Bodies to Agriculture/Grass/Secondary Growth/Riparian Vegetation	0.15	0.88	0.28	0.41	0.32
19.	Water Bodies to Rangeland and Shrubs	0.22	0.29	0.35	0.11	0.12
20.	Water Bodies to Urban Built-up/ Open/ Transitional Areas	0.22	0.08	0.41	0.19	0.22
21.	No Change	428.43	364.66	473.69	447.28	415.94
Total		**716.22**	**716.22**	**716.22**	**716.22**	**716.22**

4.3 Land Consumption Rate and Land Absorption Coefficients for the City

Findings of the analysis on the LCR and LAC for the city for the period under consideration are presented in Tables 4.3 and 4.4 respectively.

Table 4.3. Land Consumption Rate

Year	Total Area Under Built Up, Open and Transitional Lands (Hectares)	Total Population	Land Consumption Rate
1988	7308	1,265,110	0.0058
1995	12436	1,724,935	0.0072
2000	15520	2,239,701	0.0069
2005	17519	2,791,075	0.0063
2010	18397	3,273,319	0.0056
2015	22865	3,979,827	0.0057

Note: *Population projections rates used are 4.7% for the years 1980 to 1989 and 4.5% for the years 1990 to 2015.*

The environmental implications of LCR for a city become clearer when it is interpreted in conjunction with LAC of the city.

Table 4.4. The LAC for the Built Up, Open and Transitional Areas

	Years				
	1988 - 1995	**1995 - 2000**	**2000 -2005**	**2005 - 2010**	**2010 – 2015**
Land Absorption Coefficients	0.0113	0.0060	0.0036	0.0018	0.0063

Note: *Population projections rates used are 4.7% for the years 1980 to 1989 and 4.5% for the years 1990 to 2015.*

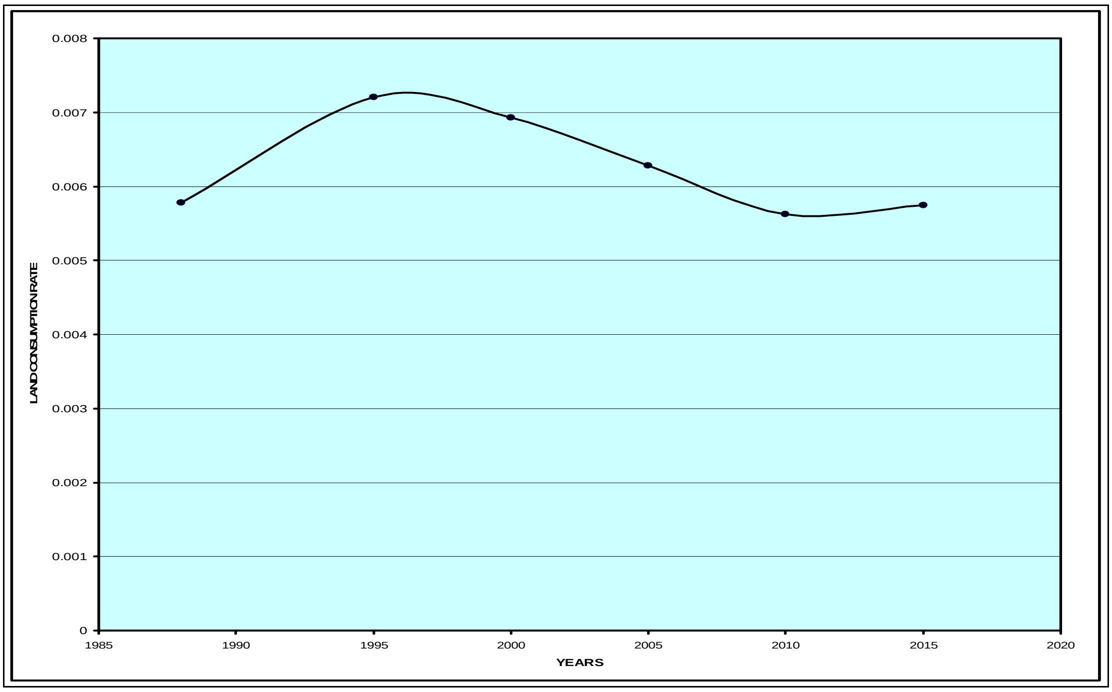

Figure 4.13. The LCR of Nairobi between the Years 1988 to 2015.

The analysis of the LCR and LAC for the city illustrated by Figures 4.13 and 4.14 respectively reveals that the built-up, open and transitional areas have increasingly expanded to the peripheries. While the expansion was rapid between the years 1988 to 1998 and 2010 to 2015, the city grew through internal densification in the years between 1998 to 2005. The expansion has been rapid to the eastern, north-eastern and the southern parts of the city due to cheaper land and housing construction costs in the zones relative to other parts of the city. Increased public investments in infrastructure such as roads, water and electricity in what used to be urban peripheries have improved quality of life and attracted more people into the neighbourhoods. Another factor which has contributed to the spread of the built up, open and transitional areas into what used to be urban peripheries is the persistent higher property and business taxes in the city centre. Since property and business taxes in the urban peripheries are relatively low, businesses which can no longer break even in the main business districts have been pushed to the urban peripheries where they have agglomerated into new satellite commercial centres. This has enabled a large proportion of the city's inhabitants to reside and work in the urban peripheries (Glaeser and Ward, 2009).

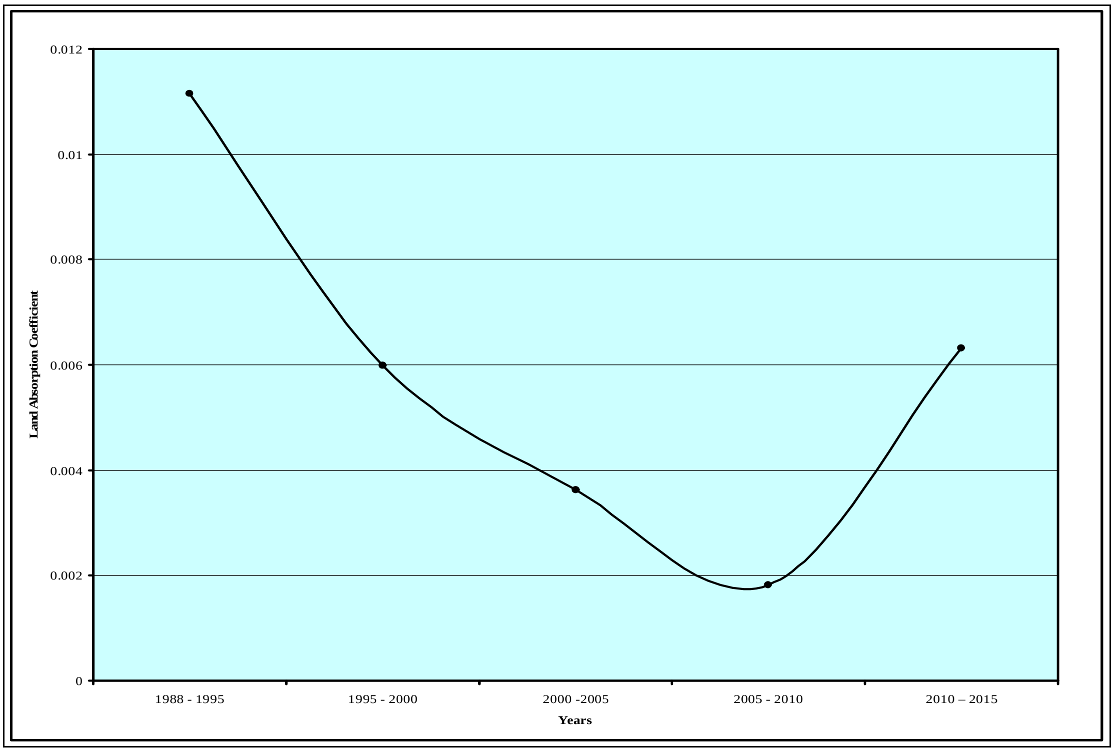

Figure 4.14. The LAC of Nairobi between the Years 1988 to 2015.

The urban sprawl which manifests through increased built-up, open and transitional areas exacerbates surface run-offs and urban floods. This has often led to loss of life and property, particularly in the informal settlements located on the flood plains. The built-up, open and transitional areas which are arenas of economic activities, generates organic, solid, oil and chemical wastes. Since these wastes are either suspended or dissolved in the surface run-offs, the organic and inorganic matter such as the fertilizers, oil and chemical compounds find their way into the drainage channels causing eutrophication and algae blooms, which decreases the oxygen content of the riparian bodies, consequently lowering the biodiversity of the same. Further to increased paved surfaces reducing water percolation to recharge the groundwater, the organic matter, oil and chemical compounds generated from the built-up, open and transitional areas also infiltrate into the aquifers consequently contaminating the ground water. Therefore, neighbourhoods of the city which depend on groundwater supply are likely to experience water crisis as the aquifer gets depleted and contaminated. Since surface run-offs leads to land compressions, increased incidences of the same is likely to exacerbate cracking of building foundations, slope collapses and land subsidence which are detrimental to the maintenance and functionality of water and sewerage networks, roads and railway. Further, increased water consumption for lawn watering and other landscaping activities which characterises the built-up environments is likely to be witnessed and will continue to strain the water supply in the city.

The urban sprawl encourages motorised modes of transportation for the spread enables people to stay far from the work stations. This has increased the vehicular traffic in the city to heighten gaseous and suspended particulate matter emissions. The sprawl also reduces the vegetation cover which moderates the urban micro-climates. With continued depletion of the same, the city has continued to experience increased urban heat island effects alongside compromised air quality. Fragmentation of agricultural land currently taking place in the urban peripheries has made it economically unviable to practice agriculture. This has occasioned conversion of agricultural lands to residential, commercial and industrial users, consequently leading to loss of fertile farmland, recreational spaces and deterioration of wetlands within the city and its environs. Further to wetlands mitigating flooding through moderation of river regime, they also absorb chemicals, organic and suspended solid particulate matter in the surface run-offs. Therefore, without wetlands buffering the natural drainage systems, the systems are likely to be contaminated and to often flood.

Anthropogenic activities such as constructions and grazing encroaching into the Nairobi National Park and migratory corridors for the animals have profound effect on wildlife and the habitat at large. Overgrazing and constructions depletes vegetation cover which leads to mass migration and death of the wildlife during dry spells. The remaining habitat is becoming smaller, degraded and more fragmented, making survival for certain wildlife species very difficult as they try to reach breeding ponds, feeding and hibernation sites and establishing viable nesting grounds. This shall spell extinction for nearly 1,200 species of plants and animals currently found in the National Park of which some are categorised as endangered species. As anthropogenic activities encroach into the park, it loses its scenic qualities which attract tourists. This will have direct impact on the national economy where tourism currently contributes 12.0% of the GDP (Government of Kenya, 2015).

4.4 Factors Influencing Land Use and Land Cover Changes In Nairobi

Land use and land cover conversions within Nairobi is a culmination of the interactions between physiographic, demographic and socio-economic factors, key among which is the urbanisation rate of the city which has been rapid compared to other African cities. This is corroborated by Nairobi’s urbanisation rate averaging 4.7% per annum since independence as compared to 3.5% per annum for other major African cities (UN-Habitat, 2010). Some of the factors which have acted in concert to influence the rapid urbanisation of the city include modest national economic growth and development, high rural-urban migration and natural population increase rates as well as the city’s favourable physiographic base.

4.4.1 Rapid Economic Growth and Development

Positive economic growth and development generally registered in Kenya and Nairobi in particular has contributed to higher urbanisation rate of the city. This is corroborated by the city’s GDP being £254 million in the year 1975, £645 million in the year 1985 and £1.1 billion in the year 1995. This rose to £1.5, £9.7 and £14.1 billions for the years 2002, 2010 and 2015 respectively (Government of Kenya, 2002; Government of Kenya, 2010; Government of Kenya, 2015). Since independence, Kenya’s economy has been characterized by mixed gains. For example from 1963 to 1973, the GDP grew at an annual average of 6.6%. This declined to 5.0% between the years 1980 to 1990 and further to 4.0% between the years 1991 to 1997. While economic stagnations persisted between the years 2000 to 2002 when the GDP grew by 1.15%, the year 2003 defined the country’s economic fortune when the GDP increased by 2.8%. In the year 2004 the growth increased to 4.3%. The economic recovery which has continued to gain ground since the year 2005 to date has realised an average growth rate of 5.2% per annum. Further to creating impetus for real estate developments, the economic growth and development has led to the establishments of more industries and expansion of the same within the city. This has subsequently led to the expansion of the built-up, open and transitional areas within the city. While the economy which grew faster in the period between the years 1975 to 1990 led to higher rate of urban expansion, the period between the years 1990 to 2002 had low economic growth corresponding to low rate of urban expansion. Since the year 2003, the economy has registered high levels of growth which has triggered higher rates of urban expansion. In this regard, increased GDP values and the urban built-up, open and transitional areas’ expansion exhibit a positive correlation.

4.4.2 High Urban Population Growth Rate

In the year 1969, the population of Nairobi was 509,286. This rose to 827, 775; 1,324,570 and 2,143,254 in the years 1979, 1989 and 1999 respectively. While the population of the city was 3,138,369 in the year 2009, it is currently estimated at 3,979,827, which is approximately eight fold increase over the 1969's population (Government of Kenya, 1969; Government of Kenya, 1979; Government of Kenya, 1989; Government of Kenya, 1999; Government of Kenya, 2009a; Government of Kenya, 2015). The accelerated urbanisation rate in the city has been accentuated by high natural population increase and rural-urban migration rates. This has increased demand for residential, commercial, industrial and institutional facilities, subsequently leading to rapid land use and land cover conversions which manifests through the urban sprawl.

4.4.3 Physiographic Factors

As corroborated by the land use and land cover change maps presented, the expansion of the city has been rapid to the north-eastern, eastern and southern frontiers. This has been occasioned by flat topography and availability of relatively cheaper land which have lowered the development costs in these frontiers. Initially, growths in these directions were constrained by poor road networks which have since changed since the year 2003. Further to the above, the trachyte, phonolite, tuffs and basanite rocks found in these zones provides excellent building materials which are extensively being used in the city's construction industry. This has been an impetus to real estate development and urban expansion in these zones. This contrasts with the northern and western parts of the city characterised by constrained expansion opportunities occasioned by rugged topography and scarcity of land. Other constraints to the expansion of the city include the national park to the south and the flight safety corridors around the Jomo Kenyatta International Airport.

4.5 The Morphological Attributes of the City

Urban morphology which embodies the development densities, spatial structure, vegetation densities and building configurations among others affects urban environmental quality in a number of ways. For example, high development densities, incompatible land-use pattern and inappropriate transformations change the urban climatological elements such as the concentration of air pollutants, wind circulations, surface temperatures, global warming and climate change. This realisation has brought forth the concept of urban sustainability which incorporates ecological rationalisation in urban design and development. The concept has further provoked scholars and development practitioners to seek new models for redesigning the urban places. In this endeavour, four models of urban sustainability notably neo-traditional development, urban containment, compact city and eco-city are currently being implemented in the cities. These models are based on seven main design concepts notably; the compactness, sustainable transportation, density, mixed land uses, diversity, passive solar design and greening. This study which was geared towards establishing the relationship existing between the urban morphology and the environmental quality parameters of surface temperatures and air quality was premised that there is a significant relationship existing between urban morphology, air pollution and surface temperature values.

4.5.1 The Land Uses of Nairobi City

As illustrated by Table 4.5 and Figure 4.15, the study established that by the year 2015 wetlands, parks and other recreational spaces, forests, commercial developments, airport land, industrial and residential developments, quarry land, urban agriculture and riparian reserves, water bodies, railway land, public purpose (educational institutions, hospitals and governmental offices) and undeveloped lands were the major land uses in the city. While

Tables 4.6 and 4.7 presents the sizes of the identified land uses in square kilometres and percentages per development zones respectively, Table 4.8 presents the aggregate numerical values of the development zones based on land uses. Information provided in Table 4.8 is transformed into Figure 4.16 showing the city's environmental quality distribution based on land uses.

Table 4.5. Proportions of Land Uses in the City from IKONOS imagery of 2015

	Land Uses	**Area (km^2)**	**Percentages**
1.	Residential Developments	204.65	28.56
2.	**Industrial Developments**		
	Secondary Industrial Developments	24.15	3.37
	Quarry Land	2.93	0.41
3.	**Commercial Developments**	41.29	5.76
4.	**Transportation and Public Purpose Developments**		
	Airport Land	17.44	2.43
	Railway Land	2.20	0.31
5.	**Public Purpose Lands**: Government Institutions, Hospitals, Schools, Universities, Colleges, Prisons and Military Barrack	20.97	2.93
6.	**Recreational and Ecological Conservation Areas**		
	Parks and Other Recreational Spaces	138.44	19.32
	Forests	26.45	3.69
	Wetlands	0.94	0.13
7.	**Public Utilities**		
	Water Bodies, Domestic and Waste Water Treatment Plants	3.81	0.53
8.	**Deferred Land Uses**		
	Urban Agriculture and Riparian Reserves	112.64	15.72
	Undeveloped Land	120.77	16.85
Total		**716.22**	**100.00**

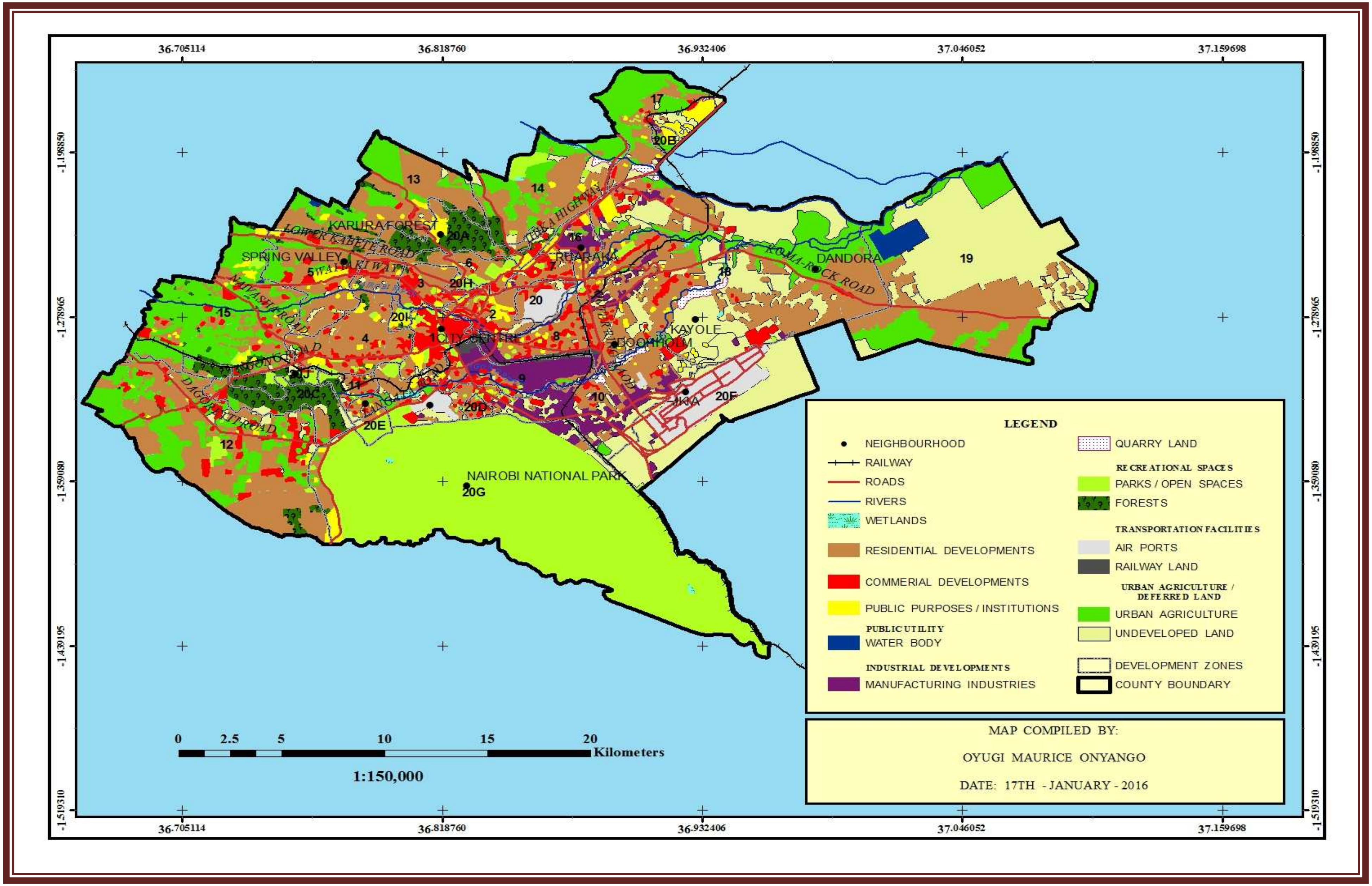

Figure 4.15. Land Uses of Nairobi in the Year 2015.

4.5.1.1 Residential Land-Uses

Residential land-uses collectively occupied 204.65 km^2 or 28.56% of the city's land. The areas consisted of high, medium and low density habitations. Even though this study did not dichotomise the residential land uses into these categories, high density residential developments consisting of areas with over 10,000 people per square kilometre are generally located in the north-eastern, south-eastern and south-western parts of the city as exemplified by Kariobangi, Dandora, Mathare, Kibera and Mukuruu neighbourhoods among others. As compared to low density residential neighbourhoods such as Karen, Muthaiga, Runda, Lavington, Kileleswa and Spring Valley which are inhabited by between 3,000 to 6,000 people per square kilometre, high density neighbourhoods are inadequately served by sanitation and drainage facilities making them environmental squalors. Most of the residential neighbourhoods in the city fall under medium density developments inhabited by between 6,000 to 10,000 people per square kilometre as exemplified by Langata, Kilimani, Embakasi, Buru-Buru and Golf Course neighbourhoods among others (See Appendix I for the development zones where the mentioned neighbourhoods fall).

The urban housing needs in Kenya is estimated at 150,000 units per year, but only 30,000 units are being built per year, resulting in an annual deficit of over 120,000 units per year (Kusienya, 2004). As accentuated by rapid increase in urban population and inadequate budgetary provisions for the housing sector, the public and private sectors have not kept pace with the increasing housing demand. This has exposed the sector to market forces which are not sensitive to the needs of the middle and low-income population cohorts, hence the continued mushrooming of informal settlements and other illegal developments such as unauthorized extensions. The proliferation of informal settlements has further been accentuated by lag in the development and expansion of housing infrastructure, low purchasing power of the majority of urban households, restrictive building by-laws and limited supply of serviced land for public purposes, restrictions on access to formal housing finance due to strict lending criteria of financial institutions, ineffective land policy that tends to allow manipulation in land tenure and alienation as well as poor urban governance leading to inefficient delivery of urban services. Therefore, tackling housing deficit in the city requires reviewing of policies which alienates the urban majority from accessing land.

Informal settlements in Nairobi have gradually grown since the year 1902 when European settlers appropriated large tracts of land in Kiambu, Limuru, Mbagathi, Ruiru and other areas within the environs of the city, consequently displacing indigenous inhabitants. While the colonialists made little provision for accommodating Africans in the city, Africanization policy after independence led to more Africans migrating into the city. This consequently led to the emergence of the slums and squatter settlements. According to Shihembesta (1989), Kenyatta’s administration allowed immigrants who could not find accommodation in the formal low-cost housing estates such as Kariokor, Bahati and others to put up temporary structures within the city as long as these structures were not too close to the CBD. According to Kusienya (2004), most of the houses in the informal settlements are single roomed yet they have occupancy of between 6 to 8 inhabitants. This is not healthy for housing units having more than 2.5 people per habitable room are considered overcrowded, a scenario which is further complicated by poor sanitary conditions and inadequate water supply prevalent in these neighbourhoods. In most cases, the informal settlements are established on marginal lands such as the flood plains, steep slopes, river banks and areas adjacent to sewers and dump sites where the inhabitants are increasingly exposed to health risks and disasters. Since slum demolition is justified by the Public Health Act (Cap 242), the inhabitants of such neighbourhoods are constantly under eviction threats and harassments.

4.5.1.2 Industrial Activities

Quarrying and manufacturing activities characterises the city's industrial sector. The need to enhance income and to reduce walking distance to the employment zones informed the *Nairobi Metropolitan Growth Strategy of 1973* in recommending restrictions on expansion of the then-existing industrial areas but encouraged developments of additional seven secondary industrial areas next to residential neighbourhoods of Komarock, Ruaraka, Kariobangi, Dandora, off Mombasa road, North Airport road and off Outer Ring road (See Appendix I for the mentioned neighbourhoods and Figure 4.15 for the mentioned roads). Since then, the city has witnessed expansion of industrial land uses which by the year 2015 stood at approximately 24.15 km^2 or 3.37% of the city's land. However, the industrial land uses are concentrated in the southern and eastern parts of the city; off and along Mombasa road, Kariobangi, Ruaraka, Dandora, Komarock, North Airport road and off Outer Ring road neighbourhoods.

As attributed to vibrant construction industry which has hiked the demand for building stones, quarrying has emerged with greater environmental concern in the city, particularly in the eastern and north-eastern neighbourhoods such as Kahawa, Kayole, Mwiki, Kasarani, Njiru and Ruai where the activity is concentrated. By the year 2015, the land use occupied approximately 2.93 km^2 or 0.41% of the city's land. Apart from reducing the aesthetic value of the human settlements, the dynamite explosives used in quarrying is a major source of noise, smoke and dust pollutions in the neighbourhoods where the quarries are situated.

4.5.1.3 Commercial and Service Centres

Apart from the commercial activities in the CBD, the *Nairobi Metropolitan Growth Strategy of 1973* recommended the development of seven other satellite commercial centres next to the industrial areas which were proposed by the strategy. The strategy further recommended implementation of new housing schemes with at least a commercial centre. Currently, commercial land uses occupy approximately 41.29 km^2 or 5.76% of the city's land. These include the CBD, Westlands, Capital Hill and Ngara areas, Eastleigh, Juja Road façade, Buru-Buru, Kayole, Karen, Dagoretti Corner, Kawangware and Kangemi among others.

4.5.1.4 Public Purpose or the Institutional Land Uses

Institutional land uses which are evenly spread across the city include airports, airfields, railway land and government institutions such as the hospitals, schools, universities, colleges, prisons and military barracks. Collectively these land uses occupies approximately 40.61 km^2 or 5.67% of city's land.

4.5.1.5 Recreational and Ecological Conservation Areas

4.5.1.5.1 Parks and other Recreational Spaces

The city's biodiversity which is constantly threatened by land fragmentation, degradation, overexploitation and pollution has been sustained by local ecological conditions such as altitude, rainfall levels and soil types. The major parks and recreational spaces in the city include the Nairobi National Park, City Park and other minor recreational spaces such as the Central Park, Uhuru Park, Jamhuri and Jeevanjee Gardens, Tom Mboya Square, Kamukunji and Hilton Park, Aga Khan Walk, Sunken Car Park, Kileleshwa, Manyani East, Joseph Kangethe, Woodley, Highridge Grounds, Brookside Drive as well as Nyayo, Kasarani and City Stadium which collectively occupy approximately 138.44 km^2 or 19.32% of the city's land. Apart from the parks being carbon sinks and moderators of urban micro-climates, they also serve as recreational spaces alongside supporting environmental education and biodiversity conservation programmes.

4.5.1.5.2 Forests

Nairobi City was established on a mosaic landscape consisting of open grasslands, closed forests, woodlands and swamps. However, the city's natural vegetation has since been modified by the anthropogenic activities with only small pockets of same still remaining. Today the forests occupy approximately 26.45 km^2 or 3.69% of the city's land. These include Nairobi Arboretum, Karura, Ngong, Ololua and Dagoretti forests which have continued to play crucial roles as micro-climate moderators and water towers for the rivers within the city. Karura Forest is the water tower for Thigiri, Karura, Ruaraka and Gitathura rivers which dissects the northern parts of the city. The forests also support plantation and indigenous trees which are sources of timber for domestic furniture and wood carvings. While Ngong Forest which consists of planted and indigenous trees as well as grasslands was excised between the years 1963 to 1994 leaving it highly fragmented, the biodiversity of Ololua Forest is under threats occasioned by mining activities. The Nairobi Arboretum has mainly been used for trials of plant species introduced in the country (JICA, 2005a).

Illegal loggings targeting high-value tree species and allocations of parts of City Park, Karura and Ngong Forests to private developers have collectively degraded and reduced the city's forests cover. In addition, implementation of the 60-meter wide southern by-pass road through Ngong Forest has led to clearance of approximately 30 hectares of forest cover. The situation will further be worsened by the on-going implementation of Standard Gauge Railway line passing through the same forest. This is likely to affect the city's microclimatic conditions and air quality (JICA, 2005b). The reduction of the forest cover has also been occasioned by weak enforcement of laws protecting the forests and budgetary constraints in the institutions responsible for forest management. For instance, the previous Forest Act (Cap.385) authorised the minister in charge of forests to gazette and/or de-gazette forest reserves without consultations. However, the Forest Act of 2005 has made the process more stringent (Gachanja, 2003).

4.5.1.5.3 Water Bodies and Wetlands

Apart from the rivers, other water bodies and wetlands in Nairobi are the Ruai waste water treatment plant and Nairobi dam. While water bodies cover approximately 3.81 km^2 or 0.53% of the city's land, wetlands covers approximately 0.94 km^2 or 0.13% of the city's land. Continued discharge of untreated waste water and surface run-offs from municipal, industrial and agricultural land uses have increasingly polluted and eutrophicated the water bodies, wetlands and the dams. For example, Nairobi (Kibera) Dam which was constructed in 1953 with a surface area and storage capacity measuring 350,000m^2 and 98,000m^3 respectively is currently shallow with an average depth of 2.76 metres. The reduction in the depth is attributed to silting of the dam as occasioned by inflow from the Ngong River and other surface run-offs from the Kibera settlement. While the water hyacinth which has clogged the dam has prevented recreational sailing and fishing which were the intended purposes for the construction of the dam, the scenario has further been complicated by the reclamation of sections of the dam for agricultural purposes through dumping of the solid wastes.

