IMPACT OF URBAN DEVELOPMENT ON CLIMATE AND RIVER SYSTEMS: IMPLICATIONS FOR THE ENVIRONMENTAL HEALTH SUSTAINABILITY OF THE MANGAUNG METROPOLIS, SOUTH AFRICA

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DECLARATION OF INDEPENDENT WORK

I, SAMSON SANYA SENBORE, identity number ________ and student number ________, do hereby declare that this research project submitted to the Central University of Technology, Free State, for the Doctor of Philosophy in Environmental Health, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State; and has not been submitted before to any institution by myself or any other person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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SIGNATURE OF STUDENT **DATE**

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ABSTRACT

The emigration to urban areas puts pressure on available resources, thereby increasing the scarcity of natural resources and changes in lifestyles. The overpopulation of urban centres accelerates land use patterns, slum creation and generation of contaminants. Urban centres are known to generate carbon dioxide and other compounds that increase greenhouse gases. In the process of combating food insecurity, farmers resort to chemicals such as fertilisers, pesticides and fungicides. Likewise, unplanned human slums and unregulated industries generate a lot of known and unknown emerging contaminants that pollute urban soils and water sources.

Rapid urbanisation alters living styles and standards in the Mangaung Metropolitan Municipality (MMM). The MMM is faced with environmental challenges such as unplanned urban slums, incessant water and air pollution due to rapid urban development and human activities. Likewise, urbanisation in the study area triggered rural-urban migration that accelerate population growth in the study area; hence, the population rate in the MMM has shown an increase with numbers reported as 603 528 in 1996, 747 431 in 2011, 759 693 in 2016, 853 141 in 2018 and 861 651 in 2019.

As such, this research sought to investigate the impact of rapid urban development in the MMM on water sources and environmental health sustainability. Systemic scientific methods were employed to investigate the urban land cover change, water quality and environmental health of the MMM. Remote sensing and geographic information systems were employed to analyse land use / land cover, Normalised Difference Vegetation Index, Normalised Difference Moisture Index, Normalised Difference Built-up Index and Normalised Difference Water Index changes for a period from 1978 to 2018 in the MMM. Furthermore, the historical water quality of important river systems and dams located on these rivers were studied to detect the impact of urban contamination.

Consequently, the challenges accompanying rapid urbanisation in the MMM has led to the development of an urban health sustainability index to assess the status of environment health of the MMM. This is to ensure sustainability in all spheres of our environment and to mitigate the impact of urbanisation confronting us as people. The urban health sustainability index tracks a set of environmental and social environmental indicators that influence sustainability in an urban setting. The developed model observes the relationship between urban sprawl, land use / land cover changes, climatic variables, vegetation and water in terms of its sustainability. Furthermore, this research simulates the future land cover classification focussing on the urban growth development and water sources availability for the years 2028 and 2038.

The result of the land use / land cover from satellite imagery revealed that an exponential increase in urban areas led to loss of vegetation cover and shortage of water availability in the MMM. This suggests that urbanisation accelerates the loss of vegetation cover, thus causing an increase in temperature and reduction in the amount of rainfall, thereby reducing the surface water quantity in the MMM. The change detection analysis observed between 1978 and 2018 revealed that agricultural areas increased by 22.6%. This can be linked to the increase in population growth and the upsurge in demand of farm products in the MMM. In addition, the Water Quality Index (WQI) of most of the water sources revealed deterioration in water quality from 1988, with a WQI of 20.1, 23.2 and 18.6 indexed as excellent, to 2018 with a WQI of 25.6, 41.0 and 49.0 indexed as good. This suggests the impact of urbanisation on water sources in the MMM. Conclusively, the results from the land cover classification and water quality assessment informed that the expansion in agricultural areas to enhance food security has led to the generation of more contaminants polluting the urban water system in the MMM.

The urban health sustainability classification in the MMM ranged from low (30–50) to high (65–80) sustainability scores. The low sustainability class is typical of areas with a high concentration of built-up areas, agricultural landmass and human activities where pollutants are mostly generated. Meanwhile, the high sustainability class is typical of areas with low-generating polluting media to the atmosphere and water sources. Likewise, the comprehensive environmental pollution index method categorised selected areas in the MMM into high, moderate and low polluted areas with index scores of 51–68, 42–44 and 32–37, respectively. The high and moderate polluted areas should be kept under environmental monitoring and pollution control for sustainable environmental health.

The research recommends that control measures should be implemented in the township and urban slums in the MMM to reduce generation of solid waste through mandatory regulation and education. Policymakers in the MMM should curtail increases in unplanned settlements and control internal migration. This is to meet the urban sustainability goal by 2050 as campaigned by the United Nations. Finally, an environmental geochemistry study should be carried out to trace the sources of emerging contaminants across the MMM.

Keywords: climate variables, geographic information systems, Mangaung Metropolitan Municipality, remote sensing, urbanisation, urban health sustainability model

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ABBREVIATIONS AND ACRONYMS

ADB	Asian Development Bank
ADI	Average daily intake
CDI	City Development Index
CEPI	Comprehensive Environmental Pollution Index
CF	Climate factor
COP	Conference of the Parties to the United Nations Framework Convention on Climate Change
DEM	Digital elevation model
DMS	Dissolved Major Salts
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EC	Electrical conductivity
EF	Ecological Footprint
EPA	Environmental Protection Agency
EPI	Environmental Performance Index
ESI	Environmental Sustainability Index
ETM+	Enhanced Thematic Mapper Plus
EVI	Environmental Vulnerability Index
EWI	Ecosystem Well-being Index
FAO	Food and Agriculture Organization of the United Nations
GCS	Geographic coordinate system
GDP	Gross Domestic Product
GIS	Geographic Information System
GNI	Gross national income
GPS	Global Positioning System
HDI	Human Development Index
HI	Hazard Index
HWI	Human Well-being Index
IPCC	Intergovernmental Panel on Climate Change
KR	Kelly ratio
LPI	Living Plant Index
LULC	Land use / land cover
MAR	Magnesium adsorption ratio
MMM	Mangaung Metropolitan Municipality
MOLUSCE	Modules for Land Use Change Evaluation
NDBI	Normalised Difference Built-up Index
NDVI	Normalized Difference Vegetation Index

NDMI	Normalized Difference Moisture Index
NDWI	Normalized Difference Water Index
NIR	Near infrared
OECD	Organisation for Economic Co-operation and Development
PCA	Principal Component Analysis
P_{ET}	Potential Evapotranspiration
RfD	Reference dose
RQ	Risk quotient
SADC	Southern African Development Community
SANS	South African National Standard
SAR	Sodium adsorption ratio
SAWS	South African Weather Service
SE–NW	South-east to north-west
SSP	Sodium adsorption percentage
StatsSA	Statistics South Africa
SOPAC	South Pacific Applied Geoscience Commission
SW–NE	South-west to north-east
SWIR	Short-wave infrared band
TDS	Total dissolved solids
TM	Thematic Mapper
UHS	Urban health sustainability
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme i
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
UN-Habitat	UN-Habitat (United Nations Human Settlements Programme
UNICEF	United Nations Children's Fund
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WBI	Well-being Index
WCED	World Commission on Environment and Development
WGS	World Geodetic System
WHO	World Health Organization
WMO	World Meteorological Organization
WQI	Water Quality Index