4.5.1.6 Deferred Land Uses

4.5.1.6.1 Urban Agriculture

Urban agriculture has continued to manifest in the city through livestock rearing, horticulture, trees nurseries as well as cultivation of crops and fodder. Currently, approximately 112.64 km^2 or 15.72% of land in Nairobi is under urban agriculture. In Nairobi, farming takes place along railway and road reserves, within flood plains and backyards of low density residential neighbourhoods and unutilized industrial plots in the industrial areas as well as in the peri-urban areas where land holdings are large enough to accommodate cultivation and livestock rearing. According to Ayaga *et al.* (2004), apart from being a source of income, urban agriculture is a boost to food security as well as improvement of households' nutritional status. Further, urban agriculture reduces environmental pollution for it utilises organic wastes as inputs.

While urban agriculture presents opportunities for alternative livelihood, it is not without adverse environmental impacts ranging from upsurge of zoonotic diseases to chemical poisoning and environmental damage. Unattended livestock consume industrial effluents contaminated with heavy metals which often end up in the food chain. Low-income farmers in Nairobi also block open sewers to irrigate their crops. This predisposes consumers of such products to pathogens and contamination with heavy metals. Chicken, goats and cattle reared in the informal settlements and urban peripheries contribute to the waste volumes in form of dung which contaminates the watercourses.

Kenya is lacking policies on urban agriculture yet she is a signatory to the *Harare Declaration of 2003* on urban and peri-urban agriculture in Eastern and Southern Africa which recommends enactment of policies integrating urban agriculture into the urban economies. Moreover, this is contrary to the stipulations of the National Land Policy and County Government Act of 2012 which advocates for multi-functional urban land use. Noting that policy gap has led to undesirable farming practices such as diversion of sewage, deliberate bursting of water pipes to harness water for irrigating farms and illegal invasion of open-spaces and conversion of the same into gardens, there is a need for the enactment of policy and legal framework which embodies public participation in land use decision-making and sound environmental management to govern urban agriculture (Ayaga *et al.* 2004).

4.5.1.6.2 Undeveloped Land

The undeveloped land which covers approximately 120.77 km^2 or 16.85% of the city are commercial, residential and industrial properties not developed by the owners. The spatial concentration of the parcels in the eastern and north-eastern parts of the city is attributed to the share certificate tenure system under which the majority of these properties belong. This tenure system involves land acquisition through joint purchase by the land buying companies, cooperatives, trusts, societies and self-help groups which thereafter issue share certificates to the members. However land speculations by these organizations make them hold the tenure documents for long at the detriment of the members who end up lacking documents to facilitate the approvals of their proposed developments by the city authority. Under such circumstances, land remains undeveloped for long periods - a phenomenon which is further compounded by individuals and companies who have bought land in these neighbourhoods for speculations.

Table 4.6. Land Uses in Square Kilometres by Zones

Development Zones	Wetlands	Parks and Other Recreational Spaces	Forests	Commercial Developments	Airport Land	Industrial Developments	Residential Developments	Quarry Land	Undeveloped Land	Urban Agriculture	Water Body	Railway Land	Public Purposes	TOTAL
1	0.00	1.12	0.08	4.27	0.00	0.00	1.41	0.00	0.08	0.00	0.00	0.01	1.14	**8.10**
2	0.00	0.46	0.00	2.30	0.13	0.01	3.01	0.00	0.35	0.00	0.00	0.05	0.99	**7.28**
3	0.00	0.38	0.06	1.85	0.00	0.00	3.52	0.00	0.01	0.00	0.00	0.00	0.37	**6.20**
4	0.00	0.81	0.59	3.07	0.00	0.00	14.45	0.00	0.48	0.19	0.00	0.00	1.23	**20.82**
5	0.00	0.03	0.82	1.68	0.00	0.00	11.20	0.00	0.46	3.40	0.00	0.00	1.56	**19.16**
6	0.00	1.20	0.731	0.47	0.00	0.00	3.73	0.00	0.21	0.00	0.00	0.00	0.39	**6.75**
7	0.00	0.16	0.01	1.45	0.00	0.13	1.62	0.00	0.25	0.00	0.00	0.00	0.42	**4.03**
8	0.00	0.25	0.00	2.47	0.46	1.25	4.67	0.00	0.33	0.00	0.00	1.00	0.34	**10.76**
9	0.00	0.50	0.00	1.81	0.02	7.07	2.20	0.06	0.37	0.14	0.00	0.99	0.15	**13.31**
10	0.31	2.25	0.02	2.95	2.24	8.28	11.56	0.65	9.14	1.62	0.00	0.00	0.76	**39.78**
11	0.00	0.36	0.63	0.47	0.00	0.00	1.36	0.00	0.29	0.15	0.00	0.00	0.09	**3.34**
12	0.00	1.03	1.31	5.08	0.00	0.00	31.70	0.00	1.48	18.96	0.05	0.00	0.98	**60.59**
13	0.00	0.00	2.55	0.33	0.00	0.00	14.80	0.00	0.30	9.18	0.26	0.00	0.86	**28.27**
14	0.24	2.09	1.47	0.98	0.00	0.00	11.41	0.26	2.00	9.89	0.00	0.00	0.74	**29.08**
15	0.00	0.61	1.71	2.24	0.00	0.00	8.73	0.00	0.33	25.45	0.07	0.00	1.50	**40.64**
16	0.00	0.00	0.08	0.31	0.00	1.75	0.99	0.00	0.41	0.24	0.00	0.00	0.63	**4.40**
17	0.00	0.13	0.00	0.62	0.00	0.19	4.94	0.66	1.83	9.41	0.00	0.00	2.19	**19.97**
18	0.14	0.62	0.00	6.52	0.02	3.80	42.21	1.30	38.13	15.66	0.04	0.16	3.00	**111.60**
19	0.00	0.00	0.00	0.00	0.00	0.00	21.91	0.00	41.59	16.27	3.39	0.00	0.00	**83.15**
20	0.00	0.00	0.00	0.70	2.45	0.00	1.09	0.00	0.25	0.00	0.00	0.00	0.00	**4.49**
20A	0.00	0.01	6.33	0.14	0.00	0.00	2.31	0.00	0.35	0.16	0.00	0.00	0.83	**10.13**
20B	0.00	0.00	0.00	0.01	0.00	0.06	0.32	0.00	0.07	0.47	0.00	0.00	0.58	**1.51**
20C	0.03	0.31	7.21	0.71	0.00	0.00	2.14	0.00	1.02	1.00	0.00	0.00	0.00	**12.46**
20D	0.00	0.21	0.00	0.48	0.00	0.00	0.52	0.00	0.15	0.00	0.00	0.00	0.00	**1.36**
20E	0.00	1.69	0.00	0.00	0.00	0.00	0.38	0.00	0.18	0.00	0.00	0.00	0.05	**2.30**
20F	0.00	0.16	0.00	0.07	12.12	0.42	0.05	0.00	19.19	0.00	0.00	0.00	0.06	**32.07**
20G	0.21	122.55	0.11	0.07	0.00	1.20	1.72	0.00	1.28	0.39	0.00	0.00	1.34	**128.87**
20H	0.00	0.44	0.00	0.04	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.11	**0.91**
20I	0.00	0.19	0.10	0.04	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.63	**1.29**
20J	0.00	0.86	2.64	0.15	0.00	0.00	0.07	0.00	0.24	0.06	0.00	0.00	0.04	**4.05**
Total	**0.94**	**138.44**	**26.45**	**41.29**	**17.44**	**24.15**	**204.65**	**2.93**	**120.77**	**112.64**	**3.81**	**2.20**	**20.97**	**716.68**

Table 4.7. Land Use Percentages by Zones

Development Zones	Wetlands	Parks and Other Recreational Spaces	Forests	Commercial Developments	Airport Land	Industrial Developments	Residential Developments	Quarry Land	Undeveloped Land	Urban Agriculture	Water Body	Railway Land	Public Purposes	TOTAL
1	0.00	13.84	0.99	52.70	0.00	0.00	17.36	0.00	0.99	0.00	0.00	0.03	14.13	100.00
2	0.00	6.34	0.00	31.57	1.72	0.02	41.35	0.00	4.79	0.00	0.00	0.73	13.58	100.00
3	0.00	6.14	1.04	29.84	0.00	0.00	56.67	0.00	0.23	0.00	0.00	0.00	6.04	100.00
4	0.00	3.91	2.85	14.74	0.00	0.00	69.41	0.00	2.30	0.93	0.00	0.00	5.90	100.00
5	0.00	0.18	4.30	8.77	0.00	0.00	58.48	0.00	2.40	17.77	0.00	0.00	8.14	100.00
6	0.00	17.83	10.87	7.02	0.00	0.00	55.35	0.00	3.12	0.00	0.00	0.00	5.81	100.00
7	0.00	3.98	0.13	36.03	0.00	3.17	40.28	0.00	6.12	0.00	0.00	0.00	10.35	100.00
8	0.00	2.33	0.00	22.94	4.26	11.59	43.44	0.00	3.04	0.00	0.00	9.25	3.16	100.00
9	0.00	3.79	0.00	13.62	0.15	53.14	16.53	0.43	2.78	1.02	0.00	7.44	1.09	100.00
10	0.78	5.65	0.04	7.43	5.64	20.83	29.08	1.63	22.99	4.06	0.00	0.00	1.91	100.00
11	0.00	10.75	18.87	14.03	0.00	0.00	40.66	0.00	8.84	4.40	0.00	0.00	2.60	100.00
12	0.00	1.71	2.17	8.42	0.00	0.00	52.52	0.00	2.45	31.41	0.08	0.00	1.62	100.00
13	0.00	0.00	9.02	1.17	0.00	0.00	52.35	0.00	1.05	32.49	0.92	0.00	3.05	100.00
14	0.82	7.17	5.04	3.39	0.00	0.00	39.24	0.90	6.89	34.02	0.00	0.00	2.55	100.00
15	0.00	1.49	4.22	5.52	0.00	0.00	21.50	0.00	0.82	62.70	0.17	0.00	3.68	100.00
16	0.00	0.00	1.72	7.06	0.00	39.76	22.38	0.00	9.32	5.45	0.00	0.00	14.21	100.00
17	0.00	0.65	0.00	3.10	0.00	0.95	24.73	3.31	9.17	47.15	0.00	0.00	10.95	100.00
18	0.13	0.56	0.00	5.84	0.02	3.40	37.84	1.17	34.18	14.04	0.04	0.14	2.69	100.00
19	0.00	0.00	0.00	0.00	0.00	0.00	26.35	0.00	50.02	19.56	4.07	0.00	0.00	100.00
20	0.00	0.00	0.00	15.68	54.64	0.00	24.16	0.00	5.47	0.00	0.00	0.00	0.00	100.00
20A	0.00	0.11	62.45	1.36	0.00	0.00	22.76	0.00	3.48	1.61	0.00	0.00	8.22	100.00
20B	0.00	0.15	0.00	0.49	0.00	4.15	21.19	0.00	4.80	30.83	0.00	0.00	38.06	10.000
20C	0.28	2.65	57.96	5.73	0.00	0.00	17.23	0.00	8.18	8.07	0.00	0.00	0.00	100.00
20D	0.00	15.47	0.00	35.59	0.00	0.00	38.16	0.00	10.89	0.00	0.00	0.00	0.00	100.00
20E	0.00	73.50	0.00	0.00	0.00	0.00	16.58	0.00	7.68	0.00	0.00	0.00	2.35	100.00
20F	0.00	0.49	0.00	0.23	37.81	1.31	0.15	0.00	59.86	0.00	0.00	0.00	0.17	100.00
20G	0.17	95.28	0.08	0.06	0.00	0.93	1.34	0.00	1.00	0.30	0.00	0.00	1.04	100.00
20H	0.00	48.48	0.00	3.98	0.00	0.00	34.64	0.00	0.00	0.00	0.00	0.00	12.52	100.00
20I	0.00	14.42	7.56	3.00	0.00	0.00	25.80	0.00	0.00	0.00	0.00	0.00	49.12	100.00
20J	0.00	21.14	65.10	3.67	0.00	0.00	1.77	0.00	6.00	1.45	0.00	0.00	0.94	100.00

Table 4.8. Land Use Numerical Values

Development Zones	**Wetlands (9.0)**	**Parks and Other Recreational Spaces (8.0)**	**Forests (10.0)**	**Commercial Developments (3.0)**	**Airport Land (4.0)**	**Industrial Developments (1.0)**	**Residential Developments (2.0)**	**Quarry Land (1.0)**	**Undeveloped Land (7.0)**	**Urban Agriculture (6.0)**	**Water Body (6.5)**	**Railway Land (4.5)**	**Public Purposes (5.0)**	**TOTAL (ZONAL) NOMINAL VALUES**
1	0.000000	1.106555	0.099030	1.580432	0.000000	0.000000	0.347046	0.000000	0.069304	0.000000	0.000000	0.001434	0.706123	**3.909924**
2	0.000000	0.506284	0.000000	0.946176	0.068872	0.000228	0.826106	0.000000	0.334749	0.000000	0.000000	0.032959	0.678387	**3.393761**
3	0.000000	0.491242	0.104183	0.895442	0.000000	0.000000	1.133947	0.000000	0.016115	0.000000	0.000000	0.000000	0.302101	**2.94303**
4	0.000000	0.312414	0.285241	0.442049	0.000000	0.000000	1.387726	0.000000	0.160612	0.055887	0.000000	0.000000	0.294762	**2.938691**
5	0.000000	0.014374	0.430022	0.262988	0.000000	0.000000	1.169053	0.000000	0.168008	1.065673	0.000000	0.000000	0.406991	**3.517109**
6	0.000000	1.426105	1.087121	0.210704	0.000000	0.000000	1.107032	0.000000	0.218279	0.000000	0.000000	0.000000	0.290457	**4.339698**
7	0.000000	0.318154	0.012792	1.080131	0.000000	0.031704	0.805080	0.000000	0.428377	0.000000	0.000000	0.000000	0.517337	**3.193575**
8	0.000000	0.186716	0.000000	0.688213	0.170323	0.115885	0.868736	0.000000	0.212474	0.000000	0.000000	0.416174	0.157929	**2.81645**
9	0.000000	0.303572	0.000000	0.408717	0.006067	0.531345	0.330653	0.004342	0.194391	0.061054	0.000000	0.334789	0.054705	**2.229635**
10	0.070150	0.451853	0.004318	0.222826	0.225513	0.208232	0.581249	0.016270	1.608754	0.243764	0.000000	0.000000	0.095318	**3.728247**
11	0.000000	0.858599	1.884272	0.420354	0.000000	0.000000	0.811993	0.000000	0.617970	0.263547	0.000000	0.000000	0.129638	**4.986373**
12	0.000000	0.136567	0.216191	0.251622	0.000000	0.000000	1.046503	0.000000	0.170736	1.877588	0.004971	0.000000	0.080487	**3.784665**
13	0.000000	0.000000	0.901217	0.035003	0.000000	0.000000	1.046688	0.000000	0.073132	1.948890	0.059531	0.000000	0.152228	**4.216689**
14	0.073939	0.573708	0.504273	0.101544	0.000000	0.000000	0.784648	0.008975	0.482490	2.040691	0.000000	0.000000	0.127273	**4.697541**
15	0.000000	0.119138	0.421624	0.165291	0.000000	0.000000	0.429550	0.000000	0.057191	3.758249	0.011299	0.000000	0.183950	**5.146292**
16	0.000000	0.000000	0.172280	0.212139	0.000000	0.397976	0.448003	0.000000	0.653058	0.327064	0.000000	0.000000	0.711383	**2.921903**
17	0.000000	0.051765	0.000000	0.093104	0.000000	0.009474	0.494580	0.033054	0.641920	2.828733	0.000000	0.000000	0.547590	**4.70022**
18	0.011622	0.044507	0.000000	0.175197	0.000619	0.034031	0.756517	0.011662	2.391490	0.841794	0.002412	0.006381	0.134554	**4.410786**
19	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.526895	0.000000	3.501245	1.173794	0.264824	0.000000	0.000000	**5.466758**
20	0.000000	0.000000	0.000000	0.470734	2.186729	0.000000	0.483439	0.000000	0.382809	0.000000	0.000000	0.000000	0.000000	**3.523711**
20A	0.000000	0.009058	6.245337	0.040925	0.000000	0.000000	0.455125	0.000000	0.243825	0.096720	0.000000	0.000000	0.410888	**7.501878**
20B	0.000000	0.012108	0.000000	0.014869	0.000000	0.041659	0.425201	0.000000	0.336927	1.855749	0.000000	0.000000	1.909232	**4.595745**
20C	0.025150	0.211464	5.790776	0.171697	0.000000	0.000000	0.344348	0.000000	0.571983	0.483461	0.000000	0.000000	0.000000	**7.598879**
20D	0.000000	1.236444	0.000000	1.066422	0.000000	0.000000	0.762395	0.000000	0.761410	0.000000	0.000000	0.000000	0.000000	**3.826671**
20E	0.000000	5.873321	0.000000	0.000000	0.000000	0.000000	0.331243	0.000000	0.537010	0.000000	0.000000	0.000000	0.117488	**6.859062**
20F	0.000000	0.039173	0.000000	0.007000	1.511891	0.013141	0.003034	0.000000	4.188803	0.000000	0.000000	0.000000	0.008692	**5.771734**
20G	0.014881	7.607395	0.008830	0.001667	0.000000	0.009286	0.026718	0.000000	0.069691	0.017973	0.000000	0.000000	0.051937	**7.808378**
20H	0.000000	3.893112	0.000000	0.119892	0.000000	0.000000	0.695410	0.000000	0.000000	0.000000	0.000000	0.000000	0.628460	**5.336874**
20I	0.000000	1.154645	0.757115	0.089957	0.000000	0.000000	0.516462	0.000000	0.000000	0.000000	0.000000	0.000000	2.458706	**4.976885**
20J	0.000000	1.689791	6.505639	0.110020	0.000000	0.000000	0.035387	0.000000	0.419866	0.086849	0.000000	0.000000	0.046948	**8.8945**

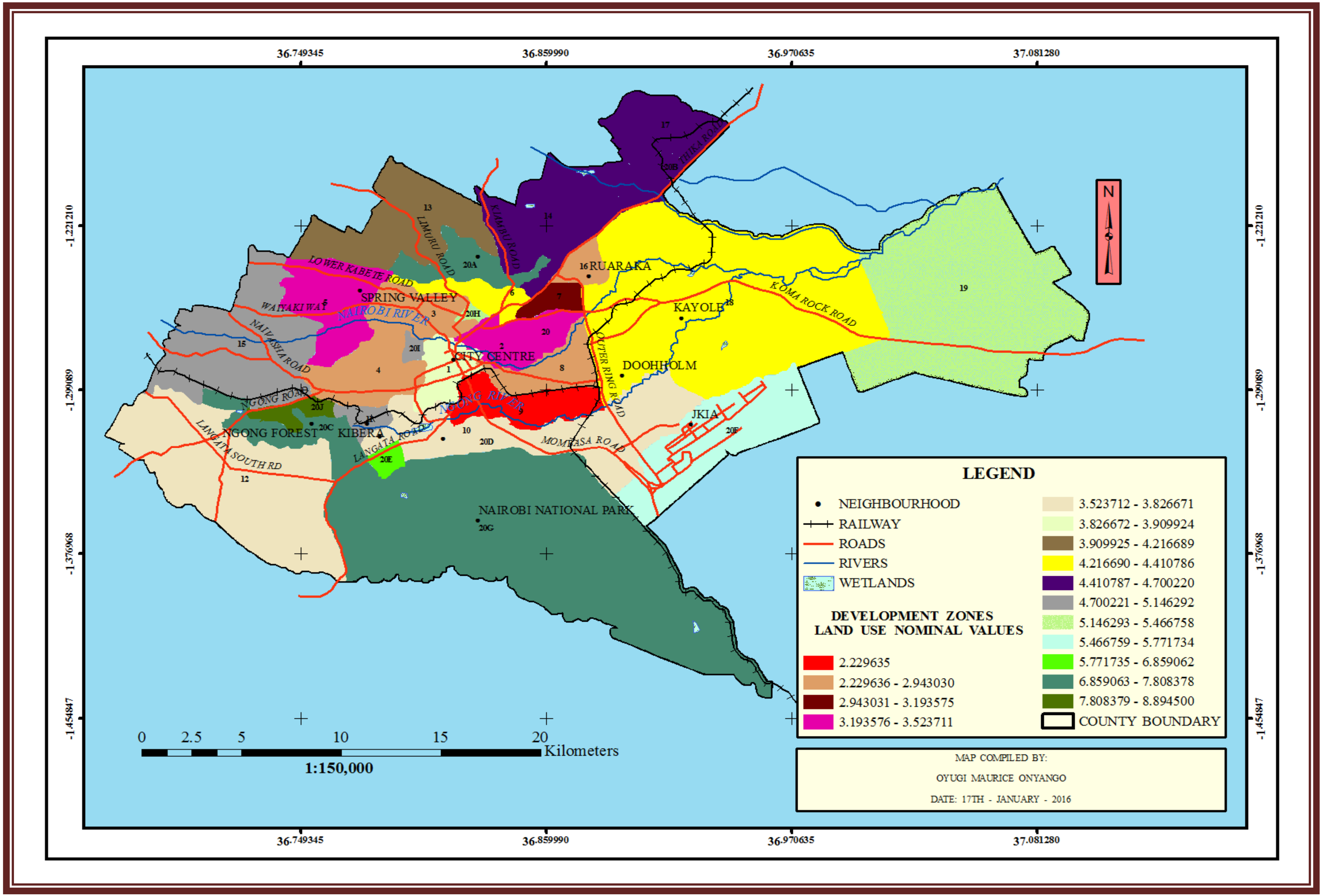

Figure 4.16. Environmental Quality of Nairobi Based on Land Uses.

4.5.2 Development Density Variations within the City

As illustrated by Table 4.9 and Figure 4.17, development densities vary across the city. For instance, CBD (zone 1), Eastlands (zones 7, 8, 16 and 20) and industrial area (zone 9) have the highest development densities of 56.71%, 57.67%, 57.02%, 53.87%, 53.81% and 66.88% respectively. There are marked differences even within the same development zone. For example, zone 11 comprising of Kibera, Ayany, Olympic, Fort Jesus and Karanja neighbourhoods collectively have a modest development density of 33.06% while Kibera neighbourhood which is an informal settlement within the zone have high densities approximated at 87%. Since high development densities reduces the vegetation cover, such neighbourhoods experience elevated surface temperatures and increased concentrations of air pollutants which subsequently compromise the neighbourhood's environmental quality. Further analysis was undertaken on how development densities and land uses (urban form) affects the urban environmental quality, results of which is presented in Table 4.10 and Figure 4.18 illustrating how the city's environmental quality varies with the urban form.

4.5.3 Biomass Variations within the City

Even though air purification and temperature moderation abilities of the vegetation are influenced by type and distribution of the vegetation, it is the biomass component of the vegetation which significantly influences the same. Therefore, it is imperative to consider biomass index in studies focussing on the effect of vegetation on urban environmental quality. Chapter three details out how the analysis of the effects of biomass index on urban environmental quality was undertaken, results of which is presented in Table 4.11 and further transformed into Figure 4.19 showing how environmental quality varies within the city with vegetation density.

Table 4.9. The Environmental Quality Nominal Values for the Development Densities in the City

Development Zones	Built-Up Land Uses by Areas (km^2)						The Zone's Total Land Areas (km^2)	Actual Built Up Spaces - Areas (km^2)	Development Density (%)	Development Density Nominal Value
	Commercial Developments	Airport Land	Industrial Developments	Residential Developments	Railway Land	Public Purposes				
1	4.27	0.00	0.00	1.41	0.01	1.14	8.10	4.59	56.71	4.5
2	2.30	0.13	0.01	3.01	0.05	0.99	7.28	3.59	49.32	5.5
3	1.85	0.00	0.00	3.52	0.00	0.37	6.20	3.01	48.56	5.5
4	3.07	0.00	0.00	14.45	0.00	1.23	20.82	5.84	28.04	7.5
5	1.68	0.00	0.00	11.20	0.00	1.56	19.16	4.49	23.45	8.0
6	0.47	0.00	0.00	3.73	0.00	0.39	6.75	1.15	17.05	8.5
7	1.45	0.00	0.13	1.62	0.00	0.42	4.03	2.32	57.67	4.5
8	2.47	0.46	1.25	4.67	1.00	0.34	10.76	6.14	57.02	4.5
9	1.81	0.02	7.07	2.20	0.99	0.15	13.31	8.90	66.88	3.5
10	2.95	2.24	8.28	11.56	0.00	0.76	39.78	16.49	41.47	6.0
11	0.47	0.00	0.00	1.36	0.00	0.09	3.34	1.10	33.06	7.0
12	5.08	0.00	0.00	31.70	0.00	0.98	60.59	10.05	16.58	8.5
13	0.33	0.00	0.00	14.80	0.00	0.86	28.27	4.00	14.14	9.0
14	0.98	0.00	0.00	11.41	0.00	0.74	29.08	3.28	11.29	9.0
15	2.24	0.00	0.00	8.73	0.00	1.50	40.64	4.36	10.73	9.0
16	0.31	0.00	1.75	0.99	0.00	0.63	4.40	2.37	53.87	5.0
17	0.62	0.00	0.19	4.94	0.00	2.19	19.97	4.19	20.96	8.0
18	6.52	0.02	3.80	42.21	0.16	3.00	111.60	28.17	25.24	8.0
19	0.00	0.00	0.00	21.91	0.00	0.00	83.15	10.95	13.17	9.0
20	0.70	2.45	0.00	1.09	0.00	0.00	4.49	2.42	53.81	5.0
20A	0.14	0.00	0.00	2.31	0.00	0.83	10.13	0.92	9.04	9.5
20B	0.01	0.00	0.06	0.32	0.00	0.58	1.51	0.54	35.87	6.5
20C	0.71	0.00	0.00	2.14	0.00	0.00	12.46	1.00	8.03	9.5
20D	0.48	0.00	0.00	0.52	0.00	0.00	1.36	0.64	47.50	5.5
20E	0.00	0.00	0.00	0.38	0.00	0.05	2.30	0.22	9.69	9.5
20F	0.07	12.12	0.42	0.05	0.00	0.06	32.07	7.58	23.63	8.0
20G	0.07	0.00	1.20	1.72	0.00	1.34	128.87	1.69	1.31	10
20H	0.04	0.00	0.00	0.32	0.00	0.11	0.91	0.18	19.77	8.5
20I	0.04	0.00	0.00	0.33	0.00	0.63	1.29	0.35	27.30	7.5
20J	0.15	0.00	0.00	0.07	0.00	0.04	4.05	0.09	2.23	10.0

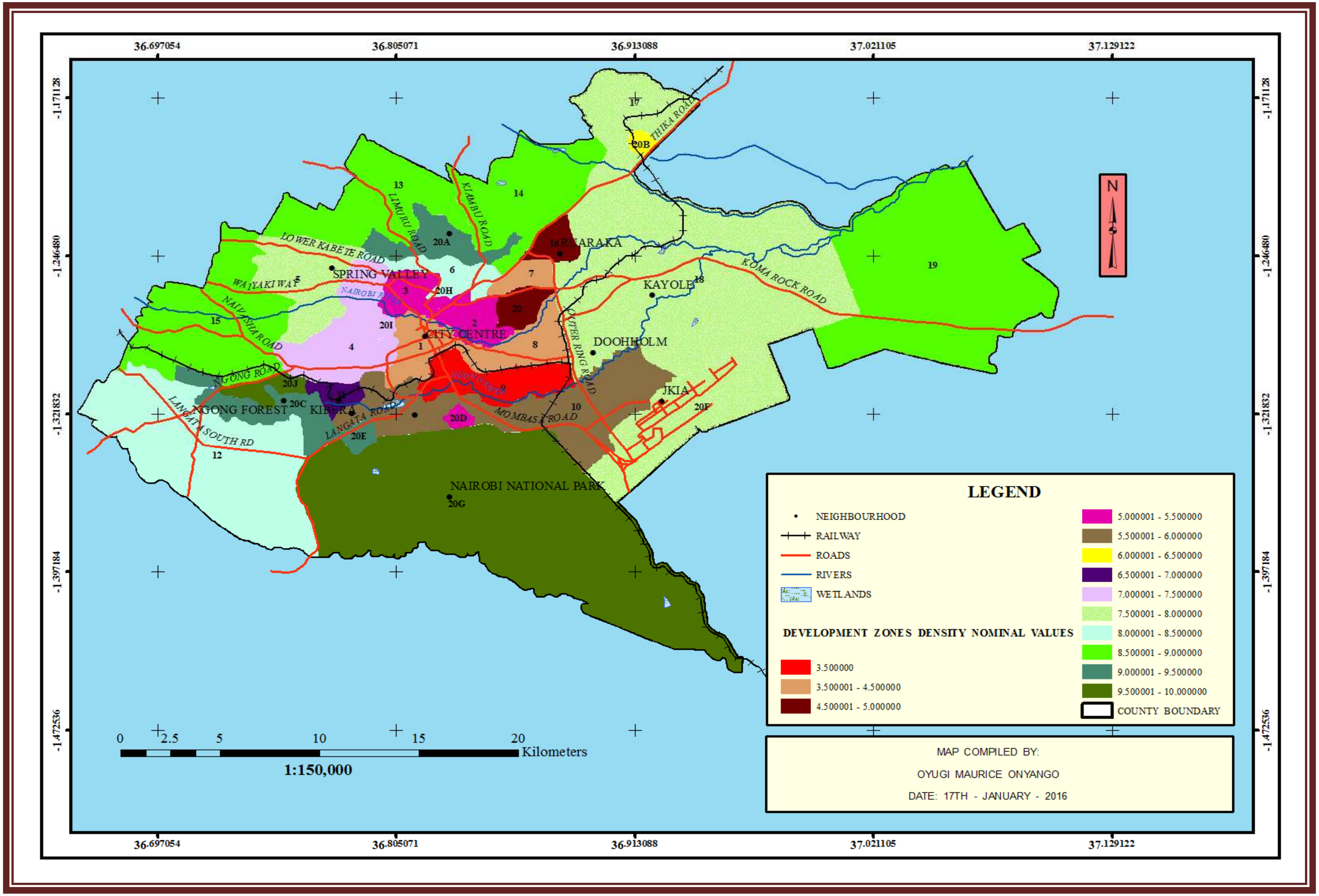

Figure 4.17. Spatial Distribution of Nairobi's Environmental Quality Based on Development Densities.

Table 4.10. Urban Form Nominal Values

Development Zones	Development Density (%)	Development Density Nominal Value	Land Use (Spatial Structure) Nominal Values	Total Urban Form Nominal Values	Urban Form Nominal Values
1	56.710748	4.5	3.909924	8.409924	**4.204962**
2	49.319672	5.5	3.393761	8.893761	**4.4468805**
3	48.556148	5.5	2.94303	8.44303	**4.221515**
4	28.036458	7.5	2.938691	10.438691	**5.2193455**
5	23.452928	8.0	3.517109	11.517109	**5.7585545**
6	17.046051	8.5	4.339698	12.839698	**6.419849**
7	57.674833	4.5	3.193575	7.693575	**3.8467875**
8	57.022857	4.5	2.81645	7.31645	**3.658225**
9	66.884362	3.5	2.229635	5.729635	**2.8648175**
10	41.467649	6.0	3.728247	9.728247	**4.8641235**
11	33.064927	7.0	4.986373	11.986373	**5.9931865**
12	16.580288	8.5	3.784665	12.284665	**6.1423325**
13	14.136434	9.0	4.216689	13.216689	**6.6083445**
14	11.290671	9.0	4.697541	13.697541	**6.8487705**
15	10.733175	9.0	5.146292	14.146292	**7.073146**
16	53.871775	5.0	2.921903	7.921903	**3.9609515**
17	20.961019	8.0	4.70022	12.70022	**6.35011**
18	25.243432	8.0	4.410786	12.410786	**6.205393**
19	13.172386	9.0	5.466758	14.466758	**7.233379**
20	53.814018	5.0	3.523711	8.523711	**4.2618555**
20A	9.0427297	9.5	7.501878	17.001878	**8.500939**
20B	35.871602	6.5	4.595745	11.095745	**5.5478725**
20C	8.0292232	9.5	7.598879	17.098879	**8.5494395**
20D	47.497805	5.5	3.826671	9.326671	**4.6633355**
20E	9.6909317	9.5	6.859062	16.359062	**8.179531**
20F	23.632255	8.0	5.771734	13.771734	**6.885867**
20G	1.3148732	10.0	7.808378	17.808378	**8.904189**
20H	19.766024	8.5	5.336874	13.836874	**6.918437**
20I	27.298526	7.5	4.976885	12.476885	**6.2384425**
20J	2.2314792	10.0	8.8945	18.8945	**9.44725**

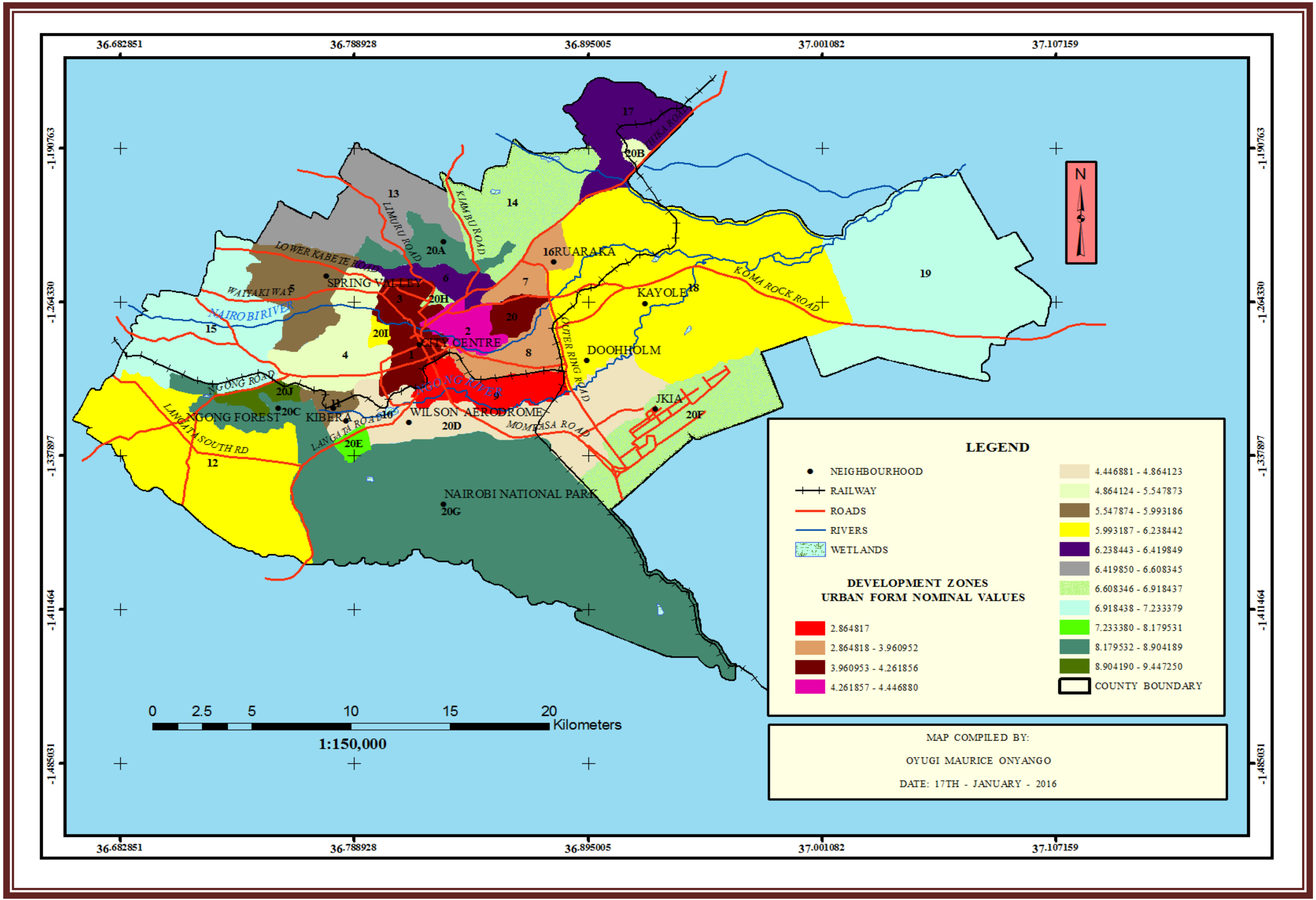

Figure 4.18. Spatial Distribution of Nairobi's Environmental Quality Based on Urban Form.

Table 4.11: Environmental Quality Variations within the City with Biomass Variations

Devt Zones	**Vegetation Categorization in the Un-built Spaces And Weightings**									**Actual Built Up Spaces (km^2)**	**Un-Built Spaces or the Open-Land (km^2)**	**The Zone's Total Land Areas (km^2)**	**The Zonal Aggregate Vegetation Density (Scale to 100%)**	**The Vegetation Density Nominal Value (Scale to 10: Aggregate VD/10)**
	Wetlands (0.3)	**Parks and Other Recreational Spaces (0.8)**	**Forests** (1.0)	**Quarry Land (0.1)**	**Undeveloped Land**				**Urban Agriculture (0.5)**					
					Short grass (0.2)	**Tall grass** (0.4)	**Shrub** (0.6)	**Small Tree** (0.7)						
1	0.00000	11.06555	0.990304	0.000000	19.92690291297487				0.000000	**4.5946226**	3.5072324	**8.101855**	31.98275691	**3.198275691**
2	0.00000	5.062841	0.000000	0.000000	24.39347754208919				0.000000	**3.5918866**	3.6909814	**7.282868**	29.45631854	**2.945631854**
3	0.00000	4.912421	1.041826	0.000000	30.98304937970983				0.000000	**3.0110299**	3.1901001	**6.20113**	36.93729638	**3.693729638**
4	0.00000	3.124143	2.852406	0.00000	44.99214346191361				0.465729	**5.8378999**	14.9846301	**20.82253**	51.43442146	**5.143442146**
5	0.00000	0.143740	4.300220	0.000000	38.01415182853201				8.880609	**4.4943926**	14.6690674	**19.16346**	51.33872083	**5.133872083**
6	0.00000	14.26105	10.87121	0.000000	37.97949957862139				0.000000	**1.149878**	5.595837	**6.745715**	63.11175958	**6.311175958**
7	0.00000	3.181539	0.127923	0.000000	15.28812854831922				0.000000	**2.3228164**	1.7046186	**4.027435**	18.59759055	**1.859759055**
8	0.00000	1.867155	0.000000	0.000000	16.25729430693				0.000000	**6.1350151**	4.6238549	**10.75887**	18.12444931	**1.812444931**
9	0.00000	3.035720	0.000000	0.043421	11.14768699186075				0.508787	**8.900389**	4.406741	**13.30713**	14.73561499	**1.473561499**
10	0.233834	4.518533	0.043177	0.162697	20.86733768285843				2.031366	**16.494168**	23.281822	**39.77599**	27.85694468	**2.785694468**
11	0.000000	8.585986	18.84272	0.000000	13.18697082169686				2.196222	**1.1047478**	2.2363992	**3.341147**	42.81189882	**4.281189882**
12	0.000000	1.365673	2.161910	0.000000	33.72676795101381				15.64657	**10.045748**	50.542752	**60.58850**	52.90091783	**5.290091783**
13	0.000000	0.000000	9.012166	0.000000	30.41782569665947				16.24075	**3.9967628**	24.2760172	**28.27278**	55.67074211	**5.567074211**
14	0.246462	5.737083	5.042728	0.089746	24.45883344433858				17.00576	**3.283633**	25.799077	**29.08271**	52.58060923	**5.258060923**
15	0.000000	1.191383	4.216238	0.000000	14.52504004964926				31.31874	**4.3616468**	36.2754132	**40.63706**	51.25140067	**5.125140067**
16	0.000000	0.000000	1.722804	0.000000	15.58174453607362				2.725530	**2.3717852**	2.0308638	**4.402649**	20.0300778	**2.00300778**
17	0.000000	0.517654	0.000000	0.330541	11.17637620594075				23.57277	**4.1856745**	15.7831755	**19.96885**	35.59734386	**3.559734386**
18	0.038743	0.445074	0.000000	0.116617	23.53515808337627				7.014946	**28.172301**	83.430199	**111.6025**	31.1505382	**3.11505382**
19	0.000000	0.000000	0.000000	0.000000	31.59508330013146				9.781616	**10.953225**	72.199705	**83.15293**	41.37669893	**4.137669893**
20	0.000000	0.000000	0.000000	0.000000	27.71158848671764				0.000000	**2.4164814**	2.0739496	**4.490431**	27.71158849	**2.771158849**
20A	0.000000	0.090579	62.45337	0.000000	18.74504260924758				0.805997	**0.9160674**	9.2143626	**10.13043**	82.09498926	**8.209498926**
20B	0.000000	0.121076	0.000000	0.000000	19.82874503853213				15.46457	**0.5413491**	0.9677809	**1.50913**	35.41439372	**3.541439372**
20C	0.083834	2.114637	57.90776	0.000000	16.15781578136139				4.028845	**1.0001779**	11.4565421	**12.45672**	80.29289628	**8.029289628**
20D	0.000000	12.36444	0.000000	0.000000	14.81865947027431				0.000000	**0.6438299**	0.7116641	**1.355494**	27.18309635	**2.718309635**
20E	0.000000	58.73321	0.000000	0.000000	6.757021439463436				0.000000	**0.2233219**	2.0811201	**2.304442**	65.49023321	**6.549023321**
20F	0.000000	0.391730	0.000000	0.000000	37.93903355739015				0.000000	**7.5797408**	24.4939692	**32.07371**	38.33076373	**3.833076373**
20G	0.049603	76.07395	0.088304	0.000000	1.823707152418088				0.149776	**1.6945100**	127.17799	**128.8725**	78.18533939	**7.818533939**
20H	0.000000	38.93112	0.000000	0.000000	22.09905695722698				0.00000	**0.1793743**	0.7281137	**0.907488**	61.03017696	**6.103017696**
20I	0.000000	11.54645	7.571148	0.000000	35.48808159168221				0.00000	**0.3524546**	0.9386574	**1.291112**	54.60567959	**5.460567959**
20J	0.000000	16.89791	65.05639	0.000000	7.099584332155229				0.723742	**0.0904257**	3.9618483	**4.052274**	89.7776214	**8.97776214**

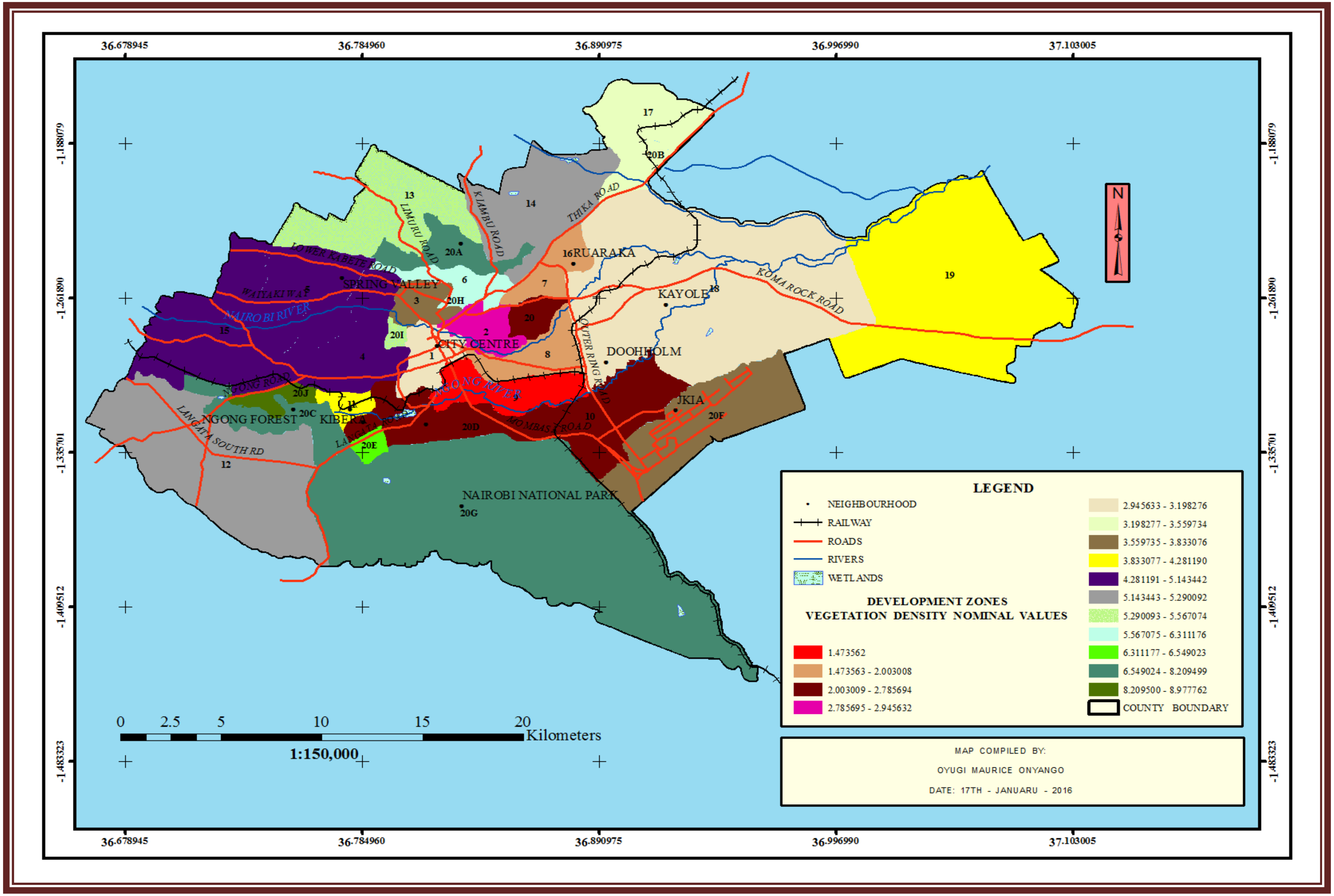

Figure 4.19. The Distribution of the Nairobi's Environmental Quality Based on Biomass Values.

The relationship existing between urban morphology and the environmental quality is demonstrated by the 19th century's industrial cities of Europe. At the peak of industrialization, these cities experienced population influx which they accommodated through increased development densities. This led to loss of biodiversity, increased air pollution and deteriorating quality of life. This made majority of the urban inhabitants to move their residents outside the cities, leading to formation of suburbs and urban sprawl as is currently being experienced in Nairobi. Therefore, urban morphology is a significant determinant of urban environmental quality and sustainability. However, for the achievement of urban sustainability, urban morphology must be accompanied by strong transportation system and well-planned infrastructure (Jenks, 2000; Richardson *et al.* 2000). This point to the fact that the various planning epochs which Nairobi has gone through since its establishment as a colonial city has not been appropriate. It is therefore apparent that the deterioration of Nairobi's environmental quality even though shaped by the morphology, it has also been complicated by inadequate infrastructure provision and weak transportation network. The above being the case, this study established how environmental quality of Nairobi City varies with urban morphological parameters of spatial structure (land uses), development density and the vegetation (index) density. The findings of the analysis is presented in Table 4.12 and further spatially presented in Figure 4.20 which illustrates how environmental quality varies with the city's morphological changes.

Table 4.12. Environmental Quality Variations within the City with Morphological Changes

Development Zones	Urban Form Nominal Values		Vegetation Density Nominal Values (VDNV)	Aggregate Urban Morphology Nominal Values (DDNV+LUNV+VDNV)	Average Urban Morphology Nominal Values (DDNV+LUNV+VDNV)/3
	Development Density Nominal Value (DDNV)	Land Use Or Urban Spatial Structure Nominal Values (LUNV)			
1	4.5	3.909924	3.198275691	11.60819969	**3.869399897**
2	5.5	3.393761	2.945631854	11.83939285	**3.946464285**
3	5.5	2.94303	3.693729638	12.13675964	**4.045586546**
4	7.5	2.938691	5.143442146	15.58213315	**5.194044382**
5	8.0	3.517109	5.133872083	16.65098108	**5.550327028**
6	8.5	4.339698	6.311175958	19.15087396	**6.383624653**
7	4.5	3.193575	1.859759055	9.553334055	**3.184444685**
8	4.5	2.81645	1.812444931	9.128894931	**3.042964977**
9	3.5	2.229635	1.473561499	7.203196499	**2.4010655**
10	6.0	3.728247	2.785694468	12.51394147	**4.171313823**
11	7.0	4.986373	4.281189882	16.26756288	**5.422520961**
12	8.5	3.784665	5.290091783	17.57475678	**5.858252261**
13	9.0	4.216689	5.567074211	18.78376321	**6.261254404**
14	9.0	4.697541	5.258060923	18.95560192	**6.318533974**
15	9.0	5.146292	5.125140067	19.27143207	**6.423810689**
16	5.0	2.921903	2.00300778	9.92491078	**3.308303593**
17	8.0	4.70022	3.559734386	16.25995439	**5.419984795**
18	8.0	4.410786	3.11505382	15.52583982	**5.17527994**
19	9.0	5.466758	4.137669893	18.60442789	**6.201475964**
20	5.0	3.523711	2.771158848672	11.29486985	**3.764956616**
20A	9.5	7.501878	8.209498926	25.21137693	**8.403792309**
20B	6.5	4.595745	3.541439372	14.63718437	**4.879061457**
20C	9.5	7.598879	8.029289628	25.12816863	**8.376056209**
20D	5.5	3.826671	2.718309635	12.04498064	**4.014993545**
20E	9.5	6.859062	6.549023321	22.90808532	**7.63602844**
20F	8.0	5.771734	3.833076373	17.60481037	**5.868270124**
20G	10.0	7.808378	7.818533939	25.62691194	**8.54230398**
20H	8.5	5.336874	6.103017696	19.9398917	**6.646630565**
20I	7.5	4.976885	5.460567959	17.93745296	**5.979150986**
20J	10.0	8.8945	8.97776214	27.87226214	**9.290754047**

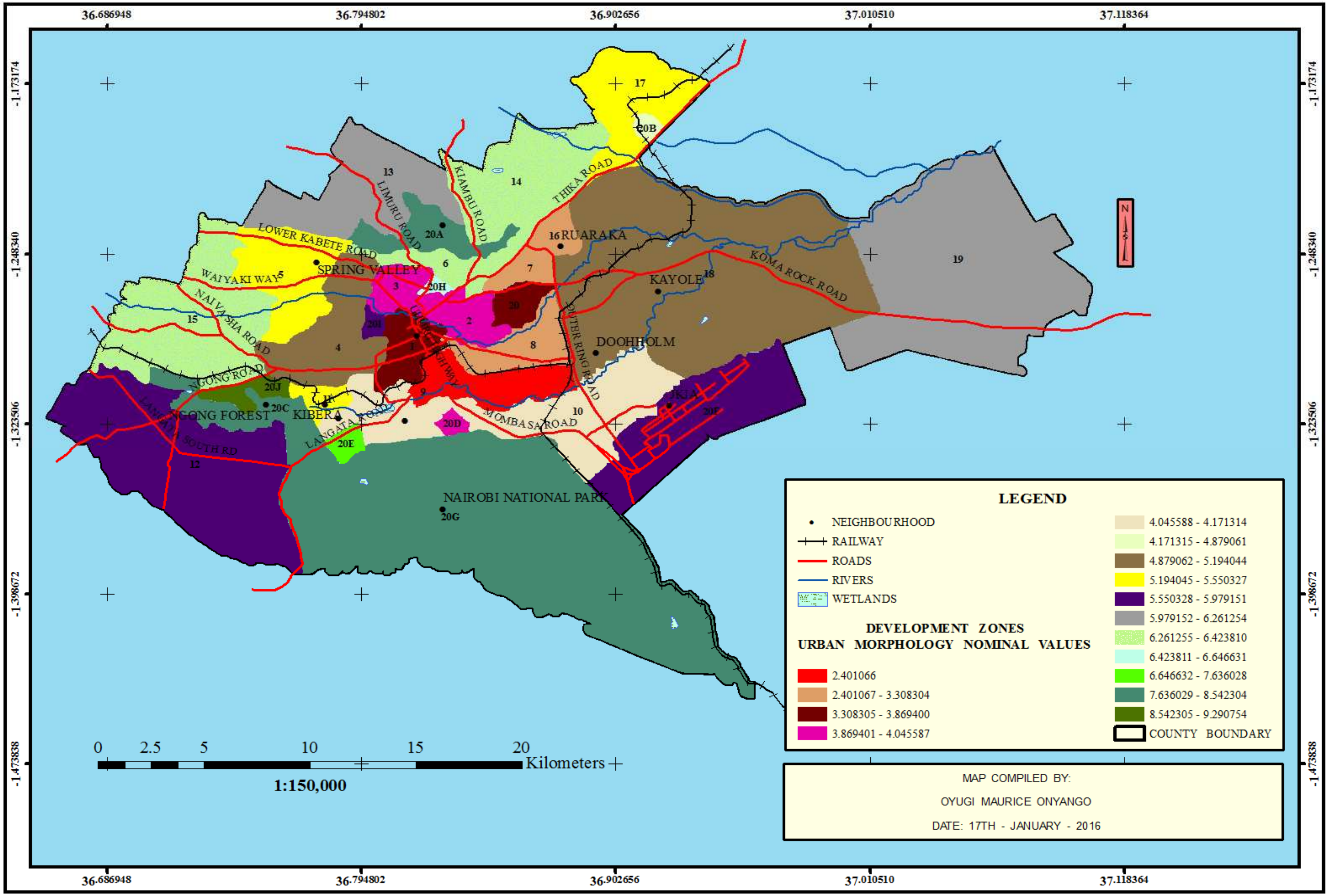

Figure 4.20. Spatial Distribution of the Nairobi City's Environmental Quality Based on the Urban Morphology.

4.6 The Effects of Urban Morphology on the Environmental Quality of the City

Higher urbanization rates present a major challenge to urban sustainability especially to the developing countries which are characterised by low technical and financial capacities for urban environmental management. In the recent decades, realisation that global warming and climate change is caused and exacerbated by increased urbanisation and GHG emissions has heightened studies on the links between urbanisation indicators such as development densities, land uses, vegetation index and the environmental quality parameters such as the urban heat islands, air quality, climate change and global warming. The urban morphological attributes notably the development densities, building materials and configurations, street orientations and widths, man-made structures and green belts attenuates wind flow within the street canyons and the urban canopy layers which in turn affects the distribution of the urban thermal values as well as the dispersal and concentration of the air pollutants. The above further explains the occurrences of higher surface temperatures in the cities relative to their hinterlands. Scholars therefore agree that there is a significant relationship existing between urban morphology and the urban environmental quality parameters of surface temperatures and air quality. The fundamental question is therefore to what extent are individual urban morphological parameters determining the urban environmental quality distribution.

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4.6.1 The Surface Temperature Distribution in the City

The determination of the relationship existing between the city’s morphological parameters of land use, development density and biomass index and the environmental quality parameter of surface temperature were undertaken as detailed out in chapter three. The findings on the same are presented in Figures 4.21 to 4.26 and Tables 4.13 and 4.14.

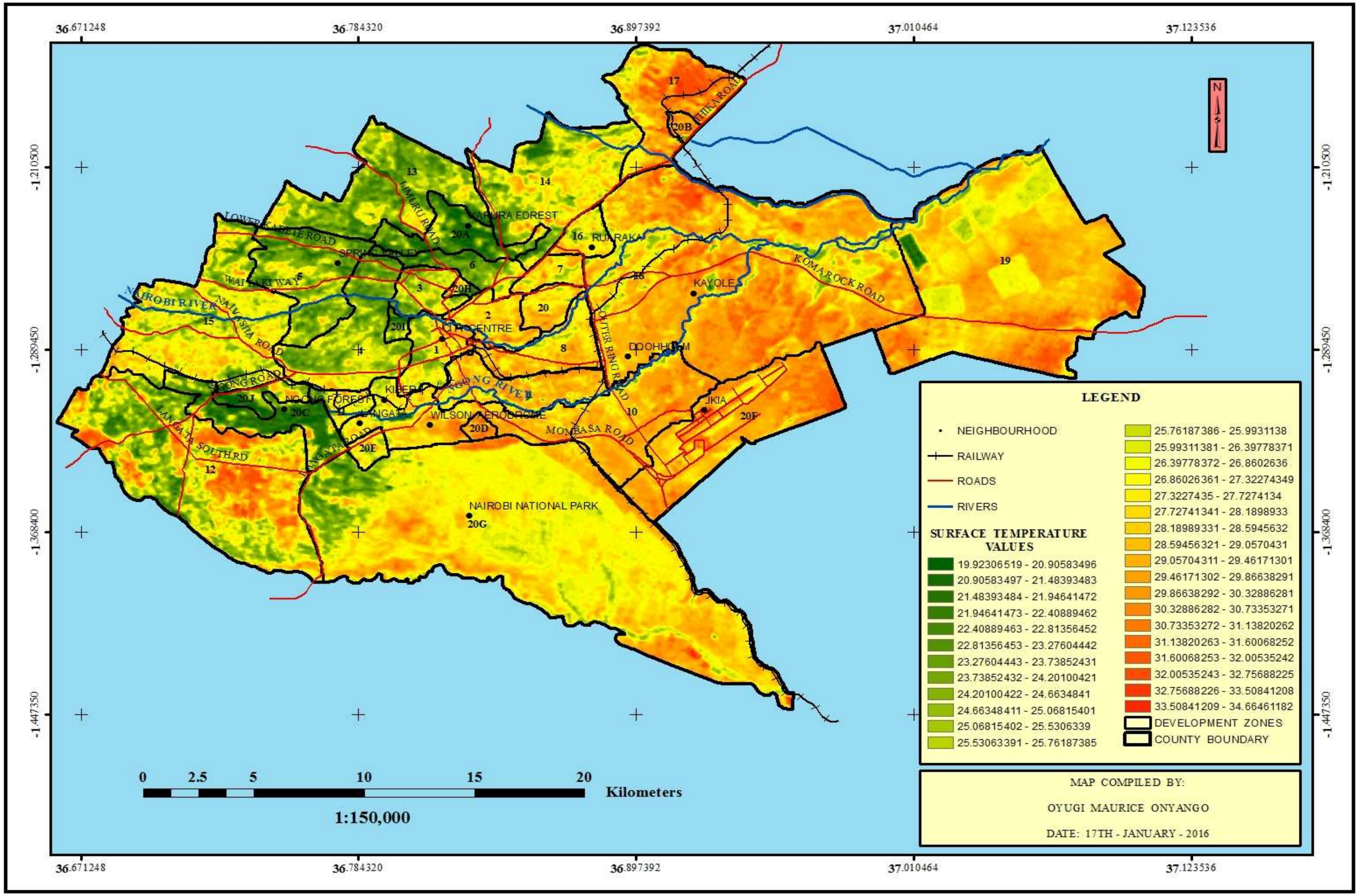

Figure 4.21. The Spatial Distribution of the Surface Temperature Values of Nairobi City in the Year 1988.