LIST OF CHEMICAL SYMBOLS

As	Arsenic
Ca	Calcium
Ca^{2+}	Calcium ion
CaCl	Calcium chloride
CaMg	Calcium–Magnesium
Cd	Cadmium
Cl	Chlorine
Cl^{-}	Chloride
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
F	Fluorine
H_2O	Water
HCO_3	Bicarbonate
Hg	Mercury
Ir	Iridium
K	Potassium
K^{+}	Potassium ion
Mg	Magnesium
Mg^{2+}	Magnesium ion
Mn	Manganese
N	Nitrogen
Na	Sodium
Na^{+}	Sodium ion
NH_3	Ammonia
NH_4	Ammonium
Ni	Nickle
NO_2	Nitrogen dioxide
NO_3	Nitrate
NOx	Nitrogen oxides

Os	Osmium
P	Phosphorus
Pb	Lead
Pd	Palladium
Pt	Platinum
PO_4	Phosphate
Rh	Rhodium
Ru	Ruthenium
Sb	Antimony
Si	Silicon
SO_2	Sulphur dioxide
SO_4	Sulphate
SO_4^{2-}	Sulphate iron
V	Vanadium

LIST OF MEASURING UNITS

°C	Degree Celsius
%	Percentage
cm^2	square centimetre
cm^3	cubic centimetre
kg	Kilogram
km	Kilometre
km^2	Square kilometre
m	metre
Ma	Million years ago
mEq/l	Milliequivalent per litre
mg/kg/day	Milligram per kilogram per day
mg/l	Milligram per litre
Ml	Megalitre
mm	Millimetre
µS/cm	microSiemens per centimetre

Chapter 1

INTRODUCTION

1.1 Background statement

Rapid urban development is a driver of environmental change in many developed and developing cities (Gustavo et al., 2019; Hagen et al., 2017). Urbanisation is the concentration of people in urban areas and the process of change in land use patterns, resulting from migration of people in rural areas into urban, suburban, and industrial communities (Dan-Jumbo et al., 2018; Sako & Nimi, 2018; Savini & Kammerer, 1965; United Nations [UN], 2019). There has been an increase in urban populations in recent decades across the globe and this rapid population growth is a major threat on environmental health sustainability (UN, 2019). The world population living in urban centres was 30% in 1950, 55% in 2018 and it has been projected to be 68% by 2050 (UN, 2019).

Africa has the least urban centres with 43% of its populace living in urbanised regions, as compared to Asia 50%, Oceania 68%, Europe 74% and America 82%. It has been anticipated that Africa and Asia are more susceptible to the impact of urbanisation such as climate change, flooding, environmental pollution and drought, due to poor adaptive capacity (Li et al., 2014; Osti et al., 2008; Sako & Nimi, 2018; UN, 2019; UN Framework Convention on Climate Change [UNFCCC], 2007). The study of urban development is relatively new and relevant to scientists, following the rapid population growth in urban cities and the various impacts it has imposed on the environment within a short period of time since the Industrial Evolution. The various impacts of urbanisation include water scarcity, health issues, poor sanitation, urban slums, and degradation of ecosystems, with an adverse impact on environmental and health sustainability (Adepoju, 1993; Zamin et al., 2019).

The emigration to urban areas puts pressure on available resources, thereby increasing the scarcity of natural resources and changes in lifestyles (Tam et al., 2019; Xiong et al., 2019). The overpopulation in urban centres accelerates land use patterns, food insecurity, overstretching of infrastructure and rapid expansion of urban slums (Hassan Rashid et al., 2018; O'Connor, 2021; Zamin et al., 2017; Zhang et al., 2018). Urban centres are known to generate carbon dioxide and other compounds that increase greenhouse gases (Al-Maliki et al., 2022; Kweku et al., 2018). In the process of combating food insecurity, farmers resort to chemicals such as fertilisers, pesticides and fungicides (Banda & Kumarasamy, 2020; Cohen & Garrett, 2009; Khalik et al., 2013).

In addition, unplanned human slums and unregulated industries generate a lot of known and unknown emerging contaminants that pollute urban soils and water sources (Banda & Kumarasamy, 2020; Barbooti, 2015; McGrane, 2016; Prasad et al., 2015; Shen et al., 2019). These emerging contaminants flow into streams and river systems that end up being deposited as bottom sediments (Cullis et al., 2019; Fang et al., 2019; Sojka et al., 2018). River sediments affect the quality of surface water which serves as source of municipal water supply and as habitat for aquatic life (Kulbat & Sokołowska, 2019). The recycling of contaminants threatens our environmental health sustainability through consumption of chemical and emerging contaminants that are harmful to human health and aquatic life (Fang et al., 2019; Okaka & Odhiambo, 2018).

The population rate in the Mangaung Metropolitan Municipality (MMM) (Figure 1.1) has shown an increase with numbers reported as 603 528 in 1996, 747 431 in 2011, 759 693 in 2016, 853 141 in 2018 and 861 651 in 2019 (Statistics South Africa [Stats SA], 2016, 2019). Bloemfontein, capital city of the Free State, and is the sixth-largest city in South Africa (Das & Emuze, 2014). Bloemfontein, Botshabelo and Thaba 'Nchu are major city centres experiencing rapid development in the MMM. Due to the rapid development and an increase in population in these areas, there have been an increase in urban slum, occurrence of sewage system spillage and high industrial activities. Furthermore, various harmful emerging contaminants and toxic emissions are generated from the slums, wastewater plants, sewage systems, transportation and industrial activities (Stats SA, 2020). These harmful contaminants and toxic emissions are released into the environment. A proportion of the emerging contaminants and toxic materials on land percolate into the ground, while some are transported through erosion into the drainage and river systems, which are deposited as bottom sediments, thereby contaminating the aquatic environment and water sources. The cycle of these generated contaminants from the sources ends up as consumables to the populace through drinking and eating, with an impact on human health.