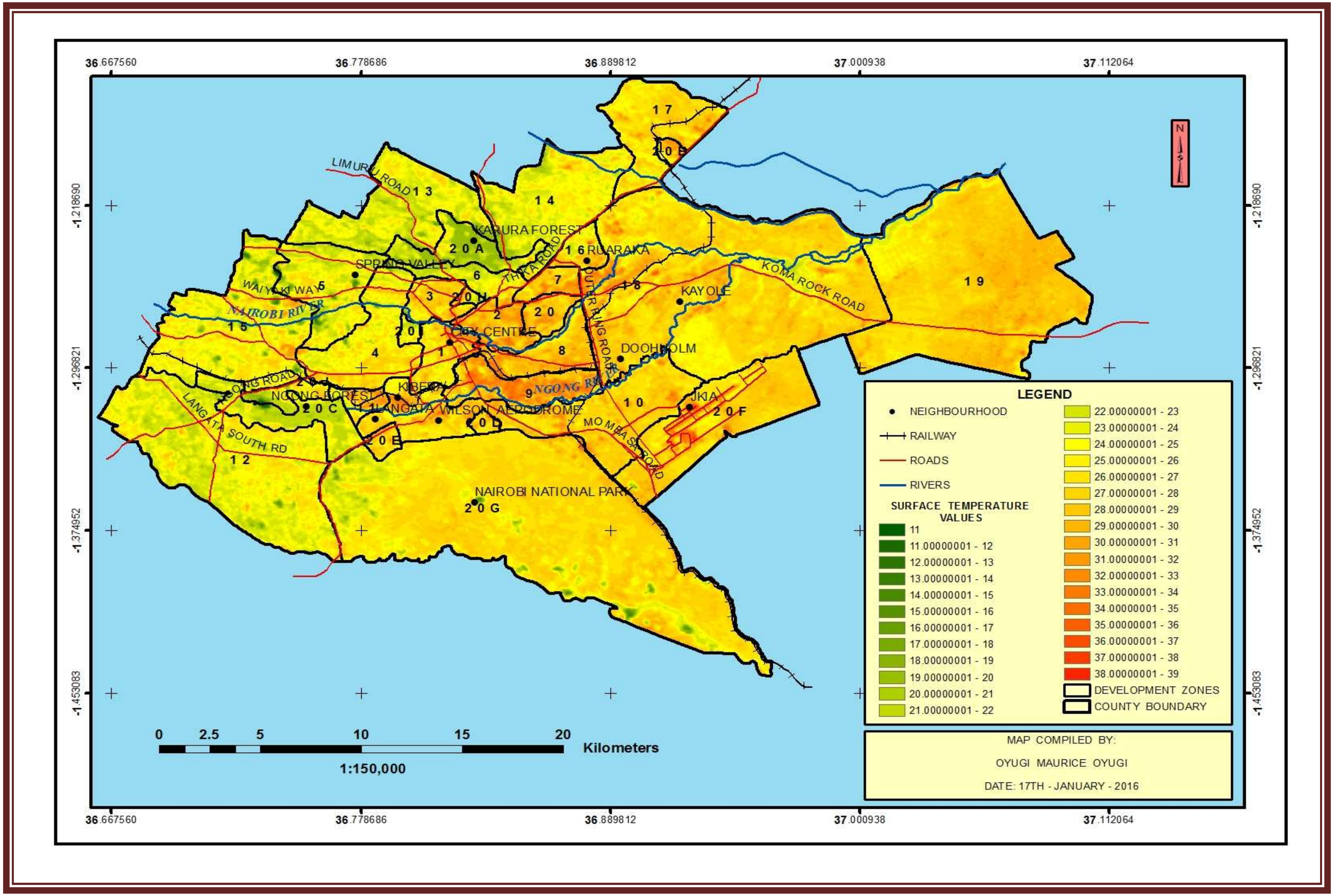

Figure 4.22. The Spatial Distribution of the Surface Temperature Values of Nairobi City in the Year 1995.

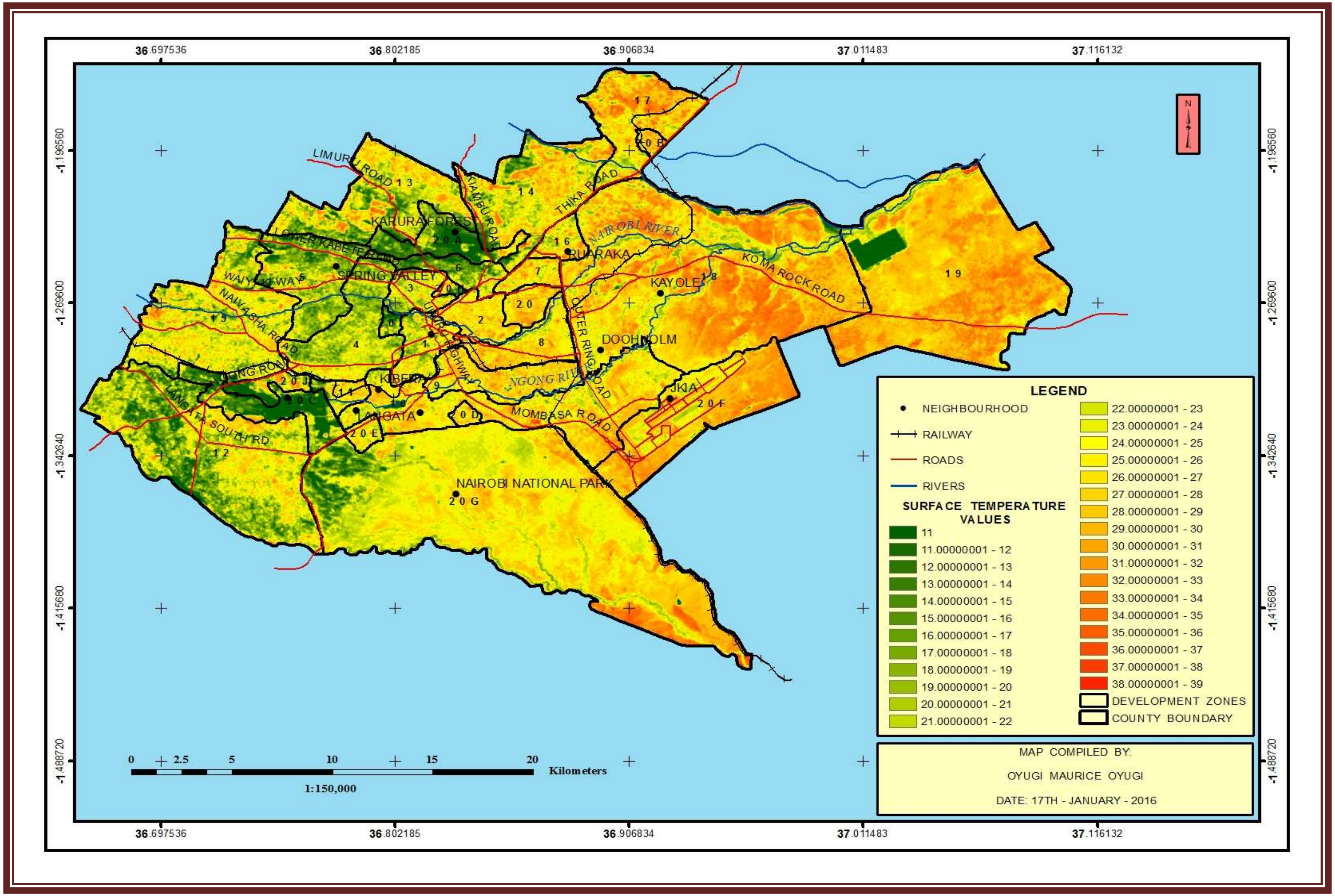

Figure 4.23. The Spatial Distribution of the Surface Temperature Values of Nairobi City in the Year 2000.

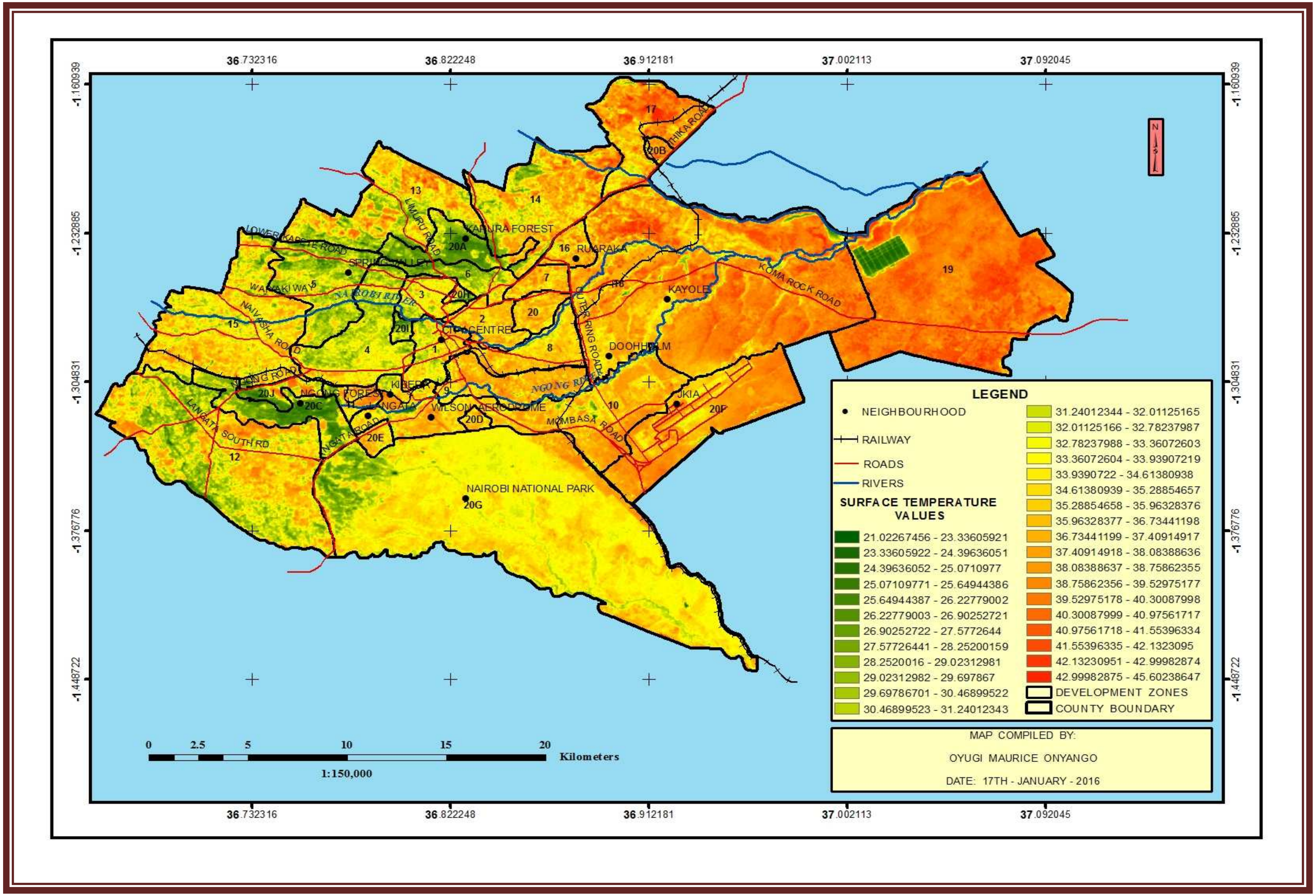

Figure 4.24. The Spatial Distribution of the Surface Temperature Values of Nairobi City in the Year 2005.

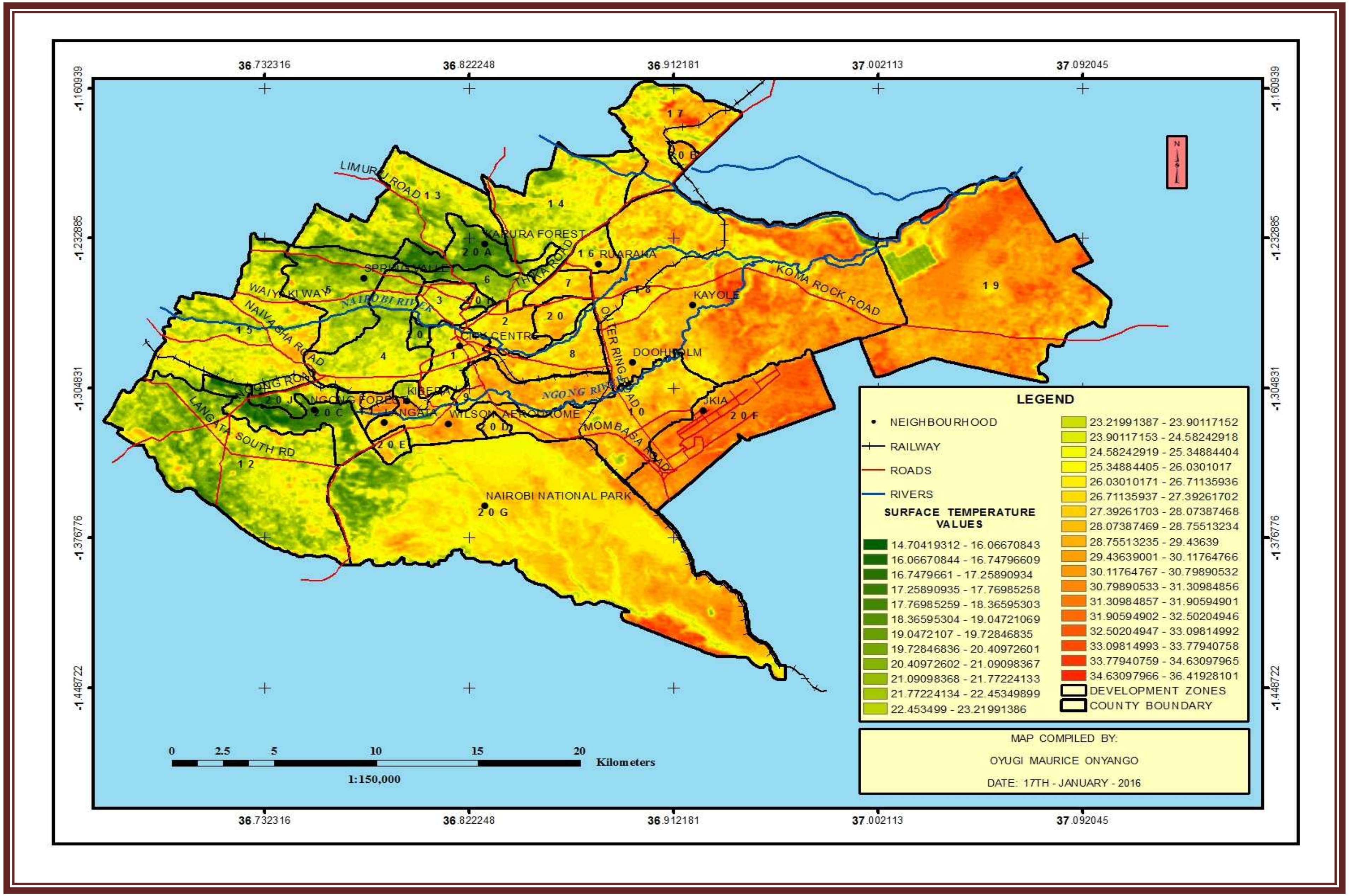

Figure 4.25. The Spatial Distribution of the Surface Temperature Values of Nairobi City in the Year 2010.

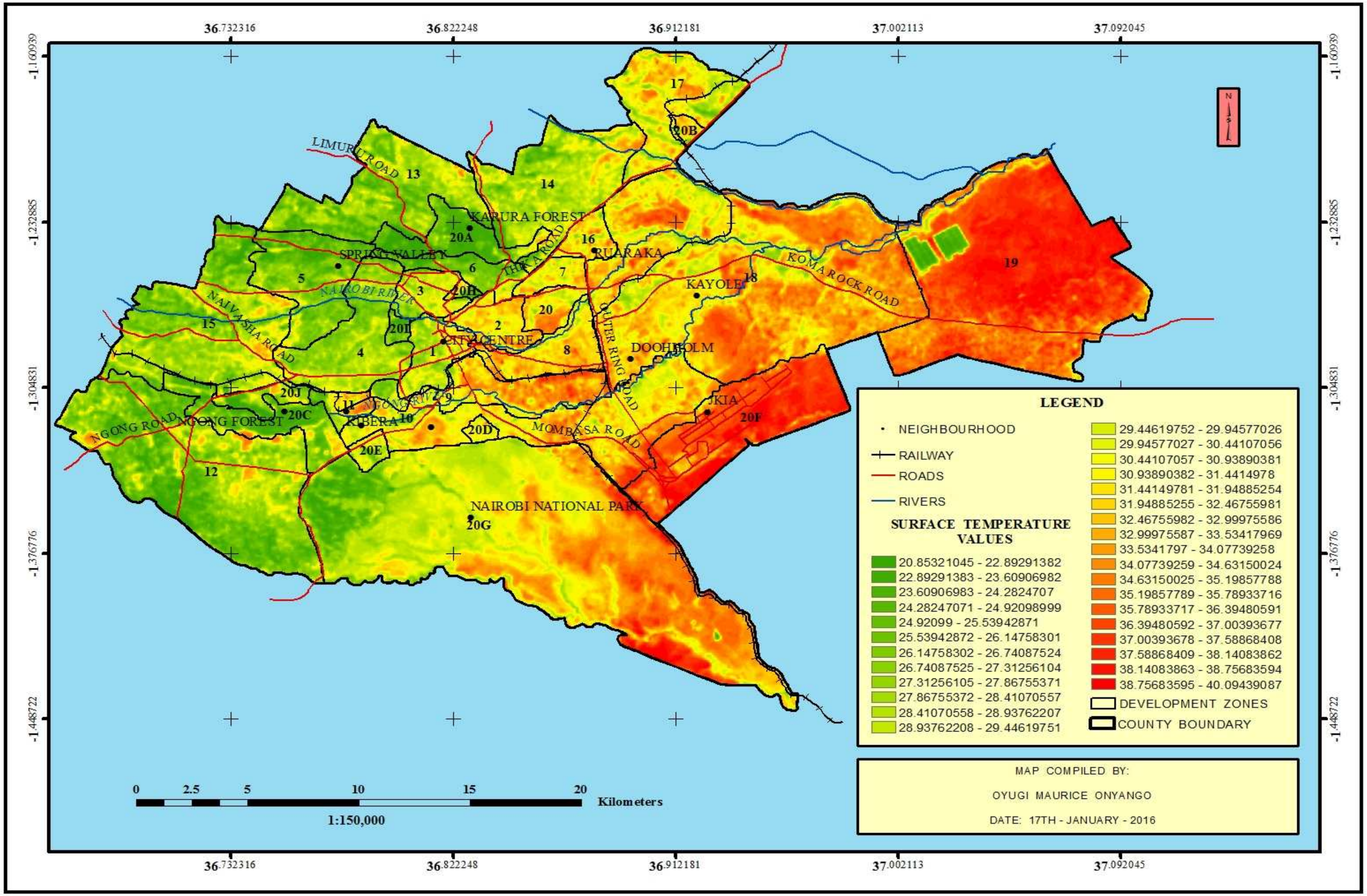

Figure 4.26. The Distribution of the Surface Temperature Values within Nairobi City in the Year 2015.

To corroborate the relationship existing between urbanisation, global warming and climate change, average surface temperature values of the city for the years under consideration were computed (results shown in Table 4.13) alongside the size of land under built-up, open and transitional areas as well as size of land under vegetation cover. Calculations of average surface temperatures values per development zone for the year 2015 was also undertaken and converted into numerical values ranging from 1 to 10 as illustrated by Table 4.14 and further transformed into Figure 4.27 showing the city's environmental quality distribution based on surface temperatures.

Table 4.13. Average Surface Temperature Values, Built-Up/Open/Transitional and Vegetation Cover Areas

Years	Average Surface Temperature Values (^{0}C) (Y)	Urban Built-Up/Open/Transitional Areas (km^2) (X_1)	Vegetation Areas (km^2) (X_2)	Total Area (km^2)
1988	24.4	73.076	640.45	716.22
1995	25.5	124.36	587.14	
2000	28.3	155.20	556.18	
2005	28.7	175.19	537.40	
2010	29.4	183.97	529.20	
2015	29.7	228.65	483.47	

The relationship existing between the size of land under built-up, open and transitional areas and the surface temperatures is strong relationship corroborated by a correlation coefficient (r) value of 0.948 and a calculated *t*-value of 5.94 compared to a critical *t*-value of 2.78. While the calculated F-value of the relationship existing between the two variables is 35.284, the critical F-value is 7.71. This confirms that the relationship existing between the variables under consideration is significantly strong and is not occurring by chance. Similarly, the relationship existing between the size of land under vegetation cover and the surface temperatures presents a significant relationship evidenced by a correlation coefficient (r) value of -0.946 and a calculated *t*-value of 5.843 compared to a critical *t*-value of 2.78. The calculated and critical F-values for the relationship are 34.136 and 7.71 respectively. This confirms that the relationship existing between the vegetation cover and surface temperatures is significantly strong and is not occurring by chance.

The model representing the relationship existing between the surface temperatures, the size of land under built-up, open and transitional areas and the vegetation cover is represented by equation 4.1.

$$\acute{Y} = 0.286X_1 + 0.247X_2 - 154.254 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.1)}$$

Where: -

$\acute{Y}$ = Estimated Surface Temperature Values

X_1 = Size of land under Urban Built-Up, Open and Transitional Areas

X_2 = Size of Land under Vegetation Cover

Other statistics for the above stated relationship are as follows:-

t_1 = The calculated *t*-value attributed to the size of land under Built-Up, Open and Transitional Areas which is 6.27

t_2 = The calculated *t*-value attributed to the size of land under vegetation cover which is 5.42

t_3 = The calculated *t*-value attributed to the error term (constant) which is 4.75

F = Calculated F-value of the relationship which is 14.673

The results confirm that in concert, urban built-up, open and transitional elements are the most significant determinant of the urban surface temperatures relative to vegetation cover. However, the significance of the t-value attributed to the error term (4.75) in the model implies that apart from the built-up, open, transitional areas and the vegetation cover, other variables which are not considered by this relationship significantly explain the spatial distribution of the surface temperatures within the city.

Table 4.14. Average Surface Temperature values within the Development Zones of the City by the Year 2015

Development Zones	Average Surface Temperatures	Surface Temperature Nominal Values
1	29.33	6.33
2	31.73	4.66
3	29.01	6.33
4	27.79	7.33
5	26.17	7.99
6	26.23	7.99
7	30.92	5.33
8	32.11	4.33
9	32.85	3.99
10	31.66	4.66
11	30.25	5.66
12	26.81	7.66
13	27.13	7.66
14	28.76	6.66
15	27.61	7.33
16	31.20	4.99
17	30.68	5.33
18	32.68	3.99
19	36.06	1.99
20	31.93	4.66
20A	24.63	8.99
20B	31.24	4.99
20C	26.12	8.33
20D	30.80	5.33
20E	29.40	6.33
20F	36.61	1.66
20G	31.29	4.99
20H	28.07	6.99
20I	25.32	8.66
20J	27.12	7.66

Figure 4.27 corroborate that Nairobi’s surface temperatures broadly manifesting in four temperature zones namely; the northern and western, southern, eastern and central zones is influenced by the interactions and variations in vegetation types and density, urban form, topographical and pedological base of the city. The red volcanic soils characterising the northern and western parts of the city are rich in nutrients and humus thus supports

vegetation growth which are effective moderators of surface temperatures. Contrary to the above, southern and eastern parts of the city characterised by undulating plains and black cotton soils with low nutrient contents supports sparse vegetation cover such as the disturbed bushes, shrubs, perennial grasses and under storey trees which are inadequate moderators of the surface temperatures. Therefore, the presence of Ngong and Karura forests and higher topographies to the northern and western parts of the city, coupled with low development densities characterising the neighbourhoods have acted in concert towards the achievement of lower surface temperatures in the zones as compared to higher surface temperatures being experienced in the southern and eastern parts of the city, further characterised by high development densities and dominance of land uses such as transportation, industrial developments and quarries which enhances thermal values. The central part of the city characterised by mixtures of red volcanic and black cotton clay soils supports moderate vegetation growth thus the zone experiences moderate surface temperatures.

4.6.2 Air Quality Distribution in the City

Improved economic growth, inadequate public transportation and rural-urban migration waves into the African cities have contributed to increased vehicular volume and gaseous emissions in the cities, making air pollution a significant problem facing African cities today. Currently, out of the 8.5 million registered cars in Kenya, approximately 5.0 million operate within Nairobi and its environs. The expanding vehicular volume has made traffic snarl and increased air pollution a permanent feature in the city. This has made Nairobi to globally rank fourth in transportation problems (UNEP, 2011; Njeru, 2010). It is projected that should the trend continue, the number of vehicle trips will increase by 148% in the year 2025 while the average speed will reduce from 35 km/hr to 11km/hr (Irungu, 2007).

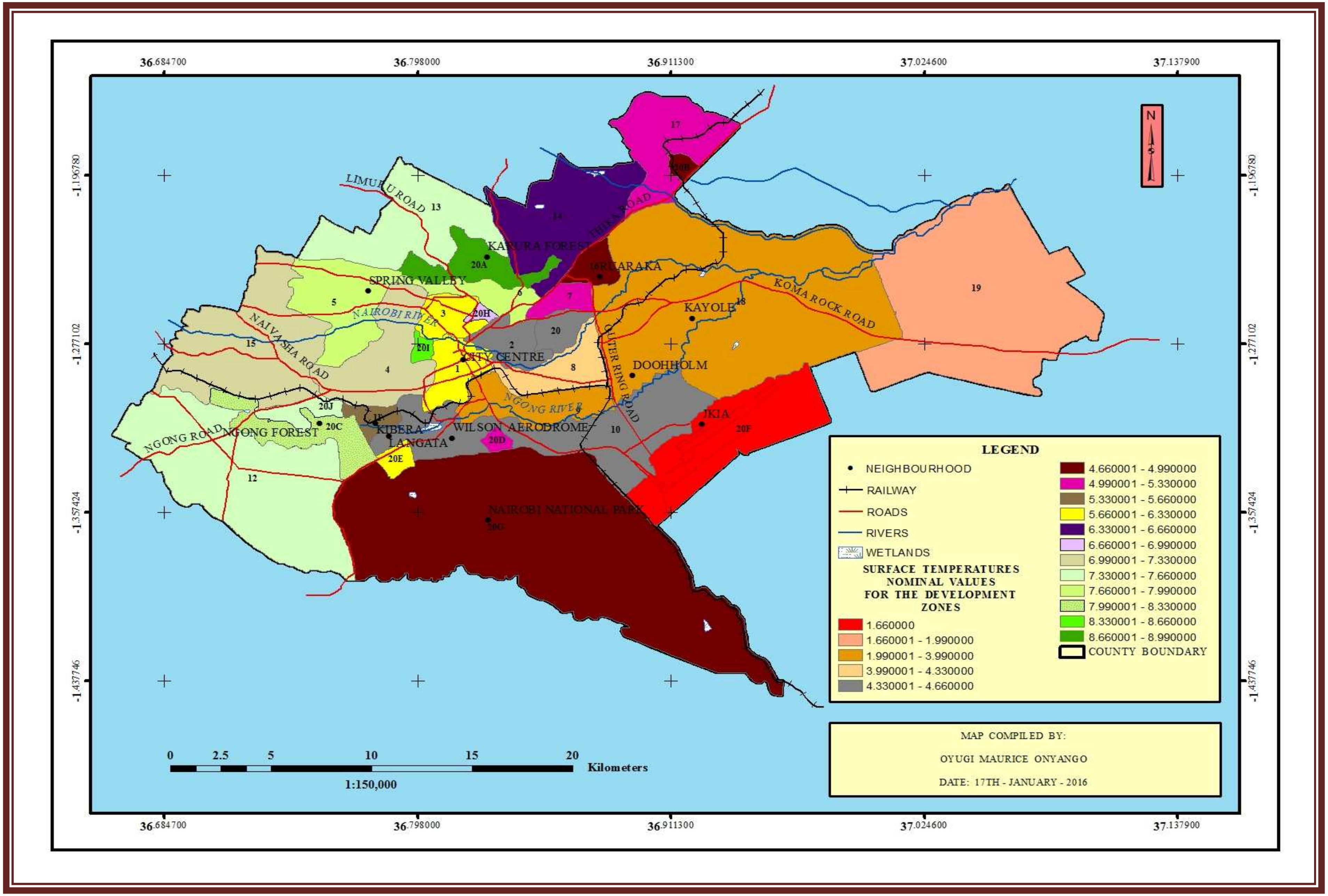

Figure 4.27. The Distribution of the Nairobi City's Environmental Quality Based on Surface Temperature Nominal Values.

Motor vehicles emit GHGs, suspended particulate matter, sulphur dioxide and a wide range of volatile organic compounds which react with sunlight to deplete the ozone layer. These pollutants have health effects which manifests in chest congestion, coughs, phlegm, sore throats and asthmatic attacks (Kinney *et al.* 2000; Hedley *et al.* 2003; Frumkin *et al.* 2004; Schwela *et al.* 2006). Of all these pollutants, $SPM_{2.5}$ which is a complex mixture of solid and liquid organic and inorganic particles less than or equal to 2.5 μm in diameter is of particular significance on climate change and health effects. Their small sizes enables them to penetrate deeply into the lungs where they exert adverse effects such as lung and heart diseases as well as exacerbating post-neonatal infant mortality (Woodruff *et al.* 2006; Pope *et al.* 2002).

The study reveals gradual decrease in gaseous concentrations from the CBD, industrial areas and satellite commercial centres in the city. The CBD, industrial areas and satellites commercial centres being employment zones, they attract increased vehicular volume which heightens the concentration of air pollutants. The above is complicated by the high development densities characterising the neighbourhoods which attenuates wind velocity and diminish the vegetation cover to consequently reduce the purification ability of the ecosystem as well as the dispersal of air pollutants. Therefore, urban morphological parameters of form, building configuration and vegetation density influence the emissions, concentration and the distribution of the air pollutants. As illustrated by Tables 4.11 and 4.15, development zones with high vegetation densities such as zones 5, 6, 12, 13, 15, 20A, 20C, 20G and 20J have comparatively low gaseous concentrations as compared to development zones such as 1, 2, 7, 8, 9, 10, 11, 16, 18, 20, 20D and 20F having low to moderate vegetation densities. Figures 4.28 to 4.31 shows that carbon dioxide is the widest spread form of air pollutant within the city followed by nitrogen dioxide, sulphur dioxide and SPM respectively.