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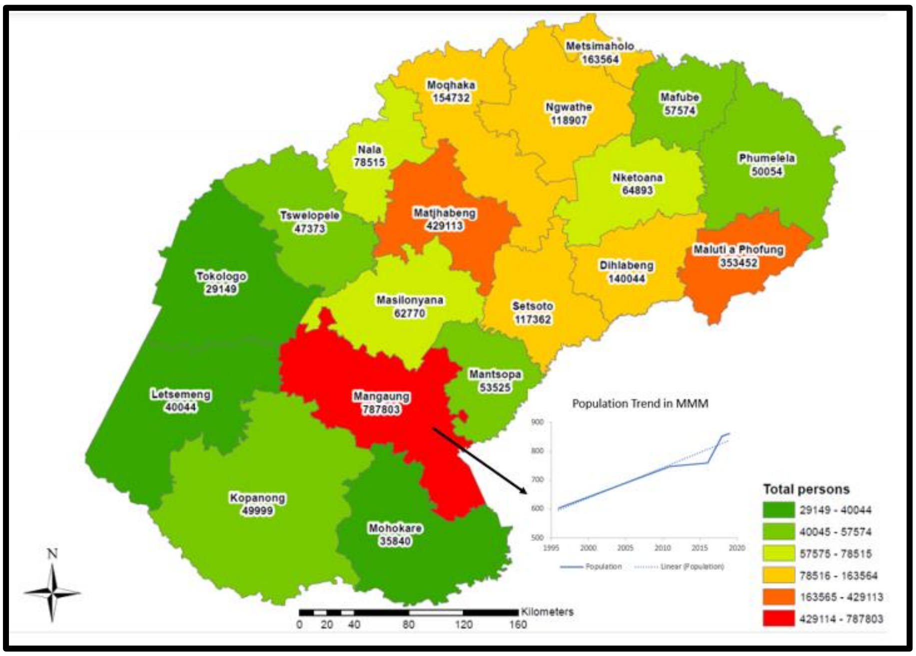


Figure 1.1: ***Free State map showing Mangaung Metropolitan Municipality and its population trend***

Source: Stats SA (2020)

1.2 Study rationale

Climate change is becoming a major threat to our planet. We have recently experienced many cases of flooding and excessive heat from the sun (Intergovernmental Panel on Climate Change [IPCC], 2012; Seip, 2020). In order to save our environment from the looming climate change, there is a need to take a stand against environmental practices that are harmful to our ecosystem. Globally, a healthy environment is a critical factor of sustainable development. Environmental health sustainability can be integrated into sustainable development by improving environmental quality, thereby reducing exposure to air pollution from carbon dioxide (CO_2) emissions, and providing clean water and sanitation (Aladejana et al., 2020; Serdeczny et al., 2017; World Health Organization [WHO], 2000, 2011).

It is imperative to protect our environment from all life-threatening hazards caused by urbanisation resulting in climate change and environmental pollution. Therefore, environmental sustainability monitoring is paramount in our cities. Environmental sustainability deals with how natural systems function, remain diverse and produce everything it needs for the ecosystem to remain balanced (Bounoua et al., 2020; Morelli et al., 2016). Sustainability and sustainable development focus on equating the marginal line between population growth and the needs to protect the environment (O'Connor, 2021). In the world today, the awareness of minimising environmental contaminants such as hazardous materials, waste and fuel must be addressed in all gatherings because of the damage it has caused the human race (UN Conference of the Parties [COP 26], 2021). In protecting the environment and the rapidly sprawling urban cities, several models of various goals have been developed by researchers at all levels. Providing solutions and balance to the present global environment, policymakers at national, regional and global scales have also committed to sustainable development by ascribing the importance to environmental issues (United Nations Conference on Environment and Development [UNCED], 1992; United Nations Department of Economic and Social Affairs [UNDESA], 2014; Zhang et al., 2018).

In a rapidly urbanised world, the effect of urban development is characterised by the physical, social, environmental and economic characteristics of its citizens, among which are inequality, urban slum creation, and changes in lifestyle (Lenzi & Perucca, 2021; McGrane, 2016). Urbanisation is associated with rural–urban migration, change in land use, and settlement patterns (Van der Meulen et al., 2020). Many functions are carried out in urban settlements that attract rapid migration from the rural communities, causing great threats on land use patterns in the urban land and negatively reduce the quality of human life. There are several rural push and urban pull factors contributing to population growth in the cities across the world. According to Jedwab et al. (2015), unemployment, poor living conditions, poverty, poor health and educational services are rural push factors. Meanwhile, urban pull factors offer the opposite, thus give room for rural–urban migration.

There have been scientifically proven models on environmental sustainability that are further discussed in Chapter 2, and a few from other scientists' point of view to maintain and sustain urban growth and the economy. However, little has been done on urban health sustainability (UHS) that is a major significance of this research to formulate a simplified way of assessing sustainable urban health for the rapid urbanised areas in the MMM. In developing a new UHS model for assessing the MMM, it is important to investigate land use / land cover classification, water quality classification and other meteorological parameters for a specified period of years.

1.3 Problem statement and justification

Urbanisation alters living styles and standards, slum generation, and food insecurity (Dan-Jumbo & Metzger, 2019; McGrane, 2016). Climate change is linked to urbanisation and is a major challenge to many regions across the globe (IPCC, 2012). Inappropriate land use is responsible for repeated drought and flooding due to climate change, thereby raising the contaminant level in rivers, leading to poor municipal water quality supply (Jiang et al., 2019; Malefane, 2016; Oke & Alowo, 2021). Urban slums and inappropriate land use alter water and elemental cycles, thereby affecting sustainability of the environment. This global trend has also been experienced in the MMM, which in the last decades has been experiencing rapid urban expansion and population growth from 603 528, 747431, 759 693, 853 141 and 861651 in 1996, 2011, 2016, 2018 and 2019, respectively (Stats SA, 2016).

Service delivery has recently become the major watchword of every citizen in South Africa and the most important of all is the availability and accessibility of quality water for sustainable living. In 2016, a delegation from the Department of Water and Sanitation (DWS) declared the Free State as a water stress province. Currently, there is no access to quality water in certain parts of the municipality due to an overstretched infrastructure. There has been frequent spillage from municipal sewerage systems, with the wastewater treatment plant handling effluents beyond their capacity as a result of rapid population growth and development (Figure 1.2). Farmers also opt for chemicals to meet up with the demand of agricultural products, which generate lot of emerging contaminants that pollute major water sources in the municipal area (Maponya & Rampedi, 2013).

Notes: (a) Informal settlement located near a spilled sewerage in the study area; (b) spilled sewerage system flowing into a stream; (c) municipal sewerage channel and spill over; (d) inappropriate waste disposal site

Figure 1.2: Pictures of environmental hazards in the study area

Surface water quality in MMM is threatened by contaminants from urban and suburban activities (Department of Water Affairs [DWA], 2012; Grant, 2015). The major settlements in the study area are Bloemfontein, Botshabelo, Thaba 'Nchu, Dewetsdorp, and Soutpan. Most of the emerging contaminants are generated from the populace in these communities, which are further transported into the larger Modder River. Contaminants generated in

Bloemfontein flow into the Bloemspruit and Renosterspruit rivers, while contaminants generated in Botshabelo are deposited into Kgabanyane River and the Klein Modder River. Thaba 'Nchu releases its discharge into Sepane River. The Dewetsdorp and Glen communities discharge their domestic waste into the Rustfontein Dam and Modder River, respectively, which are further transported into the larger Modder River, a major source of water in the municipality. The deteriorating urban environment in Mangaung is taking a toll on the people's health and diminishing their quality of life (Dlamini, 2022; Mokgele & Du Rand, 1999). Unplanned urban growth and rapid expansion leads to diversion of agricultural and forest land for commercial purposes, leading to severe biological diversity lost and environmental degradation.

Due to the aforementioned scenario, there is a need for investigating the impact of urban expansion and development on water sources and environmental health sustainability in the MMM. The rate at which emerging contaminants, particulate and other harmful emissions are being generated from urban centres, urban slums and agricultural farms into land, water sources and the atmosphere are not sustainable for the environment, aquatic life, and human health. Thus, this study sought to investigate the impact of urban development on climate and river systems: implications for the environmental health sustainability of the MMM.

1.4 Research aims and objectives

The main aim of this research was to determine the impact of rapid urban development in the Mangaung Metropolitan Municipality on water sources and environmental health sustainability with the following sub aims and objectives:

Sub-aim 1: Monitoring and characterisation of urban development

Objectives:

- To map the rate of urbanisation in the Mangaung Metropolitan Municipality using remote sensing and geographic information systems.
- To evaluate historical water quality based on physical, chemical and microbial parameters of the study area.
- To estimate historical urban water cycle components, evapotranspiration, precipitation and temperature of the study area.

Sub-aim 2: Model index development

Objectives:

- To develop an urban health sustainability index.
- To apply the developed indices to evaluate environmental health sustainability of the Mangaung Metropolitan Municipality.
- To validate the model result with health, environmental and sustainability data such as water quality standards.

1.5 Research questions

The following questions informed the basis for this research:

- How does rapid urban development impact environmental health sustainability?
- To what extent is rural–urban migration responsible for climate change impact in the Mangaung Metropolitan Municipality?
- To what extent have the contaminants affected the quality of river systems and dams in the Mangaung Metropolitan Municipality?

1.6 Location and accessibility of the study area

The MMM is one of the five municipalities in the Free State province of South Africa (Figure 1.3). The MMM shares boundaries with the Xhariep, Lejweleputswa and Thabo Mofutsanyane Municipalities. The study area lies between latitude 28° 42' S to 30° 06' S and longitude 25°−43' E to 27° 12' E. Major localities found in the area are Bloemfontein in the central region, Botshabelo and Thaba 'Nchu in the east, Dewetsdorp to the south and Soutpan in the north (Figure 1.3).

The study area is generally accessible through national (N), metropolitan (M) and regional (R) roads. The Mangaung national roads are the N1, N8 and N6. The N1 is a major road running south-west to north-east from Cape Town to Johannesburg. The N8 runs east–west, connecting Bloemfontein with Kimberley and Maseru, the capital of Lesotho. Bloemfontein is also the northern end of the N6 road heading roughly southwards to the port of East London. There are also R routes, namely the R64, which is the old road to Kimberley via Dealesville and Boshof. The R30 ends at the N1 north of the city, where the other R routes have their origin in Bloemfontein. The R706 takes its origin from the N8 in the city centre, and heads south-east towards Jagersfontein and Fauresmith. The R702 also originates from the N8 in the city centre, but heads south-west towards the towns of Dewetsdorp and Wepener. The R700 starts south of the city centre from the M30 and heads north, crossing the N8 and N1 towards Bultfontein (Figure 1.3).

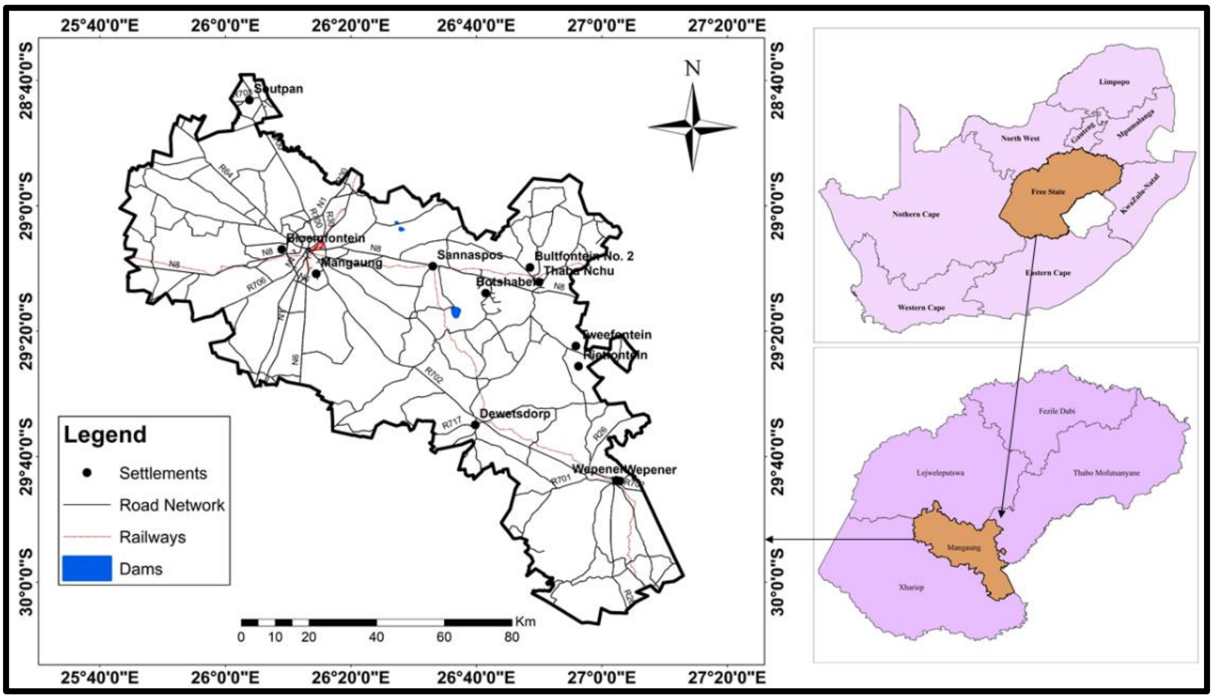


Figure 1.3: Location map of the study area

Mangaung is a Sesotho name meaning *Place of Cheetahs*. Bloemfontein was the name when it was first established as a British fort in 1846 and is now the judicial capital of South Africa. Bloemfontein has served as the capital of a number of people, including the Boers, the Griqua (a subgroup of the Khoe-speaking tribes), and the Barolong, who are descended from Tswana. Mangaung was upgraded to a metropolitan municipality in 2011, having previously served as a local municipality under the jurisdiction of the Motheo District Municipality. The MMM was merged with the Naledi Local Municipality in 2016, resulting in the current municipal boundaries being established (Figure 1.3). Further details on physiography, climate variables and characteristics of the MMM is presented in Chapter 3 of the thesis.

1.7 Definition of terms

The definition of urban development and sustainability is important in this study. There are different definitions to different fields and sectors in terms of urban development and sustainability. Other important definitions relating to this study ae highlighted in this section for clarity and understanding towards the aims and objectives of this research.

Urban development: Urban development is often simultaneously referred to as urbanisation. The European Union (n.d.) refers to urban development as urban growth that covers infrastructure for education, health, justice, solid waste, marketplaces, street pavements, and protection of cultural heritage. According to Kato (2001), definitions and interpretations of urban development vary across countries and societies as boundaries that indicate a particular place or area in which large numbers of people reside, resulting in a very high population density accelerating increase in economic, political, and cultural centres.

Urban development, based on this study, is the rapid population growth and interaction with their immediate environment and ecosystem. Urban activities by the people in urban centres change the environment through demand and consumption of food, energy, water, and land use. These activities cause a polluted urban environment that affect the health and quality of life of the urban population.