Table 4.15. Air Quality Values by Development Zones

Development Zones	Average Carbon Dioxide Values (ppm)	Carbon Dioxide Nominal Values	Average Nitrogen Dioxide Values (ppb)	Nitrogen Dioxide Nominal Values	Average Sulphur Dioxide Values (ppb)	Sulphur Dioxide Nominal Values	Average Suspended Particulate Matter Values (μg/m^3).	Suspended Particulate Matter Nominal Values	Total Air Quality Nominal Value	Average Air Quality Nominal Values
1	375.3273843	1.333	21.86913711	4.333	1.397931058	5.000	43.72404238	7.000	**17.666**	4.4165
2	375.1562179	1.333	24.08439951	3.667	1.358070192	5.000	41.88220662	7.000	**17.000**	4.250
3	268.4218268	4.667	12.93441631	7.000	0.798339207	7.667	23.36334382	8.333	**27.667**	6.91675
4	324.0294942	3.000	11.68104379	7.333	0.666766093	8.333	12.48244554	9.333	**27.999**	6.99975
5	199.4764376	7.000	6.315895618	9.000	0.365695683	9.667	7.567126579	10.000	**35.667**	8.91675
6	234.1673709	5.667	12.57827583	7.000	0.803199297	7.667	18.03380061	9.000	**29.334**	7.3335
7	318.5097735	3.000	21.45816891	4.333	1.465730172	4.667	55.37760608	6.000	**18.0**	4.500
8	398.6804694	1.000	29.31761554	1.667	1.808466573	3.000	84.28560067	3.667	**9.334**	2.3335
9	401.9675657	1.000	28.96772961	2.000	1.816320299	3.000	78.61983023	4.000	**10.0**	2.500
10	362.626869	2.000	27.60711981	2.333	1.762184159	3.333	76.63912285	4.333	**11.999**	2.99975
11	358.5499133	2.000	13.63908258	6.667	0.835341155	7.333	11.65364038	9.333	**25.333**	6.33325
12	135.5655819	8.667	6.622561647	9.000	0.36217547	9.667	10.79895334	9.667	**37.001**	9.25025
13	124.5467562	9.333	4.595086208	9.667	0.369259815	9.667	8.507089279	9.667	**38.334**	9.5835
14	189.8899161	7.333	11.33188243	7.333	0.80915219	7.667	27.1808831	8.333	**30.666**	7.6665
15	174.4507973	7.667	7.294112862	9.000	0.438063904	9.333	12.59978068	9.333	**35.333**	8.83325
16	263.7350627	4.667	17.34500771	5.667	1.242635325	5.667	49.02674775	6.333	**22.334**	5.5835
17	210.2820608	6.333	10.68198597	7.667	0.721077403	8.000	21.96880433	8.667	**30.667**	7.66675
18	260.8261195	5.000	16.32927622	6.000	1.209257799	5.667	51.32106164	6.333	**23.0**	5.750
19	202.1560919	6.667	11.15233881	7.667	0.569948411	8.667	32.43101898	7.667	**30.668**	7.667
20	371.9426306	1.667	26.70740964	2.667	1.715084576	3.333	73.52696337	4.333	**12.0**	3.000
20A	145.3792615	8.667	6.732592711	9.000	0.493918793	9.000	11.58751579	9.333	**36.0**	9.000
20B	201.7935974	6.667	8.659917943	8.333	0.764914871	7.667	17.05190196	9.000	**31.667**	7.91675
20C	237.6714935	5.667	7.53512697	8.667	0.496232504	9.000	10.79959952	9.667	**33.001**	8.25025
20D	360.9959661	2.000	25.1470125	3.000	1.547699702	4.333	51.21925666	6.333	**15.666**	3.9165
20E	272.3380896	4.667	13.65203775	6.667	0.864961293	7.333	10.41057682	9.667	**28.334**	7.0835
20F	278.5826401	4.333	21.93822999	4.333	1.265380307	5.333	68.29905488	5.000	**18.999**	4.74975
20G	247.0387195	5.333	19.47446247	5.000	0.938395711	7.000	44.58954019	6.667	**24.0**	6.000
20H	290.3748531	4.000	16.3730929	6.000	1.030352718	6.667	24.30142724	8.333	**25.0**	6.250
20I	333.1562179	2.667	15.3906373	6.333	0.851202158	7.333	18.95711386	8.667	**25.0**	6.250
20J	282.2623537	4.333	7.339038467	9.000	0.493517397	9.000	12.54840178	9.333	**31.666**	7.9165

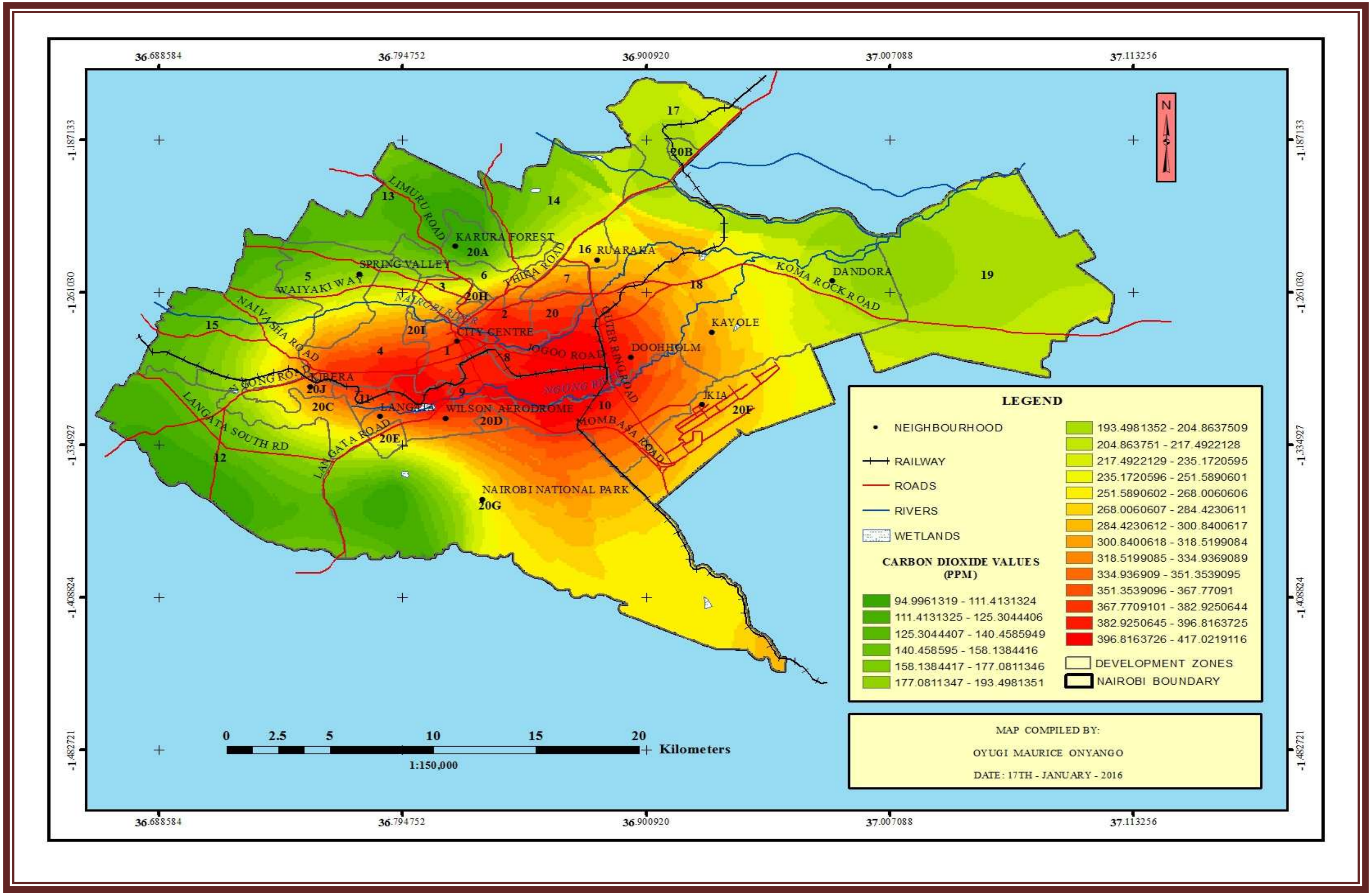

Figure 4.28. The Distribution of Carbon Dioxide Values in the City.

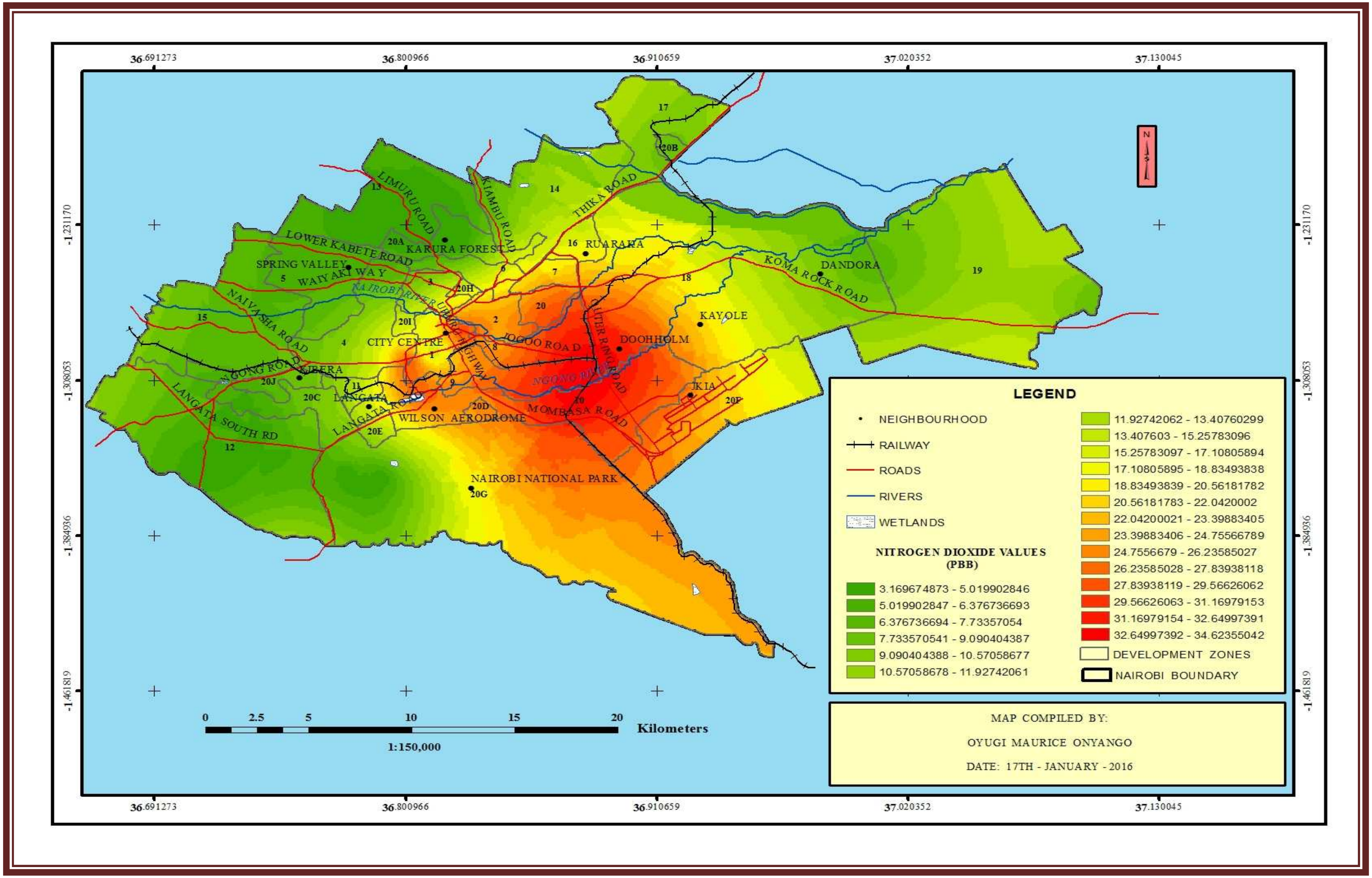

Figure 4.29. The Spatial Distribution of Nitrogen Dioxide Values in the City.

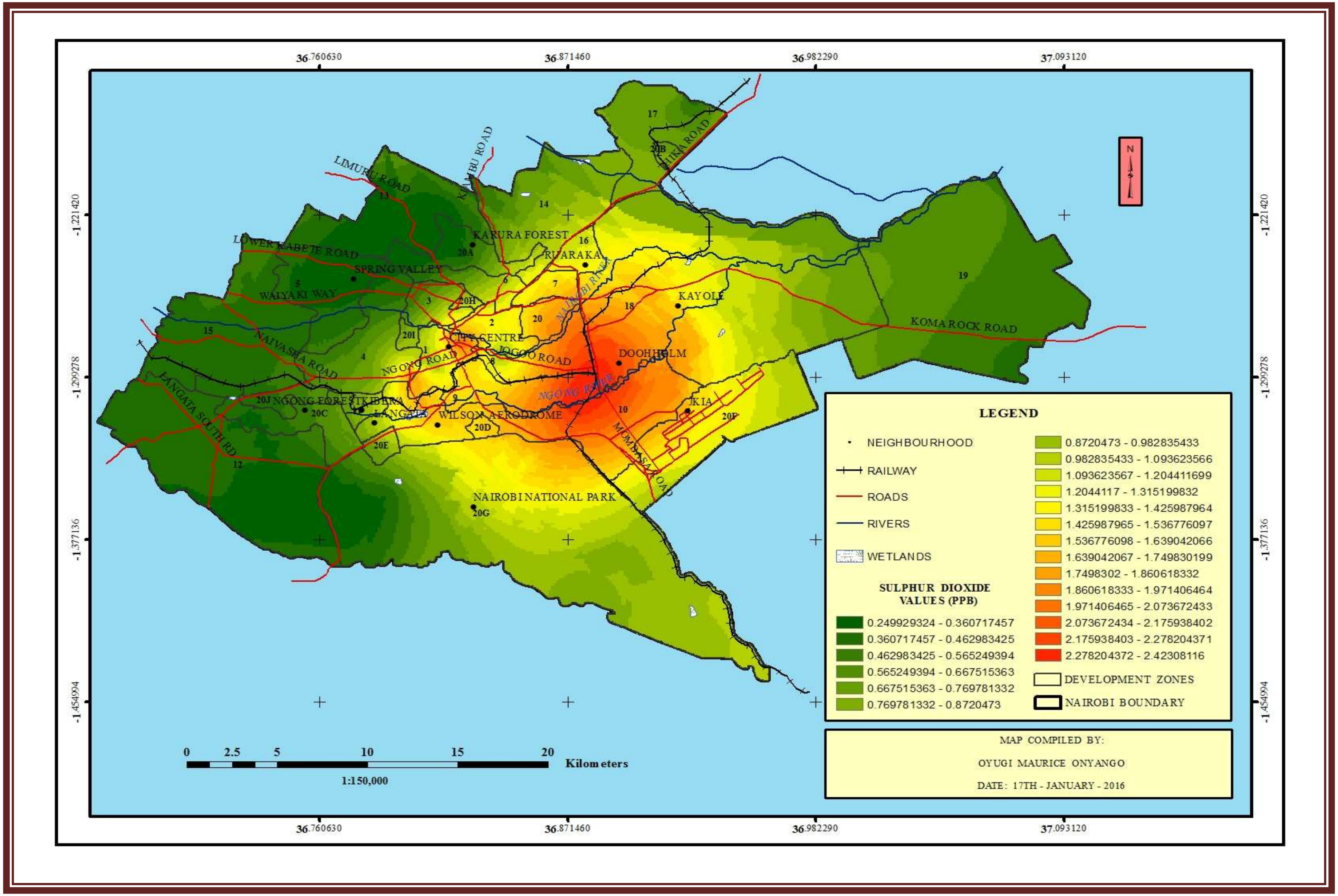

Figure 4.30. The Distribution of Sulphur Dioxide Values in the City.

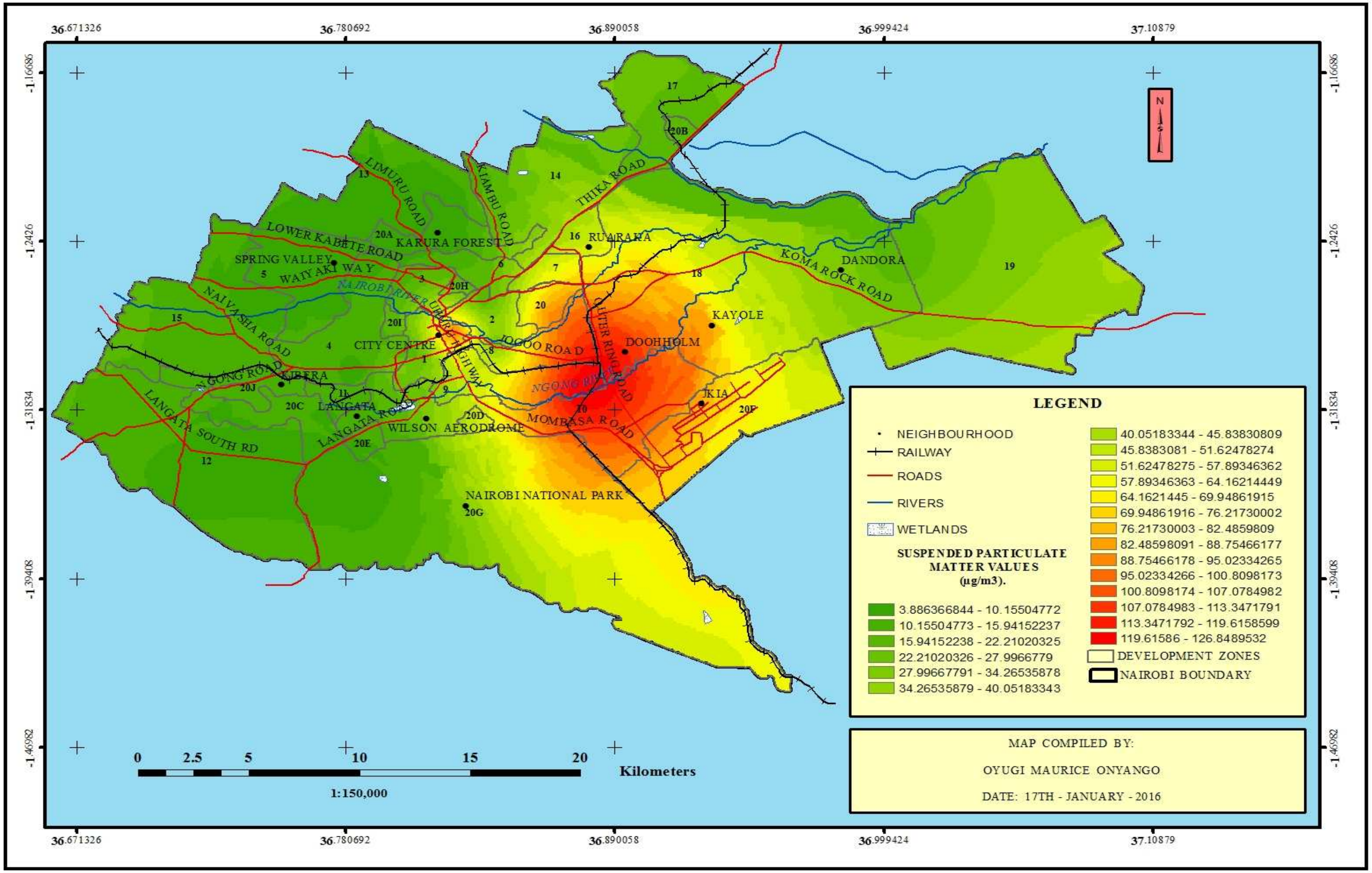

Figure 4.31. The Distribution of the Suspended Particulate Matter Values.

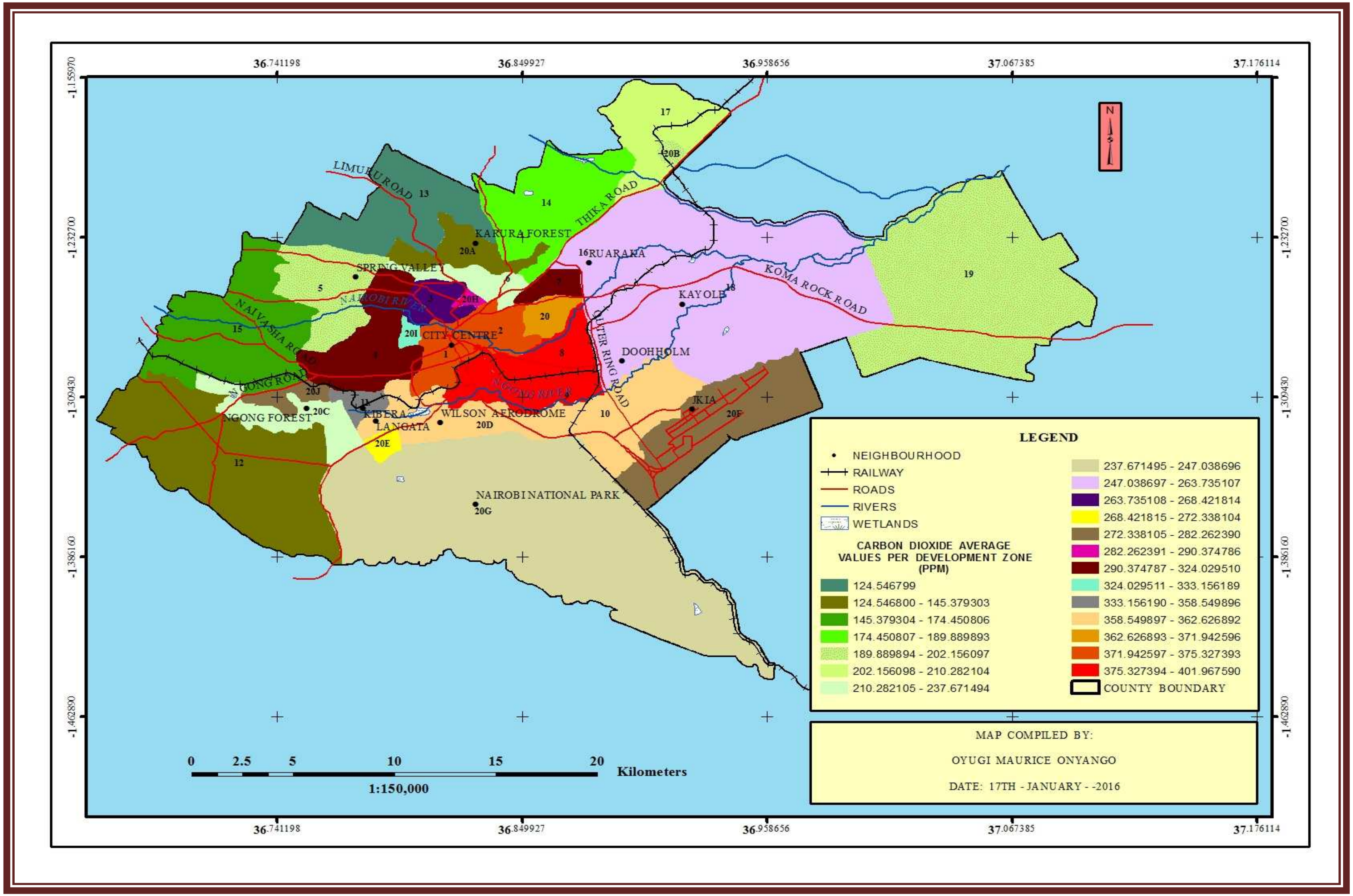

Figure 4.32. Average Carbon Dioxide Values per Development Zone.

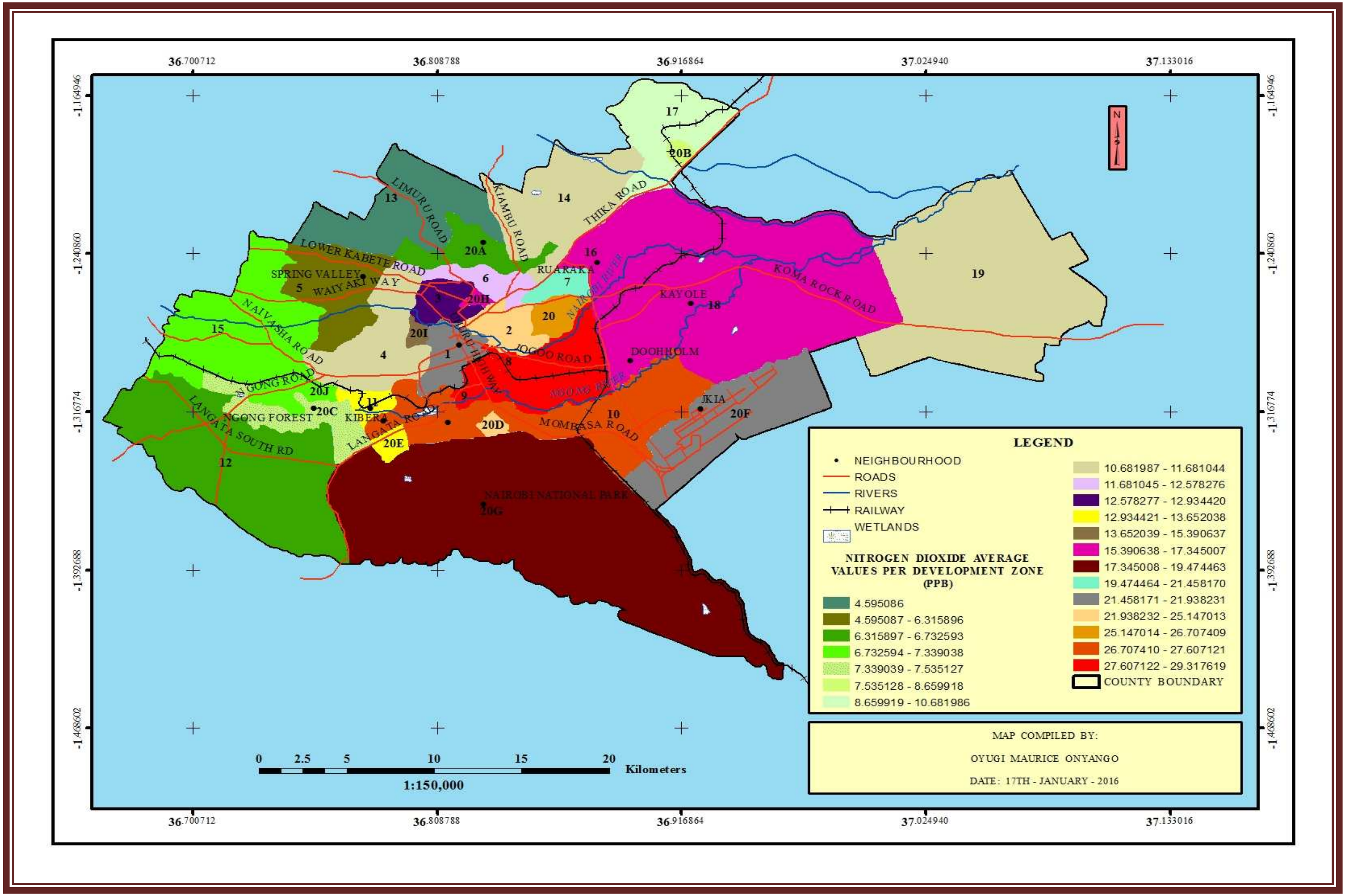

Figure 4.33. Average Nitrogen Dioxide Values per Development Zone.

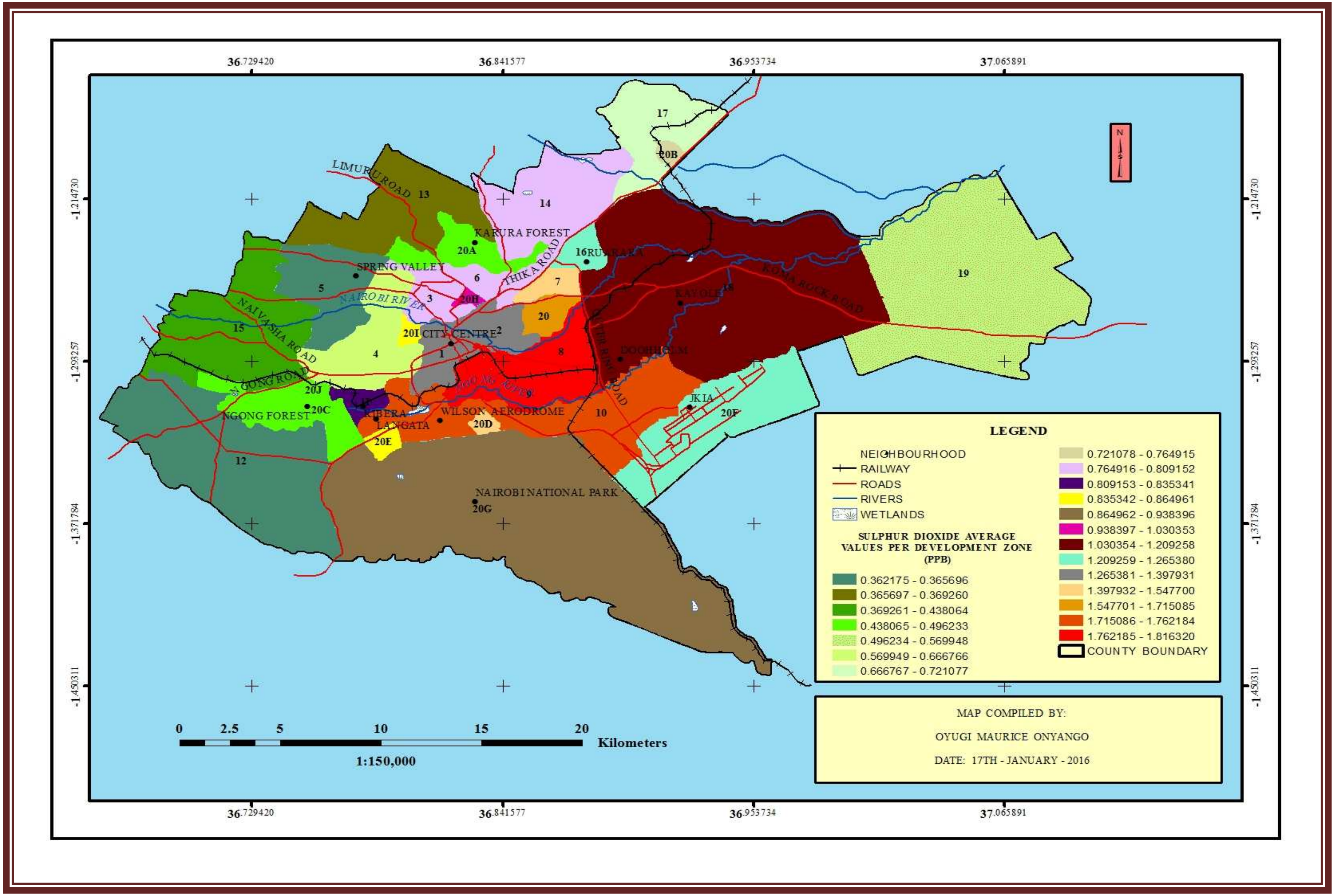

Figure 4.34. Average Sulphur Dioxide Values per Development Zone.