Urbanisation: The process through which a population of an area grows higher as higher percentages of the population migrate from rural areas to make an area or location more urban (Chappine, 2014). Thus, urbanisation according to a definition in Britannica, means an increase in the proportion of people living in urban areas compared to rural areas.

Environmental health: Environmental health focuses on the interaction of the urban populace and their environment, promoting human health and fosters healthy and safe surroundings. The environmental health indicator consists of human and environment health impacts, air quality, water and sanitation. Preventing and controlling physical, chemical and biological hazards that are harmful to human health caused by human and natural phenomena are the major interest in this area.

Sustainability: Generally, sustainability is the ability to maintain a specific condition of object or subject at a certain rate or level (UN Development, n.d.). According to a report the World Commission on Environment and Development by Brundtland (1987), sustainability means meeting our present needs "without compromising the ability of future generations to meet their own needs". In addition to natural and environmental sustainability, there is social and economic sustainability. Sustainability towards the goal of this research is environmental and human health equity. The three pillars of sustainability are the environment, economy and society (United Nations General Assembly 48, 2005).

Urban pollution: There is no universally acceptable definition of urban pollution; however, the concept of urban pollution refers to the presence of harmful substances in the urban environment, usually caused by human activities (Martínez-Bravo & Martínez-del-Río, 2019). Urban pollution may come from natural sources, but the most detrimental are those emissions related to human activities.

Water resources: Water resources are sources of water that are potentially useful to humankind in terms of drinking water, agriculture and recreation. Water resources can be found worldwide in fresh and brackish surface water sources and groundwater aquifers (Organisation for Economic Co-operation and Development [OECD], 2003).

Adaptive capacity: Adaptive capacity is the ability of an environment to adjust to changes or threats to mitigate potential disasters or cope with the consequences of climate change or environmental degradation (Gallopín, 2006; Metzger et al., 2006; Rorato et al., 2022; Schneider et al., 2007). It can be understood as the extent to which a system can react and change its circumstances to move to a less vulnerable form.

1.8 Scope of the thesis

This thesis consists of ten chapters, summarised below.

Chapter 1 introduces the general overview of the research and the rationale to the study in the chosen study location. It further emphasises the problems that inform the research in the chosen area. The aims and objectives of study are also highlighted in this chapter.

Chapter 2 discusses the review of relevant literature related to urban development and environmental sustainability. This chapter includes a detail review on intrinsic urban development in Africa and internal migration in South Africa. The chapter informs the urban activities and its impact on the environmental ecosystem and climate change stimulation. A review of the various models and factors affecting environmental health assessment and ensuring sustainability is also included.

Chapter 3 provides a review and characterisation of the MMM. It focuses specifically on the Caledon–Modder River catchment, geology, topography, soil characteristics, hydrology and water resources of the MMM. This chapter further characterises the catchment study area. This is important in understanding the catchment's water demand and adaptation strategies of the MMM.

Chapter 4 provides the scientific approach employed in this research to investigate the impact of urban development on water resources and environmental health sustainability in the MMM.

Chapter 5 captures the urban classification and hydrochemical assessment of the MMM. In this chapter, the Landsat dataset processing and analysis was carried out to investigate the urban expansion, water availability and vegetation indices. Furthermore, the chapter focuses on current water quality for drinking and human health risk assessment.

Chapter 6 presents the development of the UHS index methodology and the conceptual framework to the study. This chapter discuss the rudiments underpinning the development of the UHS index method. The specific methodology and data acquisition are described. Weighting and rating of parameters are equally explained.

Chapter 7 emphases the application of the designed UHS index**.** This chapter further details the invention of maps for all the factors considered in this study. A final UHS map is plotted using climate, water quality, social environmental and ecological factors.

Chapter 8 presents the processes involved in the validation of the environmental health sustainability index. A description of the scores is given according to the classes presented for this study. Furthermore, it is emphasised that the validation of the model was carried out specifically for the study area.

Chapter 9 focuses on the simulation of future predictions of land use / land cover in the MMM. Methodology and validation of the predicted land use / land cover for 2028 and 2038 is discussed including the implication on the environmental health sustainability of MMM.

Chapter 10 presents the conclusions and recommendations based on the findings of the study.

Chapter 2

LITERATURE REVIEW ON RAPID URBAN DEVELOPMENT

2.1 Introduction

Urbanisation is one of the factors that has become a coherent and integrated globalisation economic and social activity (Satterthwaite et al., 2007; UN, 2018). Urbanisation is the increase in the proportion of people living in cities and the process of rapid migration from rural to urban areas. Urbanisation drives economic activities that are previously separated and localised to become merged and superseded by worldwide patterns coordinated by global institutions and organisations (Bounoua et al., 2020; Saghir & Santoro, 2018; UN, 2018). Urbanisation is the process through which an area grows larger, where higher percentages of the population are migrating from rural to urban areas to make an area or location more urban (Chappine, 2014). Thus, Britannica (n.d.) defines urbanisation as a growth in the proportion of people living in urban regions compared to rural areas.

Urban development is often simultaneously referred to as urbanisation. The European Union (n.d.) refers to urban development as urban growth that covers infrastructure for education, health, justice, solid waste, marketplaces, street pavements, and cultural heritage protection. According to Kato (2001), definitions and interpretations of urban development differ across countries and societies as boundaries that indicate a specific place or area where a large number of people reside, resulting in a very high population density and an accelerating increase in economic, political, and cultural centres. Urban development, based on this study, is the rapid population growth and interaction with their immediate environment and ecosystem. Urban activities by the people in urban centres change the environment through demand and consumption of food, energy, water, and land use. These activities cause a polluted urban ecosystem that affects the human health and quality of life in an urban environment.

Developing countries have urbanised rapidly in recent decades, while their urbanisation trend is similar to that of industrialised nations in the nineteenth century (Moufad & Jawab, 2019; World Bank, 2010). Urbanisation is rapidly accelerating in today's global development. In Europe, urbanisation increased from 15% in 1800 to 40% in 1910 as a result of the Industrial Revolution. Africa and Asia did so roughly half the period, or twice as quickly, rising from 15% in 1950 to around 40% in 2010 (Organisation for Economic Co-operation and Development / Sahel and West Africa Club [OECD/SWAC], 2020). Urbanisation is significantly associated with wealth creation across nations and enormous environmental consequences (Henderson, 2010; OECD/SWAC, 2020; UN, 2019).

Researchers in economics and finance reckon with urbanism as significant engines for economic and social growth of a nation (African Development Bank, 2020; Dorosh & Thurlow, 2012; Turok & McGranahan, 2019). Turok and McGranahan (2019) opined that cities are traditionally hubs for economic development, innovation, and job creation, but many cities have grown historically due to inherent advantages in infrastructural development, for instance, capital cities are where the great bulk of modern economic activity and paid employment possibilities are concentrated in the developing world. Cities are also hubs of contemporary life, literacy, women's status, and social mobility. In addition to museums and art galleries, cities are also significant social and cultural hubs (Chen et al., 2014).