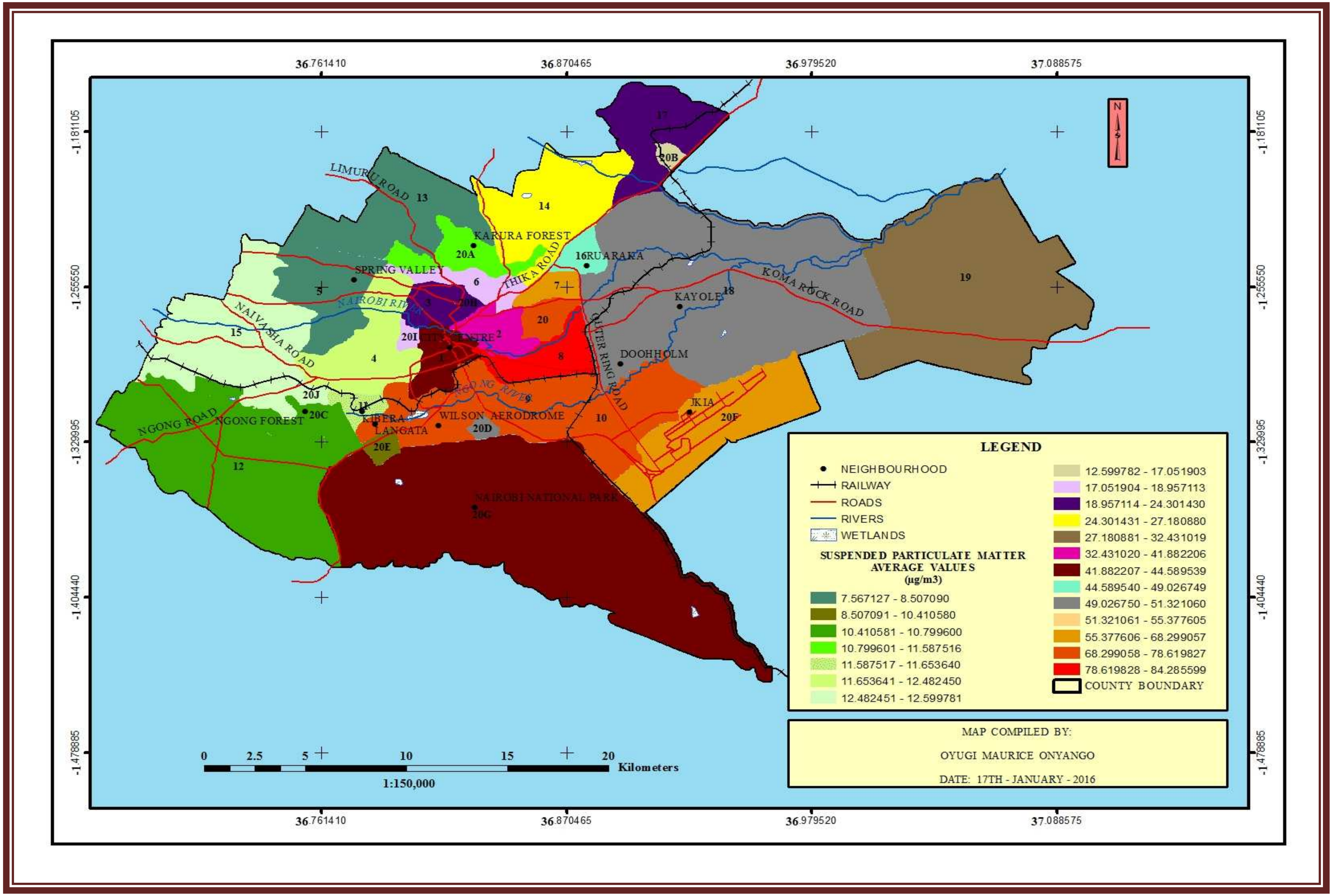

Figure 4.35. Average Suspended Particulate Matter Values per Development Zone.

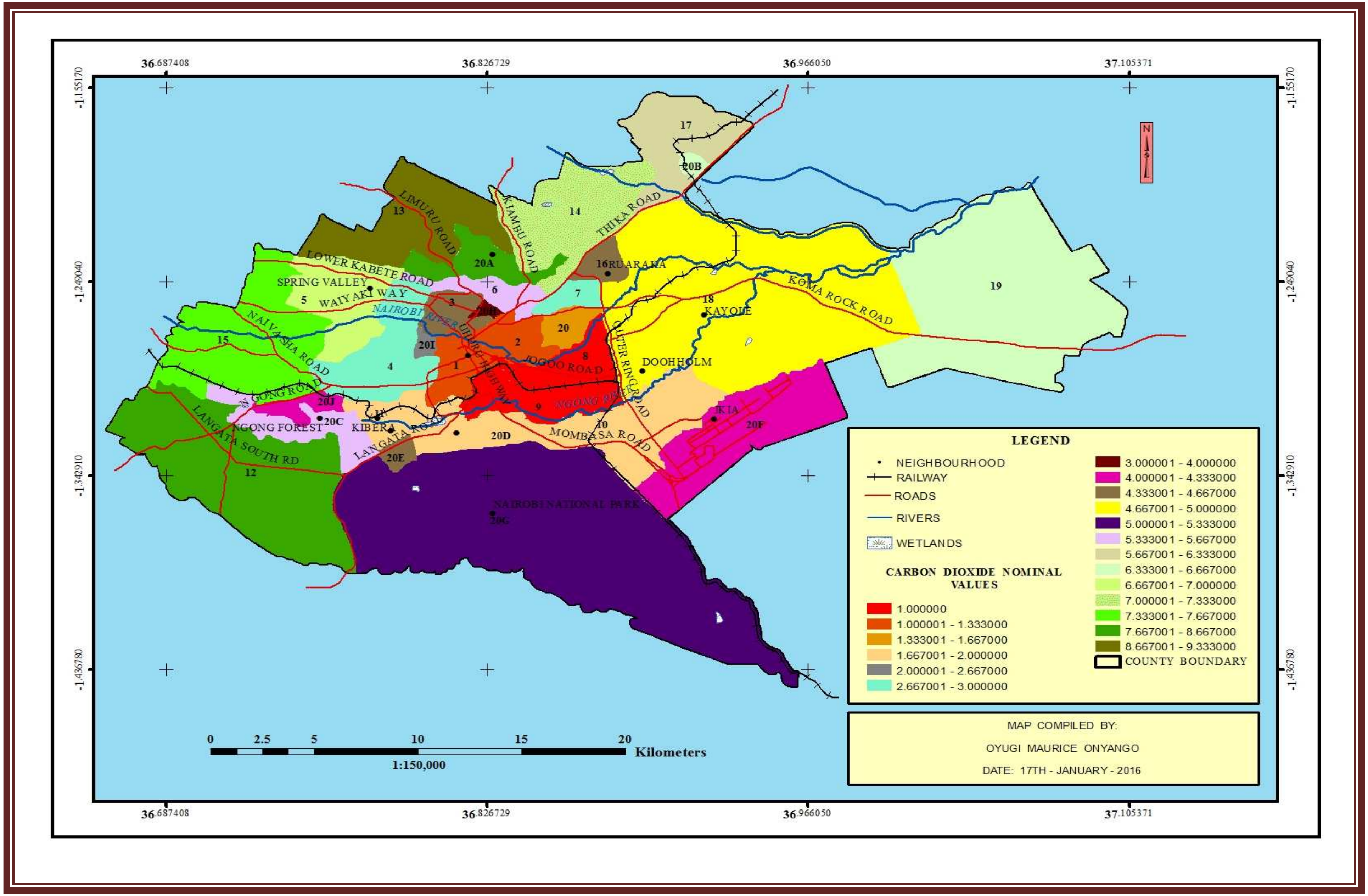

Figure 4.36. The Distribution of Nairobi City's Environmental Quality Based on Carbon Dioxide Nominal Values.

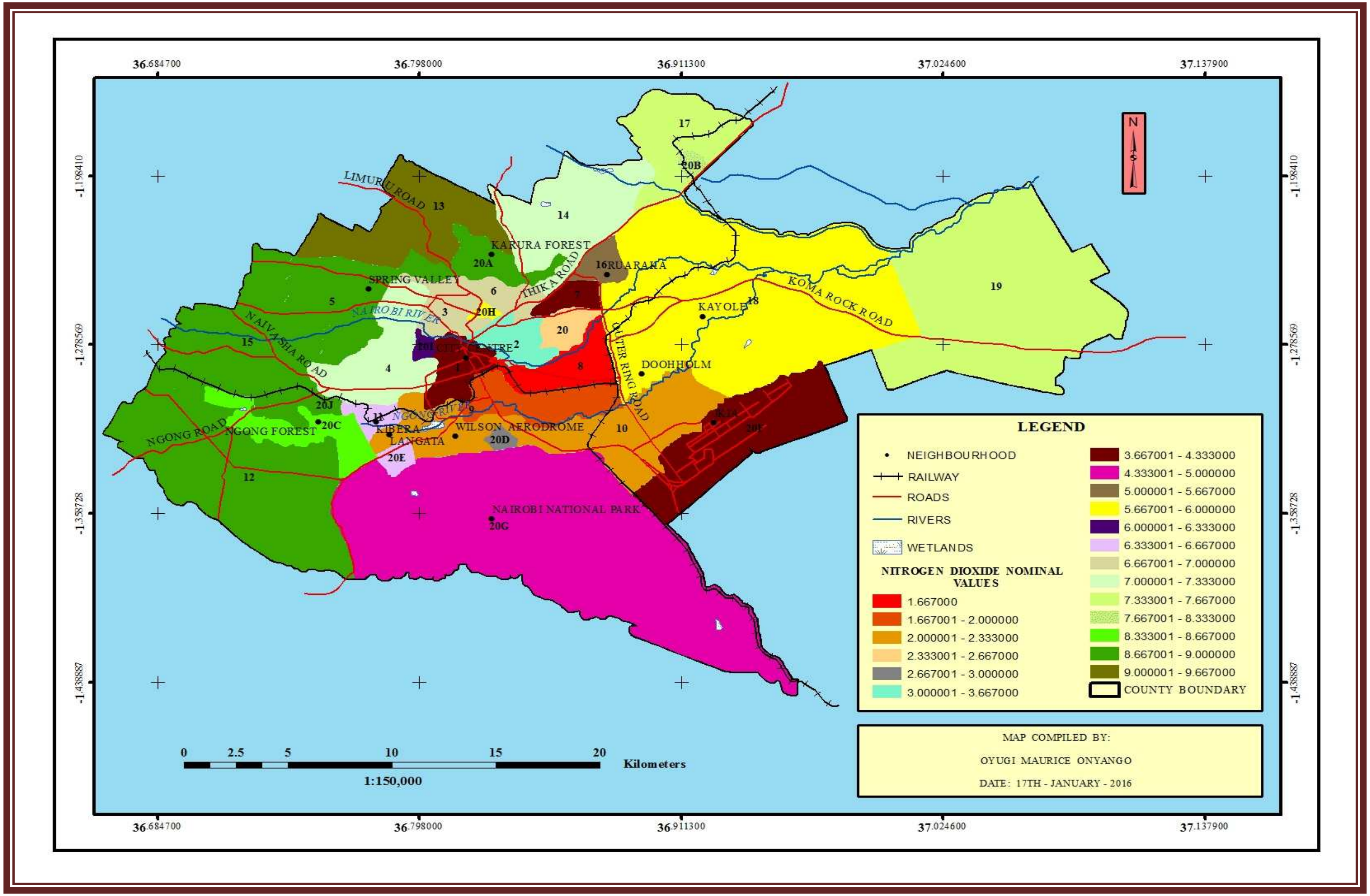

Figure 4.37. Spatial Distribution of the City's Environmental Quality Based on Nitrogen Dioxide Nominal Values.

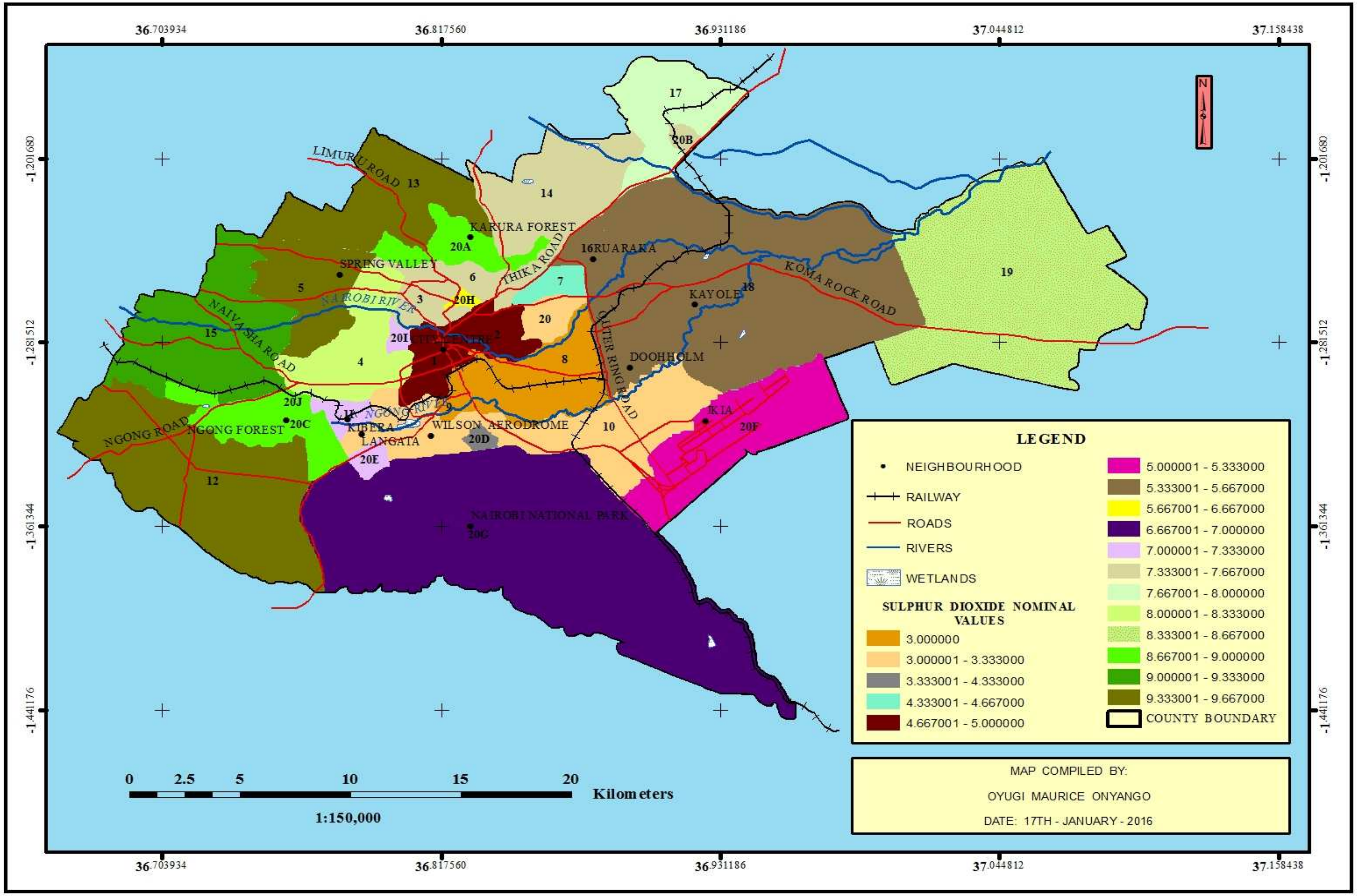

Figure 4.38. Spatial Distribution of the City's Environmental Quality Based on Sulphur Dioxide Nominal Values.

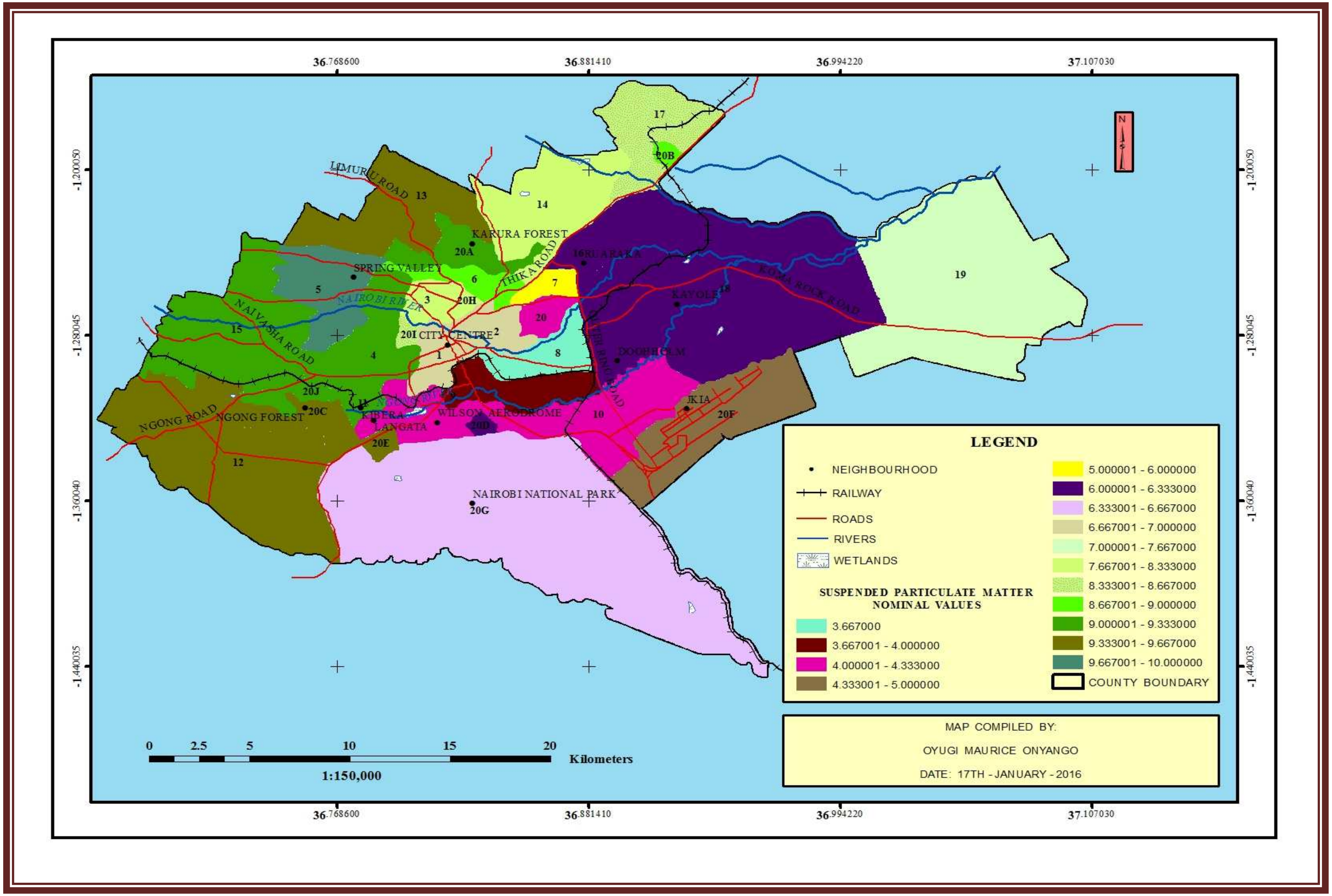

Figure 4.39. The Distribution of the City's Environmental Quality Based on Suspended Particulate Matter Nominal Values.

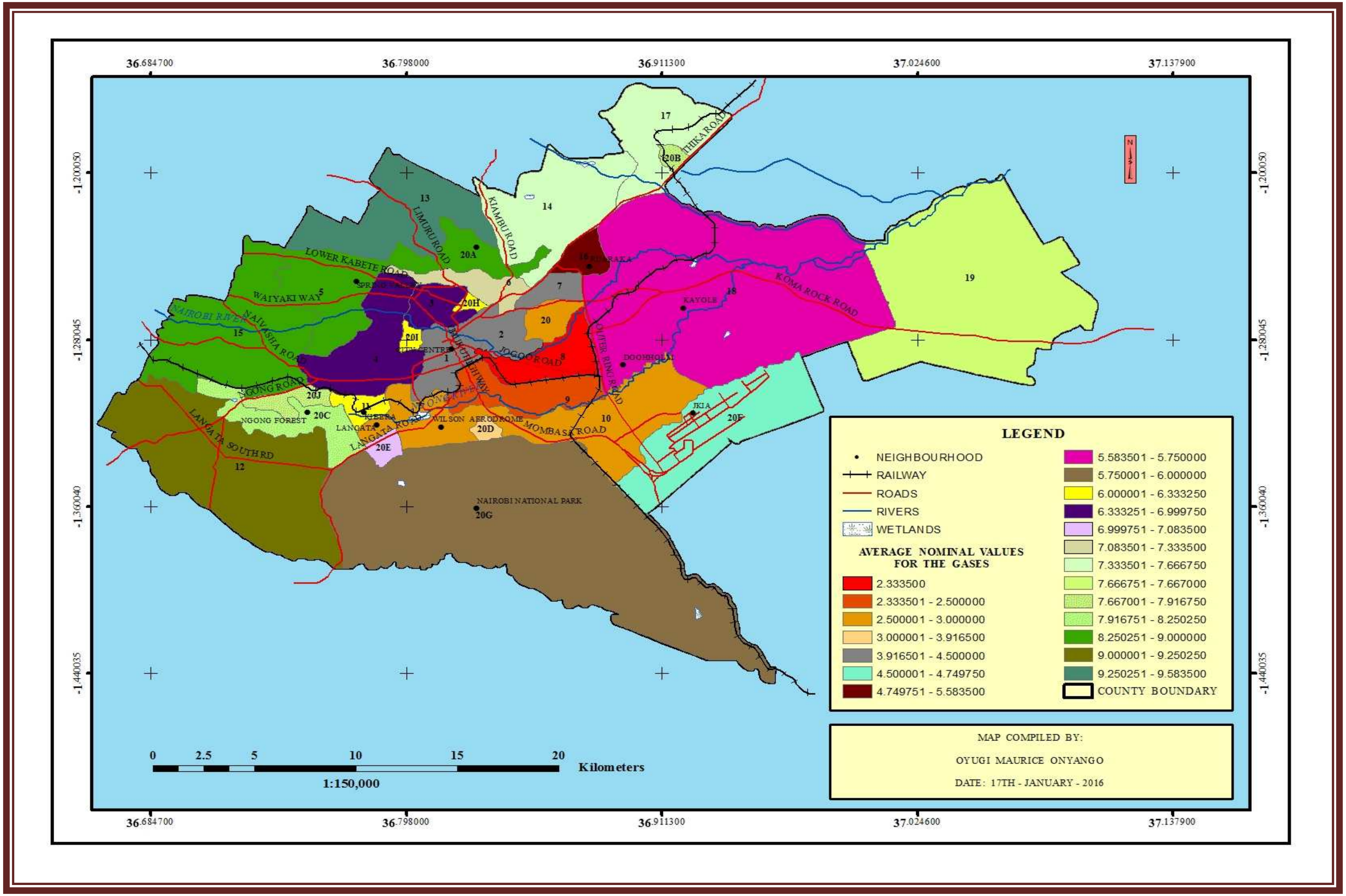

Figure 4.40. Environmental Quality of the City Based on the Air Quality Nominal Values.

Table 4.16. Environmental Quality Relationships

Development Zones	Aggregate Urban Environmental Quality Nominal Values	Average Urban Environmental Quality Nominal Values	Land Use (Urban Spatial Structure) Nominal Values	Development Density Nominal Values	Vegetation Density Nominal Values	Surface Temperature Nominal Values	Average Air Quality Nominal Values
	Y	Y_1	X_1	X_2	X_3	X_4	X_5
1	22.35469969	4.470939938	3.909924	4.5	3.198275691	6.33	4.4165
2	20.749392854	4.1498785708	3.393761	5.5	2.945631854	4.66	4.250
3	25.38350964	5.076701928	2.94303	5.5	3.693729638	6.33	6.91675
4	29.91188315	5.982376629	2.938691	7.5	5.143442146	7.33	6.99975
5	33.55773108	6.711546217	3.517109	8.0	5.133872083	7.99	8.91675
6	34.47437396	6.894874792	4.339698	8.5	6.311175958	7.99	7.3335
7	19.38333406	3.876666811	3.193575	4.5	1.859759055	5.33	4.50
8	15.79239493	3.158478986	2.81645	4.5	1.812444931	4.33	2.3335
9	13.6931965	2.7386393	2.229635	3.5	1.473561499	3.99	2.50
10	20.17369147	4.034738294	3.728247	6.0	2.785694468	4.66	2.99975
11	28.26081288	5.652162576	4.986373	7.0	4.281189882	5.66	6.33325
12	34.48500678	6.897001357	3.784665	8.5	5.290091783	7.66	9.25025
13	36.02726321	7.205452642	4.216689	9.0	5.567074211	7.66	9.5835
14	33.28210192	6.656420385	4.697541	9.0	5.258060923	6.66	7.6665
15	35.43468207	7.086936413	5.146292	9.0	5.125140067	7.33	8.83325
16	20.49841078	4.099682156	2.921903	5.0	2.00300778	4.99	5.5835
17	29.25670439	5.851340877	4.70022	8.0	3.559734386	5.33	7.66675
18	25.26583982	5.053167964	4.410786	8.0	3.11505382	3.99	5.75
19	28.26142789	5.652285579	5.466758	9.0	4.137669893	1.99	7.667
20	18.95486985	3.79097397	3.523711	5.0	2.771158847	4.66	3.0
20A	43.20137693	8.640275385	7.501878	9.5	8.209498926	8.99	9.0
20B	27.54393437	5.508786874	4.595745	6.5	3.541439372	4.99	7.91675
20C	41.70841863	8.341683726	7.598879	9.5	8.029289628	8.33	8.25025
20D	21.29148064	4.258296127	3.826671	5.5	2.718309635	5.33	3.9165
20E	36.32158532	7.264317064	6.859062	9.5	6.549023321	6.33	7.0835
20F	24.01456037	4.802912075	5.771734	8.0	3.833076373	1.66	4.74975
20G	36.61691194	7.323382388	7.808378	10.0	7.818533939	4.99	6.0
20H	33.1798917	6.635978339	5.336874	8.5	6.103017696	6.99	6.25
20I	32.84745296	6.569490592	4.976885	7.5	5.460567959	8.66	6.25
20J	43.44876214	8.689752428	8.8945	10.0	8.97776214	7.66	7.9165

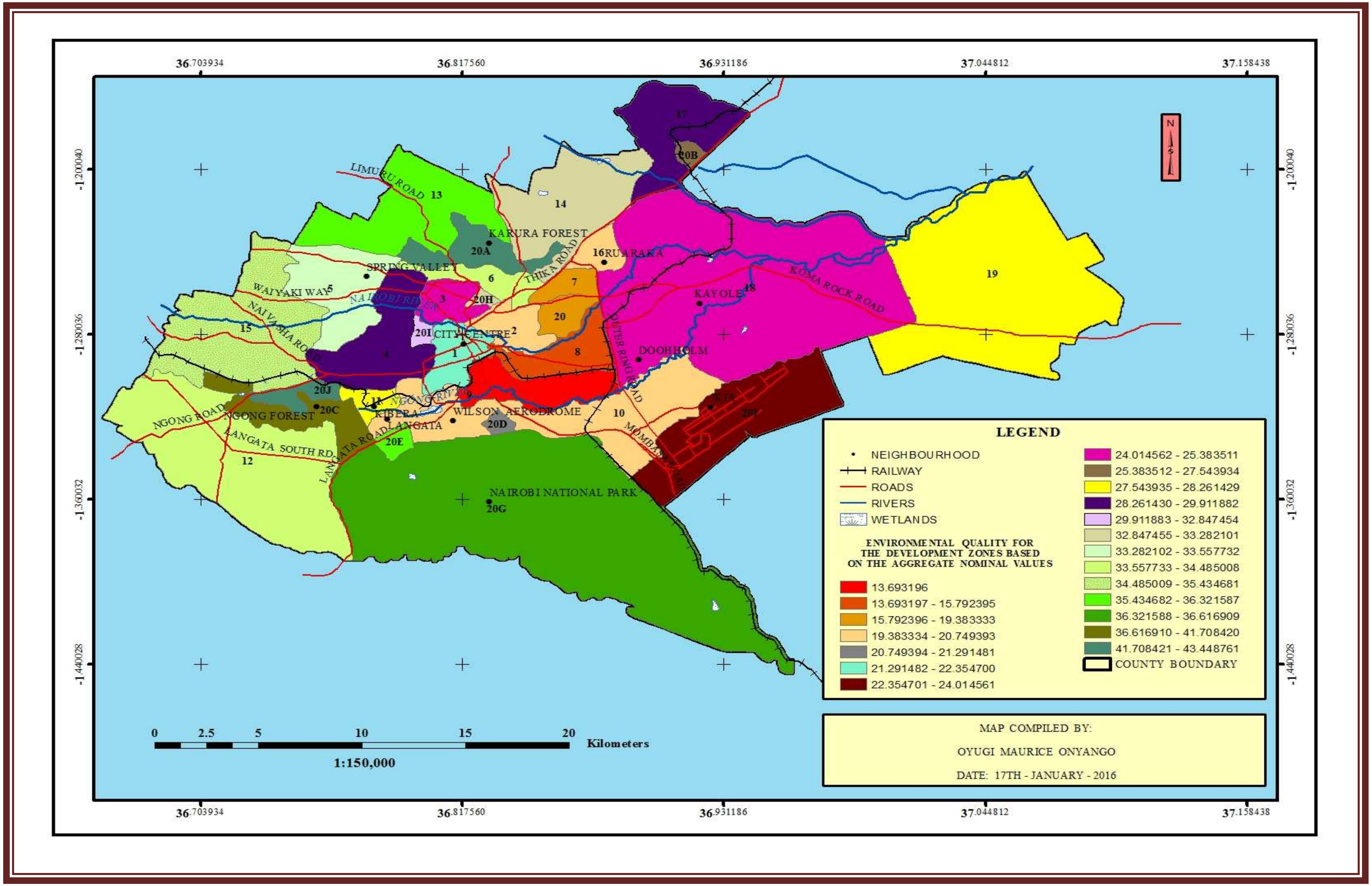

Figure 4.41. Aggregate Environmental Quality of the City

4.7 An Integrated Urban Environmental Quality Model for Nairobi City

In acknowledging that urban environmental quality assessment requires integration of multiple parameters, this study integrated urban morphological parameters of development density, land use and vegetation density with air quality and surface temperatures in the assessment of the environmental quality of Nairobi City. The results of the analysis is presented in Table 4.16 and further transformed into Figure 4.41 which is an integrated spatial model showing the environmental quality distribution within the city.

The results of the *Pearson's Product Moment Correlation Coefficient Indexes* of the relationships existing between and among the various morphological and environmental quality variables considered in the study are shown in Table 4.17.

Table 4.17. Correlation Matrix Variables

	Aggregate Environmental Quality	Air Quality	Surface Temperatures	Development Density	Land Use or Urban Spatial Structure	Vegetation Density
Aggregate Environmental Quality	1.000	0.847	-0.686	-0.915	0.779	0.958
Air Quality	0.847	1.000	-0.597	-0.775	0.446	0.684
Surface Temperatures	-0.686	-0.597	1.000	0.397	-0.236	-0.632
Development Density	-0.915	-0.775	0.397	1.000	-0.788	-0.871
Land Use or Urban Spatial Structure	0.779	0.446	-0.236	-0.788	1.000	0.840
Vegetation Density	0.958	0.684	-0.632	-0.871	0.840	1.000

Table 4.18. The Morphological and Environmental Quality Attributes of the Development Zones

Development Zones	Urban Form Nominal Values				Vegetation Density Nominal Values (VDNV)	Urban Morphology Nominal Values (DDNV+LUNV+VDNV)	Average Urban Morphology Nominal Values (DDNV+LUNV+ VDNV)/3	Surface Temperature Nominal Values	Air Quality Nominal Values	Total Environmental Quality Parameters Nominal Values	Average Environmental Quality Parameters Nominal Values
	Development Density Nominal Value (DDNV)	Land Use or Urban Spatial Structure Nominal Values (LUNV)	Urban Form Nominal Values	Average Urban Form Nominal Values							
1	4.5	3.909924	8.409924	4.204962	3.198275691	11.60819969	**3.869399897**	6.33	4.4165	10.7465	5.37325
2	5.5	3.393761	8.893761	4.4468805	2.945631854	11.83939285	**3.946464285**	4.66	4.250	8.91	4.455
3	5.5	2.94303	8.44303	4.221515	3.693729638	12.13675964	**4.045586546**	6.33	6.91675	13.24675	6.623375
4	7.5	2.938691	10.438691	5.2193455	5.143442146	15.58213315	**5.194044382**	7.33	6.99975	14.32975	7.164875
5	8.0	3.517109	11.517109	5.7585545	5.133872083	16.65098108	**5.550327028**	7.99	8.91675	16.90675	8.453375
6	8.5	4.339698	12.839698	6.419849	6.311175958	19.15087396	**6.383624653**	7.99	7.3335	15.3235	7.66175
7	4.5	3.193575	7.693575	3.8467875	1.859759055	9.553334055	**3.184444685**	5.33	4.50	9.83	4.915
8	4.5	2.81645	7.31645	3.658225	1.812444931	9.128894931	**3.042964977**	4.33	2.3335	6.6635	3.33175
9	3.5	2.229635	5.729635	2.8648175	1.473561499	7.203196499	**2.4010655**	3.99	2.50	6.49	3.245
10	6.0	3.728247	9.728247	4.8641235	2.785694468	12.51394147	**4.171313823**	4.66	2.99975	7.65975	3.829875
11	7.0	4.986373	11.986373	5.9931865	4.281189882	16.26756288	**5.422520961**	5.66	6.33325	11.99325	5.996625
12	8.5	3.784665	12.284665	6.1423325	5.290091783	17.57475678	**5.858252261**	7.66	9.25025	16.91025	8.455125
13	9.0	4.216689	13.216689	6.6083445	5.567074211	18.78376321	**6.261254404**	7.66	9.5835	17.2435	8.62175
14	9.0	4.697541	13.697541	6.8487705	5.258060923	18.95560192	**6.318533974**	6.66	7.6665	14.3265	7.16325
15	9.0	5.146292	14.146292	7.073146	5.125140067	19.27143207	**6.423810689**	7.33	8.83325	16.16325	8.081625
16	5.0	2.921903	7.921903	3.9609515	2.00300778	9.92491078	**3.308303593**	4.99	5.5835	10.5735	5.28675
17	8.0	4.70022	12.70022	6.35011	3.559734386	16.25995439	**5.419984795**	5.33	7.66675	12.99675	6.498375
18	8.0	4.410786	12.410786	6.205393	3.11505382	15.52583982	**5.17527994**	3.99	5.75	9.74	4.87
19	9.0	5.466758	14.466758	7.233379	4.137669893	18.60442789	**6.201475964**	1.99	7.667	9.657	4.8285
20	5.0	3.523711	8.523711	4.2618555	2.771158848672	11.29486985	**3.764956616**	4.66	3.0	7.66	3.83
20A	9.5	7.501878	17.001878	8.500939	8.209498926	25.21137693	**8.403792309**	8.99	9.0	17.99	8.995
20B	6.5	4.595745	11.095745	5.5478725	3.541439372	14.63718437	**4.879061457**	4.99	7.91675	12.90675	6.453375
20C	9.5	7.598879	17.098879	8.5494395	8.029289628	25.12816863	**8.376056209**	8.33	8.25025	16.58025	8.290125
20D	5.5	3.826671	9.326671	4.6633355	2.718309635	12.04498064	**4.014993545**	5.33	3.9165	9.2465	4.62325
20E	9.5	6.859062	16.359062	8.179531	6.549023321	22.90808532	**7.63602844**	6.33	7.0835	13.4135	6.70675
20F	8.0	5.771734	13.771734	6.885867	3.833076373	17.60481037	**5.868270124**	1.66	4.74975	6.40975	3.204875
20G	10.0	7.808378	17.808378	8.904189	7.818533939	25.62691194	**8.54230398**	4.99	6.0	10.99	5.495
20H	8.5	5.336874	13.836874	6.918437	6.103017696	19.9398917	**6.646630565**	6.99	6.25	13.24	6.62
20I	7.5	4.976885	12.476885	6.2384425	5.460567959	17.93745296	**5.979150986**	8.66	6.25	14.91	7.455
20J	10.0	8.8945	18.8945	9.44725	8.97776214	27.87226214	**9.290754047**	7.66	7.9165	15.5765	7.78825

Establishment of the relationship existing between urban morphology and the environmental quality of the city was sequentially undertaken in five steps notably: -

i. Analysis of the level of significance of the relationships existing between and among the urban morphological and environmental quality (surface temperatures and air quality) variables.

ii. Analysis of the relationships existing between the urban form (aggregation of the land use and development density nominal values), urban morphology and environmental quality parameters of air quality and surface temperatures.

iii. Analysis of the relationship existing between the urban form and the total environmental quality parameter (aggregation of air quality and surface temperatures nominal values) values as well as the relationship existing between urban morphology and the total environmental quality parameter values.

iv. Establishment of the levels of significance or the contributions of the individual morphological and environmental quality parameters to the aggregate environmental quality of the city.

v. Establishment of the relationship existing between urban morphology and the aggregate urban environmental quality.

This study was informed by the hypothesis which posits the existence of significant relationships existing between and among the urban morphological variables and the environmental quality parameters. In this regard, if the established correlation coefficient (r) of a relationship was zero, then the study concluded that there was no relationship existing between the variables under consideration. Similarly, if the correlation coefficient (r) value was established to be between 0 and either -0.5 or 0.5, then the study concluded that there is a weak relationship existing between the variables under consideration. While the study concludes that there is fairly significant relationship existing between the variables under consideration if the established correlation coefficient (r) value was either -0.5 or 0.5, the study concludes that there is a moderately significant relationship existing between the variables under consideration if the established correlation coefficient (r) value ranges from either -0.5 to -0.7 or 0.5 to 0.7. Correlation coefficient (r) values ranging from either -0.7 to -1.0 or 0.7 to 1.0 were considered very significant.

Table 4.19 shows that the correlation coefficient (r) for the relationship existing between the environmental quality parameters of air quality and surface temperatures is a moderate value of -0.597. To test for the significance of the relationship existing between the two variables, the relationship was further subjected to *t*-test which established that the calculated *t*-value for the relationship is 3.939 compared to the critical *t*-value of 2.048. This confirms that the relationship existing between the two environmental quality parameters is moderately significant. The Analysis of Variance (ANOVA) or the F-test was further used to test the consistency of the relationship and the calculated F-value for the relationship was established to be 15.516 compared to critical F-value of 4.20. The above being the case, this study concludes that the relationship existing between air quality and surface temperature is moderately significant and consistent.

Table 4.19. Correlation Coefficients, the t- test and the (ANOVA) F- Test of the relationships existing between and among the Urban Morphological and the Environmental Quality Parameters

	Relationship Variables			
	Air Quality and Surface Temperatures	**Development Density and Air Quality**	**Land Use (the Urban Spatial Structure) and Air Quality**	**Vegetation Index and Air Quality**
Correlation Coefficients	-0.597	-0.7751	0.446	0.684
Coefficients of Determination (r^2 or R)	0.357	0.6008	0.199	0.467
Calculated t - Value	3.939	6.492	2.638	4.956
Critical t - Value	2.048	2.048	2.048	2.048
Regression Model	**Y = -0.8357X + 35.005**	**Y = -0.085X + 8.8316**	**Ỳ = 0.567X + 3.682**	**Ỳ = 0.711X + 3.089**
ANOVA or the F- Test Value	15.516	42.149	6.961	24.56
Critical F - Value	4.20	4.20	4.20	4.20

	Relationship Variables			
	Development Density and Surface Temperatures	**Land Use (the Urban Spatial Structure) and surface temperatures**	**Development Density and Land Use (the Urban Spatial Structure)**	**Vegetation Index and Surface Temperatures**
Correlation Coefficients	0.397	-0.236	-0.788	-0.632
Coefficients of Determination (r^2 or R)	0.158	0.056	0.621	0.399
Calculated t - Value	2.288	1.288	6.767	4.311
Critical t - Value	2.048	2.048	2.048	2.048
Regression Model	**Y = 0.0609X + 27.923**	**Y = -0.4204X + 31.679**	**Y = -0.068X + 6.6709**	**Y = -0.0919X + 33.904**
ANOVA or the F- Test	5.234	1.658	45.798	18.585
Critical F - Value	4.20	4.20	4.20	4.20

	Relationship Variables		
	Development Density and Vegetation Index	**Land Use (the Urban Spatial Structure) and Development Density**	**Land Use (the Urban Spatial Structure) and Vegetation Index**
Correlation Coefficients	-0.871	-0.788	0.840
Coefficients of Determination (r^2 or R)	0.759	0.621	0.705
Calculated t-Value	9.392	6.767	8.185
Critical t - Value	2.048	2.048	2.048
Regression Model	**Y = -0.9193X + 72.639**	**Y = -9.1227X + 72.03**	**Y = 10.262X - 2.3316**
ANOVA or the F- Test	88.216	45.793	66.992
Critical F - Value	4.20	4.20	4.20

	Relationship Variables				
	Air Quality and Aggregate Environmental Quality	**Surface Temperatures and Aggregate Environmental Quality**	**Development Density and Aggregate Environmental Quality**	**Land Use (the Urban Spatial Structure) and Aggregate Environmental Quality**	**Vegetation Index and Aggregate Environmental Quality**
Correlation Coefficients	0.847	-0.686	-0.915	0.779	0.958
Coefficients of Determination (r^2 or R)	0.717	0.471	0.836	0.607	0.918
Calculated t – Value	8.427	4.992	11.966	6.581	17.740
Critical t - Value	2.048	2.048	2.048	2.048	2.048
Regression Model	**Y = 3.235X + 8.3724**	**Y = -1.8734X + 84.518**	**Y = -0.3833X + 40.132**	**Y = 3.7823X + 11.191**	**Y = 0.3806X + 11.502**
ANOVA or the F- Test	71.007	24.922	143.195	43.307	314.701
Critical F - Value	4.20	4.20	4.20	4.20	4.20

The analysis of the relationship existing between development density and air quality reveals a strong negative relationship corroborated by a correlation coefficient (r) value of -0.7751 and a calculated *t*-value of 6.492 compared to a critical *t*-value of 2.048. While the calculated F-value for the relationship existing between the two variables is 42.149, the critical F-value is 4.20. This confirms that the relationship existing between the development density and air quality is significantly strong and is not occurring by chance. Contrary to the above, land uses and air quality presents a weak relationship evidenced by a correlation coefficient (r) value of 0.446 and a calculated *t*-value of 2.638 compared to a critical *t*-value of 2.048. The calculated and critical F-values for the relationship are 6.961 and 4.20 respectively. Granted that the correlation coefficient (r) value for the relationship existing between the vegetation density and urban air quality was established to be 0.684, the study confirms that the relationship is moderately significant as corroborated by the calculated *t*-value of 4.956 compared to a critical *t*-value of 2.048. Since the calculated F-value of the relationship was established to be 24.56 compared to the critical F-value of 4.20, the study concludes that the relationship existing between vegetation density and air quality is significant and consistent.

The correlation coefficient (r) value, *t*-test and F-test established that there is a consistently weak relationship existing between the development density and surface temperatures. While the correlation coefficient (r) value for the relationship is 0.397, the calculated and critical *t*-values are 2.288 and 2.048 respectively. The calculated F-value is 5.234 compared to a critical F-value of 4.20. This confirms that development density weakly determines surface temperature variations within the city. Analysis on the relationship existing between land uses and surface temperatures reveals consistently insignificant relationship which is evidenced by an insignificant correlation coefficient (r) value of -0.236. The calculated *t*-

value of the relationship was established to be 1.288 compared to a critical *t*- value of 2.048. The calculated F-value for the relationship is 1.658 compared to a critical F-value of 4.20.

To demonstrate the intra-linkages existing between the urban morphological parameters, analysis of the relationship existing between the development density and land use was undertaken. While the first analysis focused on the relationship with land use as the dependent variable, the second analysis focused on the relationship with development density as the dependent variable. In both the cases, the relationship existing between the two variables were established to be strong with correlation coefficient (r) values of -0.788 while the calculated *t*-values and critical *t*-values are 6.767 and 2.048 respectively in both the cases. However, there is a slight difference in the calculated F-values for the two relationships as occasioned by differences in the regression models expressing the relationships existing between the two variables[1]. For the relationship in which the development density is the independent variable, the calculated F-value was established to be 45.798 compared to a critical F-value of 4.20. This had a slight difference from the relationship in which land use was the independent variable in which the calculated F-value was established to be 45.793 compared to a critical F-value of 4.20. The above confirms that the relationship existing between the two variables is consistently significant.

The study reveals that vegetation density moderately influences the spatial distribution of the surface temperatures within the city. This is evidenced by a correlation coefficient (r) value of -0.632 with a corresponding calculated *t*-value of 4.311 compared to the critical *t*-value of

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[1] Development Density and Land Use (the Urban Spatial Structure) Model: $\mathbf{Y = -0.068X + 6.6709}$
Land Use (the Urban Spatial Structure) and Development Density Model: $\mathbf{Y = -9.1227X + 72.03}$

2.048. The consistency of the relationship is confirmed by the calculated F-value of 18.585 compared to a critical F-value of 4.20. This has made development zones with higher vegetation densities such as Loresho and Lavington Estates (Zone 5), Muthaiga Estate (Zone 6), Karen neighbourhood (Zone 12), Gigiri, Kitisuru, Ridgeways and Safari Park Estates (Zone 13), Karura Forest (Zone 20A), Ngong Forest (Zone 20J), Defence College-Karen (Zone 20C), State House and Nairobi Arboretum (Zone 20I) experience relatively lower thermal values as compared to zones with low vegetation densities such as zones 7, 8, 9, 10, 16, 17, 18 and 19 which are high density residential neighbourhoods and industrial areas. As corroborated by a correlation coefficient (r) value of -0.871, calculated and critical *t*-values of 9.392 and 2.048 respectively, with a corresponding calculated F-value of 88.216 compared to a critical F-value of 4.20, the relationship existing between development density and vegetation density is confirmed to be very significant and consistent. Similarly, a correlation coefficient (r) value of 0.840, a calculated *t*-value of 8.185 compared to the critical *t*-value of 2.048, corresponding to a calculated F-value of 66.992 compared to a critical F-value of 4.20, the relationship existing between land use and the vegetation density is confirmed to be very significant and consistent.

The second level of the analysis focused on the relationships existing between the urban form and urban morphology (aggregation of the urban development density, land uses and the vegetation index nominal values) on one hand as independent variables and the environmental quality parameters of air quality and surface temperatures as dependent variables. The study established that while there is consistently moderate relationship existing between urban form and air quality, there is consistently insignificant relationship existing between urban form and surface temperatures. This is confirmed by a correlation coefficient

(r) value of 0.657 for the relationship existing between urban form and air quality while the same is -0.339 for the relationship existing between urban form and surface temperatures. The calculated *t*-value for the relationship existing between urban form and air quality is 4.614 while the same is 1.905 for the relationship existing between the urban form and the surface temperatures, of which the critical *t*-values for both the relationships are 2.048. Similarly, while the calculated F-value for the relationship existing between urban form and air quality is 21.291, the same is 3.629 for the relationship existing between urban form and surface temperatures with a corresponding critical F-value of 4.20 for both the cases. As earlier established, urban form elements of development density and land uses either weakly or insignificantly influence the spatial distribution of surface temperatures within the city. This confirms that the distribution of the surface temperatures within the city is influenced by other factors notably the vegetation density, topography, pedology, rainfall pattern and amount, slope and wind velocity but not the urban form parameters under consideration.

Similarly, a correlation coefficient (r) value of -0.458 corroborates a weak relationship existing between urban morphology and surface temperatures within the city. Due to inclusion of the vegetation density alongside urban form elements in the relationship existing between urban morphology and surface temperatures, the correlations coefficient (r) value has improved from -0.339 to -0.458. The weak relationship existing between the two variables is further corroborated by a calculated *t*-value of 2.730 compared to a critical *t*-value of 2.048. This is confirmed to be consistent through the calculated F-value of 7.452 compared to a critical F-value of 4.20. Further to the above, the study establishes a moderately significant relationship existing between urban morphology and air quality which is evidenced by a correlation coefficient (r) value of 0.682. While the significance of the relationship existing between the two variables is confirmed by a calculated *t*-value of 4.937 compared to a critical *t*-value of 2.048, the consistency of the relationship is confirmed by a calculated F-value of 24.373compared to a critical F-value of 4.20.

Further analyses whose findings are shown in Table 4.20 were undertaken on the relationship existing between the urban form and the total urban environmental quality parameter (aggregation of air quality and surface temperatures nominal) values as well as the relationship existing between urban morphology and the total urban environmental quality parameter values. As evidenced by a correlation coefficient (r) value of 0.573 corresponding to a calculated *t*-value of 3.699 compared to a critical *t*-value of 2.048, the relationship existing between urban form and the total environmental quality parameters is established to be moderately significant. The consistency of this relationship is confirmed by a calculated F-value of 13.685 compared to a critical F-value of 4.20. Similarly, the relationship existing between the urban morphology and total environmental quality parameter values is moderately significant (correlation coefficient value of 0.65).

To establish the contributions of individual urban morphological and environmental quality parameters in determining the aggregate urban environmental quality (the aggregation of the morphological and environmental quality parameter nominal values) in the city, it was imperative to establish the strengths of the relationships existing between environmental quality parameters of air quality, surface temperatures and aggregate urban environmental quality as well as the relationships existing between individual urban morphological parameters of development density, urban spatial structure, vegetation index and the aggregate urban environmental quality. As illustrated by Table 4.19, the relationships existing between air quality, development density, urban spatial structure, vegetation index and aggregate urban environmental quality were all established to be very significant as evidenced by correlation coefficient (r) values of 0.847, -0.915, 0.779 and 0.958 respectively. On the other hand, the relationship existing between surface temperatures and aggregate environmental quality was established to be moderately significant as corroborated by a correlation coefficient (r) value of -0.686. Further, the calculated *t*-values for the relationships existing between air quality, surface temperatures, development density, spatial structure, vegetation index and aggregate environmental quality were equally established to be significant with varying strengths. The F-values of 71.007, 24.922, 143.195, 43.307 and 314.701 respectively further confirms that partially the relationships are consistent.

The established correlation coefficient (r) values, the calculated *t*-values and the ANOVA assessments of the relationships existing between air quality, surface temperatures, development density, land uses, vegetation density and the aggregate urban environmental quality confirms that vegetation density is the most significant variable determining the distribution of the aggregate urban environmental quality in the city. This is followed by the development density, air quality, land use and surface temperatures in the order of significance. The study further established the regression models depicting the relationships existing between the urban morphological parameters and the aggregate urban environmental quality, regression models on the relationships existing between urban form variables, air quality and surface temperatures, regression models on the relationships existing between urban morphological parameters and the individual environmental quality parameters as well as the regression models on the relationships existing between concerted elements of urban form, morphological variables and the aggregate urban environmental quality.

Table 4.20. Coefficients of Determination, the t- test and the (ANOVA) F- Test for the Relationships Existing between Urban Morphology and Environmental Quality Parameters

	Relationship Variables	
	Urban Morphology and Surface Temperatures	**Urban Morphology and Air Quality**
Correlation Coefficients	-0.458	0.682
Coefficients of Determination (r^2 or R)	0.210	0.465
Calculated t - Value	2.730	4.937
Critical t - Value	2.048	2.048
Regression Model	**Y = -0.2553X + 33.944**	**Y = 1.0857X + 7.3336**
ANOVA or the F- Test Value	7.452	24.373
Critical F - Value	4.20	4.20
	Relationship Variables	
	Urban Morphology and Total Environmental Quality Parameter Values	**Urban Morphology and Aggregate Urban Environmental Quality**
Correlation Coefficients	0.650	0.943
Coefficients of Determination (r^2 or R)	0.423	0.889
Calculated t - Value	4.530	14.982
Critical t - Value	2.048	2.048
Regression Model	**Y = 0.4334X + 5.1122**	**Y = 1.4334X + 5.1122**
ANOVA or the F- Test	20.517	224.458
Critical F - Value	4.20	4.20
	Relationship Variables	
	Urban Form and Surface Temperatures	**Urban Form and Air Quality**
Correlation Coefficients	-0.339	0.657
Coefficients of Determination (r^2 or R)	0.115	0.432
Calculated t - Value	1.905	4.614
Critical t - Value	2.048	2.048
Regression Model	**Y = -0.2947X + 33.254**	**Y = 1.6346X + 5.6937**
ANOVA or the F- Test	3.629	21.291
Critical F - Value	4.20	4.20
	Relationship Variables	
	Urban Form Nominal Values and Total Environmental Quality Parameter Values	**Urban Form and Aggregate Urban Environmental Quality**
Correlation Coefficients	0.573	0.900
Coefficients of Determination (r^2 or R)	0.328	0.811
Calculated t - Value	3.699	10.950
Critical t - Value	2.048	2.048
Regression Model	**Y = 0.5967X + 5.1267**	**Y = 2.1389X + 3.1765**
ANOVA or the F- Test	13.685	119.894
Critical F - Value	4.20	4.20

As shown in Table 4.20, the relationship existing between urban form and aggregate urban environmental quality is characterised by a correlation coefficient (r) value of 0.900 with a corresponding calculated *t*-value of 10.950 compared to a critical *t*-value of 2.048. Further, a calculated F-value of 119.894 compared to a critical F-value of 4.20 confirms the consistency of the relationship. This confirms that at bivariate level, urban form influences the aggregate urban environmental quality in a very significant and consistent manner. As evidenced by a correlation coefficient (r) value of 0.943 and a calculated *t*-value of 14.982 compared to a critical *t*-value of 2.048, the study further establishes that there is a very significant relationship existing between urban morphology and aggregate urban environmental quality. The consistency of the relationship is confirmed by the calculated F-value of 224.458 compared to a critical F-value of 4.20.

Regression analysis facilitated the determination of the strengths of the relationships existing between morphological variables, air quality, surface temperatures, total environmental quality parameter values and the aggregate urban environmental quality. The relationship existing between air quality and the urban form elements reveals regression equation 4.2 in addition to other statistical attributes.

$$\acute{\mathbf{Y}}\mathbf{= -0.490X_1 - 2.202X_2 + 50.015} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(4.2)}$$

Where: -

$\acute{\mathbf{Y}}$ = The estimated air quality values

$\mathbf{X_1}$ = Development density values

$\mathbf{X_2}$ = Land use (urban spatial structure) nominal values

While the calculated *t*-value attributed to the development density in the model is 6.241, the calculated *t*-value attributed to land uses is 2.422, the calculated *t*-value attributed to error term (constant) is 7.944 and the combined calculated F-value for the relationship is 27.670. This corroborates the significant role the development density plays in the determination of the spatial distribution of the air quality within the city as compared to land uses.

The relationship existing between the surface temperatures and urban form variables is established to be represented by the regression model 4.3.

$$\mathbf{\acute{Y} = 0.085X_1 + 0.357X_2 + 25.542} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(4.3)}$$

Where: -

Ý = The estimated surface temperature values

X_1 = Development density values

X_2 = Land use (urban spatial structure) nominal values

Other statistical parameters in this relationship includes:-

t_1 = The calculated *t*-value attributed to development density which is 1.953

t_2 = The calculated *t*-value attributed to land uses which is 0.706

t_3 = The calculated *t*-value attributed to error term (constant) which is 7.301

F = Calculated F-value for the model which is 2.820

The above statistics implies that in concert, development densities and land uses insignificantly and inconsistently determines the distribution of the surface temperatures within the city. Granted that the calculated *t*-value attributed to the error term in the model is greater than combined calculated *t*-values attributed to urban form variables, it implies that other environmental and physiographic parameters such as the topography, pedology, rainfall pattern and amount, slope, aspects and vegetation density which are not considered by the model and/or the study significantly explains the surface temperature variations within the city. Further, when the total environmental quality parameter values were regressed against urban form elements, the regression model 4.4 and other statistical attributes were established as follows:-

$$\acute{Y} = -0.174X_1 - 0.748X_2 + 20.911 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.4)}$$

Where:-

$\acute{Y}$ = The estimated total environmental quality parameter values

X_1 = Development density values

X_2 = Land use (urban spatial structure) nominal values

Other statistical attributes of the above stated relationship are as follows:-

t_1 = The calculated *t*-value attributed to development density which is 4.285

t_2 = The calculated *t*-value attributed to land uses which in this case is 1.588

t_3 = The calculated *t*-value attributed to error term which is 6.411

F = The calculated F-value for the relationship which is 13.391.

The statistical attributes mentioned above implies that it is only the development density which significantly influences the spatial distribution of the total environmental quality parameter values within the city.

The analysis of the relationship existing between air quality and the urban morphological parameters represented by model 4.5 reveals varying levels of significance.

$$\acute{Y} = -0.389X_1 - 3.060X_2 + 0.174X_3 + 43.123 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5)}$$

Where: -

$\acute{Y}$ = The estimated air quality values

X_1 = Development density values

X_2 = Land use (urban spatial structure) nominal values

X_3 = Vegetation density values

Other statistical parameters in this relationship are:-

t_1 = The calculated *t*-value attributed to development density which is 3.978

t_2 = The calculated *t*-value attributed to land uses which is 2.992

t_3 = The calculated *t*-value attributed to vegetation density which is 1.654

t_4 = The calculated *t*-value attributed to error term which is 5.835

F = Calculated F-value of the relationship which is 20.544

It is therefore evident that development density is the most significant determinant of air quality distribution in the city, followed by land uses while vegetation density has insignificant contribution on the phenomenon.

The relationship existing between urban surface temperatures and the morphological variables is represented by the regression model 4.6.

$$\acute{Y} = -0.065X_1 + 1.630X_2 - 0.258X_3 + 35.760 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

Where: -

$\acute{Y}$ = Estimated surface temperature values

X_1 = Development density values

X_2 = Land use (urban spatial structure) nominal values

X_3 = Vegetation density values

Other statistical attributes explaining the strength of the relationship existing between surface temperatures and the urban morphological elements are:-

t_1 = The calculated *t*-value attributed to development density which is 2.006

t_2 = The calculated *t*-value attributed to land uses which is 4.805

t_3 = The calculated *t*-value attributed to vegetation density which is 7.394

t_4 = The calculated *t*-value attributed to the error term which is 14.590

F = Calculated F-value of the relationship which is 23.838

From the above, it is evident that vegetation density is the most significant factor among the urban morphological variables considered in this study which significantly explains the spatial distribution of the surface temperatures. However, the significance of the calculated *t*-value attributed to the error term (14.590) in the model implies that other factors such as the topography, pedology, rainfall pattern and amount, slope, aspects and wind velocity not considered by this relationship and/or study significantly explain the spatial distribution of the surface temperatures within the city more than the morphological variables considered by the study. Further to the above, a calculated F-value of 23.838 confirms that the relationship as established by the model is reliable.