Urbanisation has also injected abject poverty in the lives of many urban residences due to the high cost of living. However, despite high rates of urban poverty, urban inhabitants have greater access to education, health care, and other essential public amenities than rural populations (Batty, 2012; Bertinelli & Strobl, 2007). Nonetheless, as cities develop, their management becomes more challenging. The rapidity and magnitude of urbanisation in emerging countries pose daunting difficulties in the environment and human health (UN, 2019; WHO, 2018). The most significant concern is the massive growth in urban poverty and environmental degradation.

2.2 Intrinsic urban development

Following the shift in industrial revolution, there has been rapid increase in global urban areas that resulted in alterations to natural processes, environmental quality and natural resource consumption (Dan-Jumbo et al., 2018; McGrane, 2016; Seto et al., 2012; UN, 2019; UNFCCC, 2007). Natural processes are interactions among plants, animals, and the environment. Floods, erosion, the water cycle and elemental cycles is natural phenomena that have been altered by rapid urbanisation (Banister, 1998; Li et al., 2014; Osti et al., 2008). Urbanisation promotes a significant effect on climate change and environmental quality. including water and air (Grimm et al., 2008; Pautasso et al., 2011). Increasing urbanisation in developed and developing nations impact water resources which could have significant impacts on communities dependent on these water resources for domestic and agricultural activities (Cullis et al., 2019; Pieterse, 2013). Freshwater is necessary for healthy living and used for various purposes such as drinking, bathing, recreation and irrigation. This natural resource is being polluted by urban activities such as indiscriminate disposal of waste, untreated sewage due to overcapacity, untreated industrial waste, emerging contaminants and human activities such as slum creation (Cullis et al., 2019; Gadekar et al., 2012; Mohammed et al., 2018; Musingafi & Tom, Vitaliy, 2019).

Presently, according to the United Nations (2014), more than half of the world's population now live in cities. The majority of global population growth is expected to come from metropolitan regions in emerging countries in the next several decades. Over the last 30 years, population growth in the developing world has been considerably more fairly distributed across urban and rural regions (OECD/SWAC, 2020; UN, 2019). Nations are witnessing unprecedented levels of urbanisation and are recording large numbers and sizes of significance in cities. At the end of the nineteenth century, just 16 cities in the globe had a million or more residents. In 2004, over 400 cities had a million or more residents, with 70% in the developing world (UN, 2018).

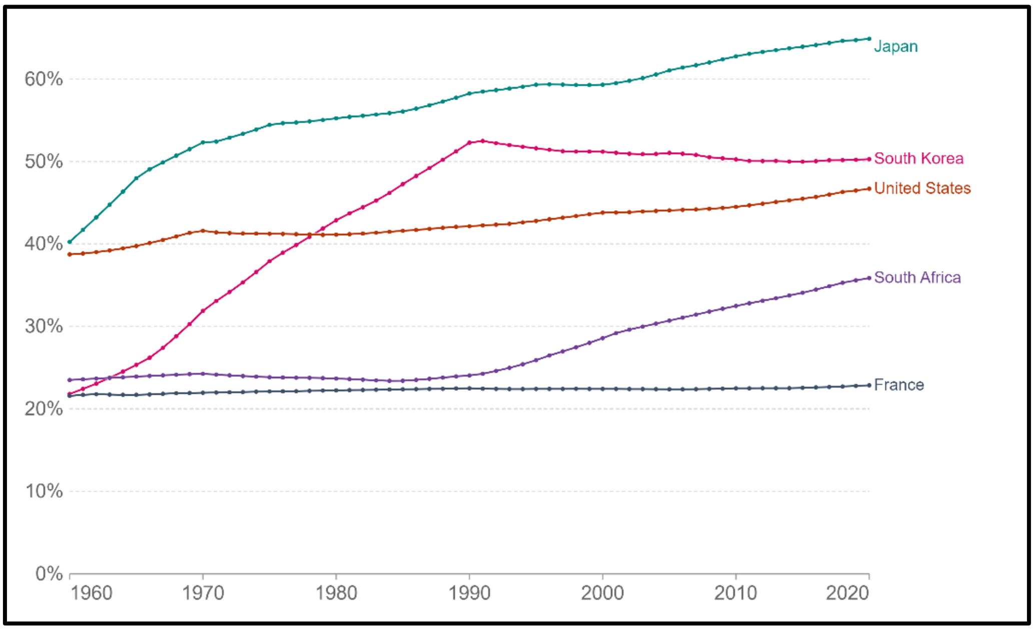


Figure 2.1: Urbanisation rates of people living in urban areas from 1960 to 2020

Source: UN Population Division (World Bank, 2020)

In several of the world's poorest nations, the share of the urban poor is growing faster than the total rate of urban population increase (UN-Habitat, 2004). In 2003, 72% of Africans lived in slums; Asia and the Pacific account for 43%, Latin America 32%, and the Middle East and Northern Africa 30% (UN-Habitat, 2004). Rapid urbanisation has outstripped the ability of most cities to provide basic services to their residents. As a result of the influx of new migrants, squatter colonies and shanty towns continued to grow, worsening urban congestion and sprawl, and impeding local governments' efforts to repair basic infrastructure and provide critical services. These urban challenges facing urban areas today are the result of many activities carried out in an urban setting which is discussed extensively in subsequent sections of this chapter.

Nations across the globe are now implementing policies for a sustainable urban environment and environmental sustainability (Ahmed et al., 2022; Olayele & Goel 2022; UN, 2020). Urban sustainability has made an extraordinary rise to fame as the main stream of the twenty-first century global reality within the space of a few decades of rapid urban development.

Today, sustainability has made a paradigm shift to our world. This new paradigm of sustainability is set to have a fundamental and preventive measure on how we manage our environment and ecosystem (Cohen, 2017; Seip, 2020). The environment represents the natural ecosystem that the society depends upon for various activities such as water, materials, food and energy (Ahmed et al., 2022; Hassan & Mahlathi, 2020; Liu et al., 2017). The nature of our ecosystem has changed drastically over the course of human history in recent years. Historically, before the advent of the modern era and urbanisation, humans were aware of their environmental limitations and interaction (OECD, 2020). However, the rise of the modern era created contention between humans and the natural environment, with a shift from a dominant pre-modern world to a modern scientific view, causing a new view of a natural environment given rise to technological change as in the case of the Industrial Revolution (Moufad & Jawab, 2019; Williamson, 1988). The Industrial Revolution started in the late 1700s and represented radical dislocation between society and the ecosystem. A major part of this changing dynamic was harnessing new energy sources more powerfully than that which humans had been using. There was a large-scale combustion to the energy sources of coal, oil and gas as there was a transition from manual to mechanical. This initiative in technology, society and ecology is being undermined in motion as there are changes such as an increase in economy and urbanisation, which has continued to rise rapidly around the world as shown in Figure 2.2 (Chappine, 2014; European Commission, 2016).