Determination of the model representing the relationship existing between the morphological variables and total environmental quality parameter values was undertaken to gain insight into the contributions of individual morphological elements in the determination of the total environmental quality parameter values. The study established that the relationship existing between the urban morphological variables and total environmental quality parameter values is represented by the regression model 4.7.

$$\acute{Y} = -0.055X_1 - 1.758X_2 + 0.204X_3 + 12.804 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.7)$$

Where

$\acute{Y}$ = Estimated total environmental quality parameter values

X_1 = Development density values

X_2 = Urban spatial structure nominal values

X_3 = Vegetation density values

The calculated *t*-values and the F-value for the above stated relationship are as follows:-

t_1 = The calculated *t*-value attributed to development density whose value is 1.452

t_2 = The calculated *t*-value attributed to spatial structure whose value is 4.423

t_3 = The calculated *t*-value attributed to vegetation density whose value is 5.006

t_4 = The calculated *t*-value attributed to the error term which is 4.458

F = Calculated F-value of the relationship whose value is 25.236

The analysis further confirms that in concert, vegetation density is the most significant variable among the urban morphological elements in determining the spatial distribution of the total environmental quality parameters. Once more, the significance of the calculated *t*-value attributed to the error term (4.458) in the model implies that together with vegetation density, other variables such as the topography, pedology, rainfall pattern and amount, slope, aspects and wind velocity which are not considered by this relationship and/or study significantly explains the spatial distribution of the total environmental quality parameter values within the city. The calculated F-value of 25.236 confirms that the established relationship is consistent.

The study also established the strength of the relationship existing between urban form variables and the aggregate urban environmental quality. The relationship was established to be represented by the regression model 4.8.

$$\acute{Y}= -0.332X_1+0.753X_2+35.111 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(4.8)}$$

Where: -

Ý = Estimated aggregate urban environmental quality values

X_1 = Development density values

X_2 = Land use (urban spatial structure) nominal values

Other statistical attributes explaining the strength of the relationship include the following:-

t_1 = The calculated *t*-value attributed to development density which is 6.454

t_2 = The calculated *t*-value attributed to land uses which is 1.263

t_3 = The calculated *t*-value attributed to the error term which is 8.508

F = Calculated F-value of the relationship which is 73.919

The above confirms that in concert, development density is the most significant variable among the urban form elements which influences the spatial distribution of the aggregate urban environmental quality in the city.

A regression model on the relationship existing between urban morphological variables and the aggregate urban environmental quality was established as equation 4.9.

$$\acute{Y} = -0.154X_1 - 0.758X_2 + 0.306X_3 + 22.984 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.9)$$

Where: -

$\acute{Y}$ = Estimated aggregate urban environmental quality values

X_1 = Development density values

X_2 = Land use nominal values

X_3 = Vegetation density values

Other statistical parameters in this relationship include:-

t_1 = The calculated *t*-value attributed to development density whose value is 4.079

t_2 = The calculated *t*-value attributed to land use whose value is 1.919

t_3 = The calculated *t*-value attributed to vegetation density whose value is 7.537

t_4 = The calculated *t*-value attributed to the error term which is 8.055

F = Calculated F-value of the relationship whose value is 170.078

The above analysis confirms that in concert, vegetation density is the most significant urban morphological variable determining the spatial distribution of the aggregate urban environmental quality in the city. This is followed by development density, which implies that the achievement of sustainable urban development must include the design and implementation of appropriate and innovative development standards. However, the calculated *t*-value for the error term whose value is 8.055 compared to a critical *t*-value of 2.048 is statistically significant, implying that there are other factors such as topography, pedology, rainfall pattern and amount, slope, aspects and wind velocity which are not included in the model and/or the study but significantly determines the distribution of the aggregate urban environmental quality.

4.8 Conclusion

The study has established that the most significant urban morphological variable influencing the spatial distribution of the urban environmental quality in the city is the vegetation density followed by development density and to a weaker extent land uses. The study further underscores that vegetation and development densities, transportation and industrialisation affects the spatial distribution of the urban environmental quality variables of air quality and surface temperatures. Urban developments lead to deforestation and increased urban impervious surfaces such as the buildings and roads which stores thermal energy during the day and slowly releasing the same in the evenings creating urban heat islands, thermal discomfort and increased energy demand in the buildings. Further to the above, urban sprawl has increased vehicular volume which exacerbates GHG, suspended particulate matter and sulphur dioxide emissions to compromise urban air quality. High development densities also influence urban air quality through attenuation of wind velocity which restricts air pollutants in the narrow canyons, leading to the concentrations of the same. Through a combination of shading, evaporative cooling effects and photosynthetic processes, vegetation mitigates urban neighbourhoods against heating and air polluting effects generated by the urban developments. This makes vegetation density an imperative urban morphological parameter determining the distribution of the urban environmental quality.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This study which finds impetus from theoretical postulations on the effects of urbanisation on global warming and climate change, provides a niche for the development of a unifying model explaining the correlation between urbanisation, urban morphology, air quality, surface temperatures, global warming and climate change. The objectives of this study were to evaluate the impact of land use and land cover dynamics on the LCR and LAC for Nairobi City between the years 1988 to 2015, to determine the relationship existing between the urban morphology of Nairobi City and the surface temperature values using geospatial techniques, to establish the relationship existing between the urban morphology of Nairobi City and the variations in air quality as well as to develop a spatial and quantitative model depicting and explaining the environmental quality variations in the city. To understand the urban morphological patterns and to establish the relationship existing between the urban morphology and the environmental quality of the city, geospatial techniques of satellite remote sensing and GIS were utilised. Whereas GIS provide platform for integrating multiple attributes of the environmental quality which is imperative in urban environmental monitoring, planning and management, satellite remote sensing was employed due to the technology’s ability to provide data which is frequent, instantaneous and complete in coverage.

5.2 Summary of Findings

While this study quantified the nature, magnitude, pattern and trends of land use and land cover dynamics within the city between the years 1988 to 2015, the implications of the changes on the environmental quality are demonstrated through the determined LCR and LAC values. Compared to a steady expansion of the urban built-up, open and transitional areas which imply an urban sprawl, the study established marked decline in agricultural, grass, secondary growth, riparian, rangeland and shrubs as well as forest covers within the study period. This has occasioned decline in the ratio of the city under vegetation cover to area under urban built-up, open and transitional lands which have significant implications on the air quality, surface temperatures and overall urban environmental quality. The decline in the percentage of land under agriculture is partially attributed to the population growth in the peri-urban areas which leads to land fragmentation to acreages which are not agriculturally viable. This necessitates conversions of such lands to residential, industrial and commercial developments. The above being the case, the city has continued to experience an overall increase in LCR and LAC or the urban sprawl.

While the expansion of the built-up, open and transitional areas was rapid between the years 1988 to 1998 and 2005 to 2015, the city grew through internal densification in the years between 1998 to 2005. The expansion has been rapid to the eastern and southern parts of the city due to the availability of cheaper land and relatively low construction costs in the zones. Similarly, increased public investments in infrastructure such as roads, water and electricity in what used to be urban peripheries have improved quality of life and attracted more people into the neighbourhoods. The persistent higher property and business taxes in the city centre has equally contributed to the spread of the built up areas into what used to be urban peripheries leading to agglomeration of the businesses into new satellite commercial centres.

The gradual encroachments and degradation of the protected areas such as the forest reserves and the Nairobi National Game Park by developments and other anthropogenic activities such as grazing has led to fragmentation and isolation of the remaining natural ecosystems and animal migratory corridors, consequently leading to mass migration and death of the wildlife during dry spell, loss of the park’s scenic qualities that attract tourists as well as the overall environmental quality of the city. Similarly, increased demand for residential facilities has up-scaled construction and quarrying activities leading to conversions of rangeland and shrubs, agricultural, grassland and riparian reserves to built-up, open and transitional (quarry) lands in the southern and eastern parts of the city.

Over the years, expansion of the built-up areas has exacerbated paved surfaces consequently leading to frequent occurrences of floods, loss of life and property as well as reduced water percolation thereby lowering the ability of the aquifers to recharge. Other environmental implications of the urban sprawl and increased development densities in the city includes increased generation and accumulation of organic, solid, oil and chemical wastes which often find their way into drainage channels through the surface-runoffs to cause eutrophication and algae blooms in the riparian bodies. The organic matter and the chemical compounds generated from the built-up areas may also infiltrate into the aquifers to contaminate the ground water supply. Increased surface-runoffs also leads to land compressions which exacerbates cracking of building foundations, slope collapses and land subsidence which often destroy and make it expensive to maintain water, sewerage and road networks.

Urban sprawl promotes motorised modes of transportation in cities such as Nairobi with the CBD being the major employment centre. This leads to increased vehicular traffic which exacerbates the emission of GHGs, sulphur dioxide and suspended particulate matter, making the city a major contributor of global warming and climate change. Granted that urban sprawl leads to loss of vegetation cover and farmlands, recreational spaces and deterioration of wetlands which collectively moderate urban surface temperatures, enhance air quality and mitigate floods, continued depletion of the urban vegetation and wetlands will exacerbate the effects of urban heat islands, compromise air quality and increase prevalence of urban floods.

The study established that by the year 2015; wetlands occupied 0.94 km^2 or 0.13% of the city, parks and other recreational spaces occupied 138.44 km^2 or 19.32% of the city, forests occupied 26.45 km^2 or 3.69% of the city, commercial developments occupied 41.29 km^2 or 5.76% of the city, airport land occupied 17.44 km^2 or 2.43% of the city, industrial developments occupied 24.15 km^2 or 3.37% of the city, residential developments occupied 204.65 km^2 or 28.56% of the city, quarries occupied 2.93 km^2 or 0.41% of the city, undeveloped land occupied 120.77 km^2 or 16.85% of the city, urban agriculture and riparian reserves occupied 112.64 km^2 or 15.72% of the city, water bodies occupied 3.81 km^2 or 0.53% of the city, railway land occupied 2.20 km^2 or 0.31% of the city and public purpose lands which occupied 20.97 km^2 or 2.93% of the city.

The study established that when urban morphological elements are collectively considered, development density is the most significant determinant of the distribution of urban air quality. This is followed by the vegetation density while land uses have insignificant contribution on the phenomenon. Contrary to the above, the analysis of the strengths of the morphological variables in determining the spatial distribution of the surface temperatures in the city established that vegetation density and land uses are most significant factors explaining the occurrence of the phenomenon. However, the regression model representing the relationship have a significant error term which implies that other factors such as the topography, pedology, rainfall pattern and amount, slope, aspects and wind velocity not considered by the study and/or the model significantly explains the distribution of the phenomenon more than the morphological variables.

The study confirms that vegetation density is the most significant urban morphological variable influencing the spatial distribution of the urban environmental quality. This is followed by the development density and land uses in the order of significance. The study further establishes that the environmental quality of the city can broadly be dichotomised into four broader categories namely; the northern and western, southern, eastern and the central parts of the city which significantly corresponds to the variations in topographical, pedological and climatological base of the city. Since the red volcanic soils which characterises the northern and western parts of the city are rich in nutrients and humus contents, they support healthy natural and exotic vegetation and biodiversity which are carbon sinks and moderators of surface temperatures. The southern and eastern parts of the city which are characterised by low lying plains and black cotton soils with low nutrient contents are dominated by sparse vegetation covers such as the disturbed bushes, shrubs, perennial grasses and under storey trees which are not effective moderators of the urban micro-climates. Therefore, the presence of forest reserves to the northern and western parts of the city coupled with low development densities characterising the regions have acted in concert towards the achievement of relatively better surface temperatures and air quality and by extension better environmental qualities in the regions. This contrasts with the southern and eastern parts of the city which are characterised by sparse vegetation covers, high development densities and dominance of land uses such as transportation, industrial developments and quarries which enhances thermal values and compromising the air quality leading to poor environmental qualities in the regions. The central part of the city which is characterised by mixtures of red volcanic and black cotton clay soils supports moderate vegetation growth thus the zone experiences moderate environmental quality. The above being the case, this study concludes that vegetation density has acted in concert with urban form, physiographical, climatological and pedological factors to influence the spatial distribution of the surface temperatures, air quality values and by extension the environmental quality variations within the city.

5.3 Conclusions

Nairobi City has continued to experience rapid land use and land cover changes. The built-up areas have significantly expanded into the natural vegetations leading to ecological disruptions. Some of the factors which have influenced the rapid urbanisation and by extension land use and land cover successions in the city include modest national economic growth and development, high rural-urban migration and natural population increase rates as well as favourable physiographical base of the city which apart from providing excellent sources of building materials has also lowered the construction costs in the city. It is therefore evident that Nairobi City whose urbanisation rate has been averaging 4.7% per annum since independence as compared to 3.5% per annum for other major African cities urgently need sound environmental management policies to achieve sustainability.

Enactment of appropriate development standards, promotion of consumption habits and practices that conserves and protects the environment should be prioritised. However, this is hard to achieve in the absence of adequate spatio-temporal data which facilitates mapping, monitoring and accurate assessment of the land suitability for urban growth. Towards this end, this study has demonstrated that lack of relevant spatial information crucial for urban planning can be alleviated through geospatial techniques notably the remote sensing and GIS which provides opportunities for periodic survey of land use and land cover changes and integrating the same with conventional *in-situ* data. However, it is imperative to note that technology alone is not sufficient in shifting cities onto sustainable environmental quality trajectory and that complex interactions between forces underpinning urban development such as the role of urban management institutions, infrastructure, land markets, regulations and people's inclinations to environmental conservation present a web of constraints and opportunities for addressing urban environmental quality problems. Therefore, a sustainable urban environmental quality can be achieved through adoption of technology and a combination of urban environmental planning and management techniques such as promotion of green infrastructure, innovative urban design and conservation. Other measures should include tightening up legislations on protection of urban ecosystems and the implementation of sustainable drainage and transportation systems. This should further involve the participation of public sector, private sector and civil society, the re-orientation of legal infrastructure and institutions towards delivering sustainable urban environmental quality, giving more scope and encouragement to local action, behavioural change and innovation. Indeed urban environmental quality as an embodiment of sustainable development should be anchored on proactive legal and management policies focussed on socio-economic development strategies and institutional capacity building for planning both at the local, county and national government levels.

5.4 Recommendations

The achievement of sustainable urban environmental quality requires implementation of multiple strategies and techniques which are known to work within the standard practice of urban environmental planning and management. As earlier mentioned such strategies should include promotion of green infrastructure, innovative urban design and conservation as well as tightening up legislations on protection of urban ecosystems such as the green belts, gardens and trees, urban river restoration and implementation of sustainable drainage and transportation networks. Urban environmental management further requires a new environmental contract encompassing civil society, public and private sector participations. Other measures should include re-orientation of legal infrastructure, institutions and development infrastructure towards delivering urban environmental quality. This should build on the strengths of planning and other environmental management strategies which give more scope and encouragement to local action, behavioural change and innovation. Therefore, urban sustainability should be anchored on proactive policies focussed on socio-economic development strategies and institutional capacity building for planning both at the community, national and county government levels. For the achievement of sustainable environmental quality of the city, the study recommends the following: -

i. ***Enhancement of the Vegetation Cover within the City through Adoption of Sustainable Urban Growth Policies:*** As demonstrated by this study, the vegetation's ability to enhance air quality and to moderate surface temperatures makes the vegetation density the most significant urban morphological variable influencing the spatial distribution of the urban environmental quality. However, this is negated by the urban sprawl currently characterising the eastern and southern parts of the city. Therefore to achieve sustainable urban environmental quality, measures such as the design and implementation of appropriate, innovative and dynamic development policies geared towards increasing the vegetation cover should be prioritised. Such policies should entail implementation of programmes such as development of urban forests, arboretum, open parks, playgrounds and/or village squares, picnic sites and walkways in the residential, commercial and industrial neighbourhoods as well as tightening up legislations protecting urban ecosystems such as the green belts, gardens and urban river restoration among others. The above can be achieved through implementation of development policies which minimises land fragmentations and urban sprawl such as up-scaling of sky lines through increments of plot coverages, ratios and minimum plot sizes for various developments.

Privatisation and restitution concepts which have found niche in the management of public affairs have altered the urban housing market. The concepts empowers the private sector to be the main providers of the urban housing yet the sector is more interested in providing housing for the middle and high-income groups. This has made housing unaffordable to the urban poor who move to the urban periphery and/or open lands to establish informal settlements, consequently leading to rapid land use and land cover changes as well as environmental degradation. Therefore, the government should roll-out sustainable urban low income housing development programmes if the environmental degradation and encroachments into the fragile ecosystems has to be managed.

The study underscores that hindrances to the enhancement of the vegetation cover in the city are *ad-hoc* enactments of the development control policies and regulations, inadequate implementation of the development plans and land speculations which over the years have accentuated proliferation of illegal developments leading to undesirable land use and land cover conversions. To rectify this, the city authority should regularly update the existing development plans and enforce strict adherence to the development control standards. This should also include shortening the time period in plan approval process which tends to promote illegal developments. The evolved development plans should spell out the number of trees to be planted per acreage of a developed plot. In accordance with the provisions of Environmental Impact Assessment Regulations of 2003, all the proposed developments within the city which are likely to compromise the air quality and increase the surface temperatures should be subjected to Environmental Impact Assessment. This should be enforced by National Environment Management Authority in conjunction with the Nairobi City County Government.

ii. ***Creation of Environmental Quality Monitoring Stations in the City to Facilitate Enactment of Appropriate Environmental Management, Transportation and Industrial Development Policies:*** Industries and motor vehicles emits GHGs, sulphur dioxide and suspended particulate matter which apart from lowering the urban air quality also makes cities major contributors of global warming and climate change. Therefore, the Nairobi City County Government should formulate policies and enact legislations and standards for the reduction of air pollution in the city. The policies should include popularisation of public transportation, none-motorised modes of transportation as well as limiting the number of vehicles coming into the city. Other transportation policy measures that should be favoured include the development of arterials which supports rapid vehicular flow for it has since been established that vehicles emit more GHGs, sulphur dioxide and suspended particulate matter when their speeds are low. The industrial and commercial districts are often characterised by high density developments and vehicular concentration which apart from compromising the vegetation cover also restricts the dispersal of air pollutants leading to the increased concentrations of the same. Therefore to ensure that air pollutants are properly dispersed, policy measures such as decentralisation of industrial and commercial developments should be pursued. However, for the above to be undertaken there is need for frequent air quality monitoring which can be achieved through the establishment of adequate network of stationary air quality monitoring stations as well as undertaking mobile air quality monitoring along road transects.

iii. ***Expansion and Regular Maintenance of the Urban Infrastructure:*** Increased frequencies of sewer blockages and bursts indicate that developments in the city have surpassed the capacity of the existing infrastructure. Therefore, for the city to continue supporting the current population through re-densification of the existing land uses (curtailing the urban sprawl), there is need for expansion and regular maintenance of the existing water reticulation, sewer and road networks.

iv. ***Instituting Geospatial, Information and Communication Technologies (GICTs) in the Urban Planning and Growth Management in line with the Sustainable Development Goals' (SDGs) Recommendations:*** In undertaking regular reviews of the development plans and standards as earlier proposed, cognisance should be taken of land use suitability. This is impetrative in protecting the fragile ecologies such as the forest and riparian reserves against encroachment by anthropogenic activities. The land use suitability analysis is also imperative in protecting human life and property against disasters such as floods. However, the above can efficiently and effectively be undertaken if the Nairobi City

County Government institute the utility of ICT and the geospatial techniques notably remote sensing and GIS as planning tools which is in line with the SDGs' stipulations.

v. ***Multi-Sector Partnership Approach to Urban Environmental Planning and Management:*** Despite the constitutional stipulations on the involvement of the citizens in the development plan formulation and implementation, it is glaring that the current urban development paradigms operational in the city are not people driven and various development agents feel left out in the process. Therefore, in the evolution and review of the development plans for the city, the people and various development agents should be brought on board. This makes it easy for people and the development agents to understand the issues entailed in the plan and to take charge in implementing the same. Therefore, the city authority should enact a policy on partnership building with citizens and other development agents as well as registering the neighbourhood associations and empowering the same to undertake self driven development control and compliance monitoring. It is equally imperative to explore broad based (in issues and stakeholders) and participatory institutional framework on which various strategies that are meant to enhance the city's environmental quality can be implemented.

5.5 Areas for Further Research

Since poverty is a major contributor to land use and land cover dynamics, this study proposes research to be undertaken on the relationship existing between the income levels and the rate of land use and land cover dynamics in the city. Since various development zones and electoral units of the city fairly correspond to income levels, they can be used in the establishment of the relationship. Whereas income levels for the development zones can be obtained through household surveys, income levels of the electoral units can be postulated using secondary data from the poverty indexes of various years which are often undertaken by the Government for all the constituencies in the country for the purposes of the disbursement of the National Constituency Development Fund. In line with the Vision 2030 which is the national development blue-print currently being implemented, the study should further project land use and land cover of the city by the year 2030 with an assumption that the current underlying factors influencing the same will not change. This is imperative in justifying the role of geospatial techniques in the evaluation of the impact of a public policy and enabling the city to safeguard against environmental degradation, attract investments and to remain being a regional economic hub.

Vegetation density is the most significant urban morphological variable determining the spatial distribution of the urban environmental quality. This is followed by urban development density and land use in the order of significance. However, the significance of the error term in the model representing the relationship existing between the urban morphological variables and the environmental quality values implies that other factors such as the topography, pedology, rainfall pattern and amount, slope, aspects and wind velocity which were not considered by the study are equally significant in determining the spatial distribution of the same. Therefore, this study proposes research to be undertaken on the relationship existing between urban environmental quality and the above stated variables collectively with morphological variables of vegetation density, development density and land uses in the city. It is further proposed that a study on institutional framework which takes cognisance of broad based stakeholders' involvement in the implementation of the urban environmental quality management be undertaken.

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APPENDIX I: THE DEVELOPMENT ZONES OF THE CITY

Zone	Areas Covered	Ground Coverage (%)	Plot Ratio (%)	Type(s) of Developments Allowed	Minimum Plot Area (Ha)	Remarks/Policy Issues
1.	**Central Business District**			Commercial/Residential/Light Industry	0.05	
	Core CBD	80	600			
	Peri CBD	80	500			
	West of Tom Mboya Street	60	600			
	East of Tom Mboya Street	80	350			
	Uhuru Highway/ University Way/ Kipande Road	80	500			
	Upper Hill Area					
	Block 1 - Offices (Community)	60	300	Commercial/Offices/ Residential	0.05	
	Block 2 - Commercial / Offices	60	250			
	Block 3 - Offices	60	300			
	Block 4 - Residential	35	150			
	Block 5 –Institutional (KNH)					
	Block 6 – Mixed (institutional, Hotels, Offices)	60	200			
2.	**Eastleigh**					
	Eastleigh District Centre	80	250	Commercial/Residential (High-rise Flats)	0.05	
	Eastleigh Commercial/Residential Area	60	240			
	Pumwani/California	60	240	Commercial/Residential (High-rise Flats)		
	Ziwani/Starehe					
	Commercial	80	150			
	Residential	35	75			
3.	**Parklands**					
	Commercial	50	100	Commercial/Offices/ Residential (High-rise Flats) – Four Storey maximum	0.05	
	Residential	35	75			
	City Park/ Upper Parklands	35	75			
	Westlands					
	Westlands Business District	80	240			
	Westlands/Museum Hill					
	Block 1 - Commercial	80	200			
	Block 2 and 3 - Offices and High-rise Residential	35	80			
	Block 4 - Offices	80	200			
	Block 5 - Commercial/Residential Hotels					
4.	Spring Valley	35(s) 25(u)	75(s) 25(u)	Residential (Four Storey maximum)	0.05	Apartments allowed on sewer only)
	Riverside Drive					
	Kileleshwa					
	Kilimani					
	Thompson					

	Woodley					
5.	Upper Spring Valley	25	25	Low Density Residential – One Family House	0.2(u) 0.1(s)	Maisonettes allowed on sewered areas of Lavington
	Kyuna					
	Loresho					
	Lavington/Bernard Estate on sewer/unsewered					
6.	Muthaiga	25	25	Low Density Residential	0.2	Single Family Dwelling
	New Muthaiga					
7.	Mathare Valey	50	75	High density residential flats/Informal Settlements (Slums)	0.05 (Lower on Site and Service Schemes)	Special Schedule High Density informal developments
	Mathare North					
	Lower Huruma					
	Kariobangi					
	Korogocho					
	Dandora					
8.	**Old Eastlands**					
	Shauri Moyo			Largely Constitute Old City Council Housing – Ripe for High Rise High Density Redevelopment		Special Schedule Areas • NCC site and service schemes as low income areas
	Maringo					
	Bahati					
	Kaloleni					
	Makongeni					
	Mbotela					
	Jericho					
	Jerusalem					
	Makadara	50	100	Mixed Residential Developments - Flats - Maisonettes - Bungalows - Site and Service Schemes - Condominium (Single Rooms)	0.05	Comprehensive Subdivision Allowed Minimum To Fit a House on Type Plan Design
	Doonholm Neighbourhoo (Block 82)	50	75			
	Uhuru (1-3)	50	75			
	Buru-Buru (1-6) (Blocks 72 -79)	50	75			
	Umoja 1 and 2	50	75			
	Umoja Inner core	50	150			
	Komarock Commercial	80	150			
	Komarock Residential	50	75			
	Kayole Commercial	80	150			
	Kayole Residential	50	75			
9.	**Main Industrial Area**	80	300	Industrial and Godowns	0.05(s)	Becoming Overdeveloped
9E.	Dandora industrial zone	80(S) 50(u)	150(s) 100(u)	Light Industrial and Godowns	0.01(u)	Ruaraka EPZ Covered
	Kariobangi Light Industrial Zone	50(u)	100(u)			
	Mathare North Light Industrial Zone	50(u)	100(u)			
10.	Nairobi West	35		High Density and Mixed		Comprehensive subdivision
	Madarak					

	South “B”	35	75	Residential Developments - Flats - Maisonettes - Bungalows	0.5	allowed with lower sizes on type plan Development density at 35 units per hectare
	South “C”					
	Nairobi Dam	50				
	Ngummo					
	High-View					
	Magiwa					
	Golf Course					
	Langata Estates					
	Southlands	75	75			
	Otiende					
	Ngei 1 And 2					
	Onyonka					
	Masai					
	Uhuru Gardens					
	Jonathan Ngeno					
10E.	Imara Daima	50	75	Mixed Residential Developments	0.5	Area not fully sewered, comprehensive subdivision allowed with lower sizes on type plan (Max. 35 units/hac)
	Tassia					
	Fedha					
	Avenue Park					
	Embakasi Village Commercial	80	150			
	Embakasi Village Residential	50	75			
11.	**Special Scheduled Area (Kibera Slums)**			Informal Mixed Developments and Comprehensive Residential Schemes	0.05	NHC Plan lacking in social infrastructure such as the schools, clinics, recreational and commercial spaces Comprehensive subdivision allowed with lower sizes on type plan
	National Housing Corporation (NHC) Estates					
	Ayany	50	75			
	Olympic					
	Fort Jesus					
	Karanja Road					
12.	Karen/Langata			Low density residential developments (one family dwelling house)	0.2	
	Karen				0.4	
13.	Gigiri	25	25	Low density residential developments (one family dwelling house)	0.2	Plan well implemented. There exist only pockets of intensive developments such as the Village Market and the American Diplomatic Housing
	Kitisuru					
	Ridgeways					
	Garden Estate					
	Safari Park					
	Balozi Housing					
14.	Roysambu	25	25	Low density residential developments (one family	0.2	Intensive developments in Marurui and Roysambu
	Thome					

	Marurui			dwelling house)		
15.	Dagoretti	35	75	Agricultural/Mixed Residential Developments - Gap Flats - Maisonettes - Bungalows	0.1(u) 0.05(s)	Area maintains agricultural character High-rise flats development becoming popular
	Riruta					
	Kangemi					
	Mutuini					
	Waithaka					
	Ruthimitu					
	Uthiru					
16.	Baba Dogo Industrial	80(s) 50(u)	300(s) 100(u)	Industrial Zone and Mixed Residential Developments	0.05 Lower if comprehensive developments	High density residential development
	Baba Dogo Residential	35(s) 25(u)	75(s) 25(u)			
	Ngumba/Ruaraka	50(s)	200(s)			
17.	Githurai 44 and 45	50(s)	200(s)	Industrial Zone and Mixed Residential Developments		Replete with unplanned developments hence *"Blanket Approval"* vide town planning resolution of 18/09/1997
	Zimmerman					
	Kahawa West Commercial	50	100			
	Kahawa West Residential	50	75			
	Kahawa West Industrial	50	100			
18.	**Kasarani**					
	Clay-works	50	100	Agricultural/Mixed Residential Developments	2.0 0.05(s) 0.1(u) Lower minimum sizes if land buying company	Area has potential for residential developments. However, the area has been invaded by land buying companies and speculators. Industrial developments not attractive here
	Clay-City					
	Sports View					
	Mwiki	50	200			
	Njiru	25	25			
	Ruai					
19.	**Special Scheduled Area**			Agricultural/Mixed Residential Developments		Area fully influenced by the city dynamics. The area is overwhelmingly dependant on services of the city. However, NCC is not in control of developments.
	Githurai - Kimbo					
	Wendani					
	Kahawa - Sukari					
20.	**Public/Strategic Reserved Areas (Gazetted)**					
	• State House • JKIA Airport • Wilson Airport			Special/Strategic Facilities and Developments		Boundaries not clearly demarcated

	Military Sites o Military Airbase Eastleigh o DoD Headquarters o Kahawa Barracks o Langata Barracks o Defence College, Karen o Forces Memorial Hospital					
20A-G	**Recreational and Forests**			Public open spaces, reserves and recreational facilities		
	• City Park • Arboretum • Ngong Forest • Karura Forest					
	National Game Park					
	Stadia					
	• Moi Sports Complex, Kasarani • City Stadium • Nyayo Stadium					
	Public Parks					
	• Uhuru Park • Central Park • Uhuru Park • Central Park • Uhuru Gardens					