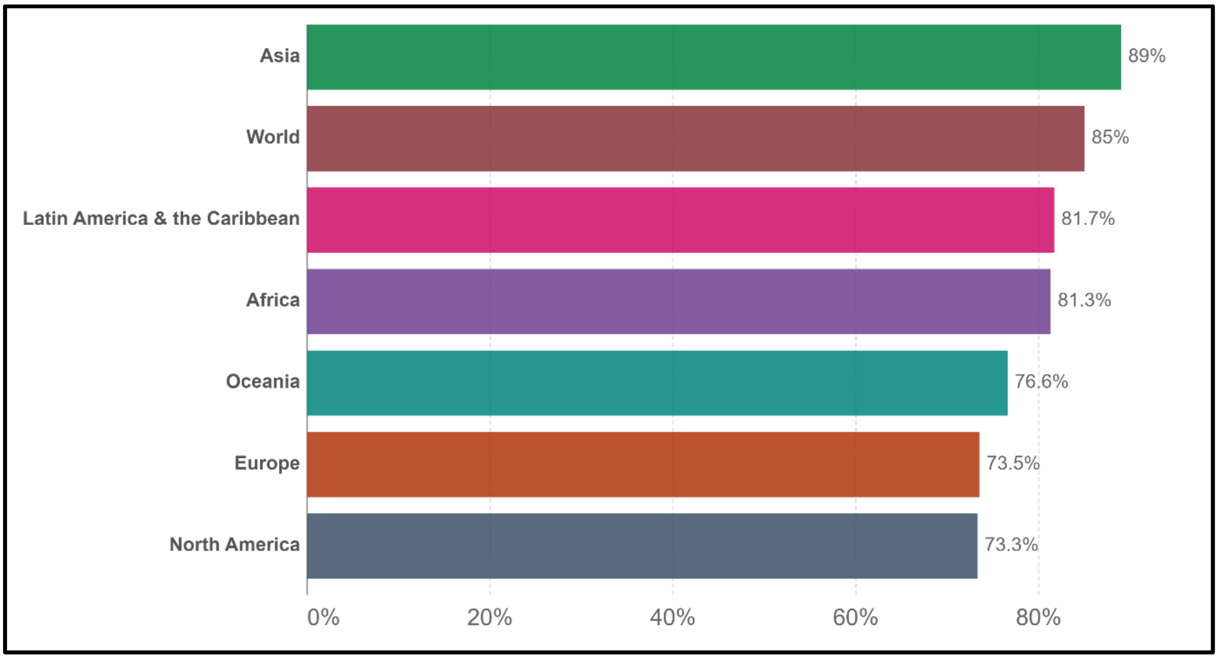


Figure 2.2: Share of the population living in urban areas as estimated by the European Commission

Source: European Commission (2016)

2.2.1 Urban development in Africa

Africa's population is rising faster than any other significant area in the globe (UN, 2015; United Nations Children's Fund [UNICEF], 2017). Research by United Nations and other agencies has shown that the population in the African region living in urban centres will grow from 794 million in 2000 to 1 489 billion in 2030 (OECD/SWAC, 2020; UN, 2019) (Figure 2.3). Within a decade, Africa's population will be overwhelming, because 70% of the population growth will occur in major African urban and suburban centres (African Development Bank, 2012; UN, 2015; UNICEF, 2017).

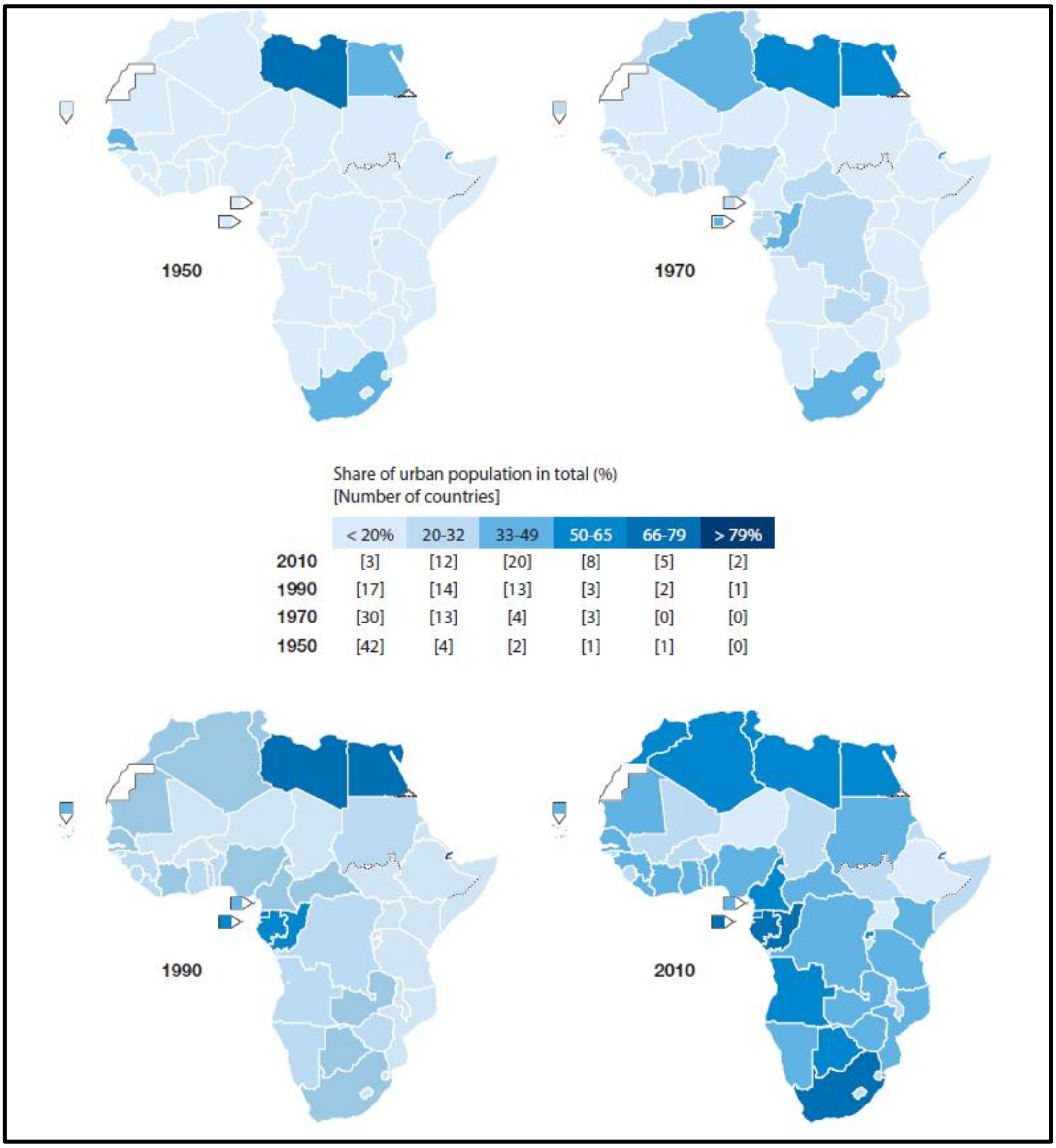


Figure 2.3: The evolution of urbanisation in Africa

Source: OECD/SWAC (2020)

By 2050, African cities are predicted to have the world's fastest urban development rate (OECD/SWAC, 2020; UNICEF, 2017). Moriconi-Ebrard (2016) reported that the urbanisation of Africa is a time of tremendous opportunity, but it is also fraught with threat on the environmental sustainability due to lack of adaptive capacity and adequate policy. Emerging urban cities are often developing without sustainable regulations that can handle the accompanying environmental and health issues. As a result, urban planning and administration are crucial concerns for the sustainability of the environment. Based on the Africapolis, the geospatial database covers 7 600 urban agglomerations in 50 African countries. Urbanisation dynamics and its impact on local, national, and continental policies must be understood in order to build focused and inclusive policies for sustainable urban and environmental health in line with African realities.

Africa's urban population is expected to be more than quadruple by 2030, surpassing North America, Europe, and Latin America on a per capita basis (UN, 2015). Unlike cities in Asia and Latin America, urbanisation in Africa appears to be disconnected from economic development and environmental awareness (National Research Council, 2003; UNICEF, 2017). Most African cities are developing despite weak adaptive capacity and environmental awareness in the looming global climate change. Unsurprisingly, a world development assessment found that African cities are not engines of growth and structural transformation (Figure 2.4); rather, they are a crucial indicator of the continent's economic and social crises (World Bank, 2010).

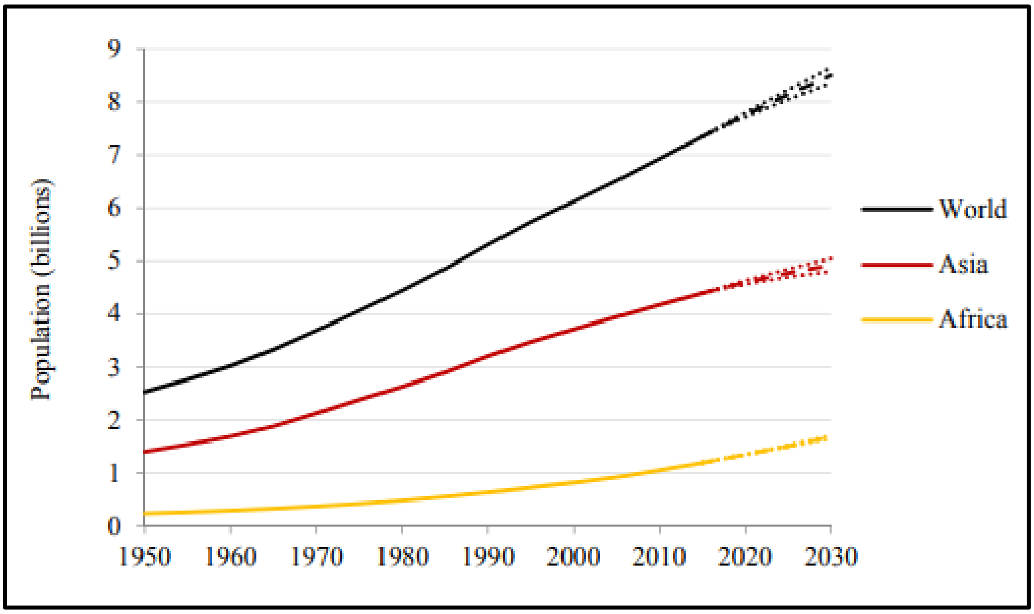


Figure 2.4: Population by major area, 1950–2030, with 95% prediction intervals

Source: United Nations (2015)

Africa confronts more developmental problems than any other large area globally due to varying policies among stakeholders and lack of adaptive capacity. The sub-Saharan African region accounted for one out of every ten poor individuals back in 1980. In 2000, it had grown to one out of three people as the population growth rate increases and sprawling urban centres (UNICEF, 2018). As urban centres continue to grow in Africa, poor people residing in slums and informal settlements are increasing annually (UN, 2019). Furthermore, future predictions indicate that one in two will be impoverished. The Africa region also has one of the lowest literacy levels, life expectancy and prone to communicable diseases (WHO, 2018).

2.2.2 Urban development and migration in South Africa

South Africa, like other African countries, has been rapidly urbanising in recent times (Ivan, 2012). Currently, 63% of the South African population are already living in urban areas and the statistics by Stats SA (2015) showed that the urban population will rise to 71% by 2030. Consequently, eight in ten people will be living in urban areas by 2050 and this will increase the demand on basic infrastructure requirements (Stats SA, 2015, United Nations Population Fund [UNFPA], 2020). Rural–urban migration in South Africa began in the late nineteenth century when mining operations pushed the country into the global monetary scene (Balie & Horn, 2021; Collinson et al., 2007). At the end of the 1800s, many left their homes to seek work in the mines as South Africa evolved. As a result, diverse groups began moving to urban centres (Ivan, 2012). It led to large-scale rural–urban migration of blacks and rural the Afrikaner. However, blacks became mining labourers, while rural white Afrikaners were taken into state employment (Balie & Horn, 2021). Internal migration was also a significant source of worry for the apartheid administration (Collinson et al., 2007). It made efforts to regulate and manage local black South African mobility in order to improve economic prospects for the white minority and to control and limit African urbanisation (Ivan, 2012; Stats SA, 2015).

However, with the new dispensation of the political era in 1994, interprovincial movements are now free (Balie & Horn, 2021). Rustenburg, Ekurhuleni, Polokwane, Nelspruit, and Vanderbijlpark experienced rapid expansion due to increased economic activity (Stats SA, 2006; UN Habitat, 2010). Compared to Cape Town's 1.4% annual population growth rate, these cities have seen a 1.6% and 2.9% annual population increase during the previous decade (Stats SA, 2012). This development is due to the annulment of apartheid regulations that limited rural–urban migration. Urban economies have grown, attracting individuals in quest of better living conditions (Collinson et al., 2007; Todes, 2012). However, increased urbanisation has repercussions such as social conflicts and xenophobic assaults by natives on immigrants (Awumbila et al., 2011). Furthermore, high unemployment and crime rates in urban areas cause substantial environmental and health hazards, posing obstacles for government service delivery (De Haas & Flahaux, 2016). Rural–urban migration affects not just government and society but also individual households.

South Africa's urban and rural populations grew almost in lockstep, with the rural population outnumbering the urban by a little margin (Figure 2.5). This began to change in 1987, when urban people became the majority, resulting in tremendous population growth in South Africa's cities, which was rapidly followed by a decrease in the rural population, a pattern that has persisted to the present day. South Africa had more urban agglomerate centres in 2020 across all the nine provinces as compared to 1970 before the annulment of the apartheid regime (Giraut & Vacchiani-Marcuzzo, 2009). There has been an increase in the number of higher learning institutions, foreign migration, tourism centres and other industries, which led to many activities in many urban centres in South Africa; therefore, the country began to experience an overstretch in infrastructure and service delivery across the nine provinces due to the unplanned rapid urbanisation. It thus poses a serious threat to human health and environmental sustainability. Drought and other climate change impacts, coupled with ineffective urban water management, plunged Cape Town and the Free State into a major water security disaster between 2016 and 2018, making the city to nearly run out of water (DWS, 2018).

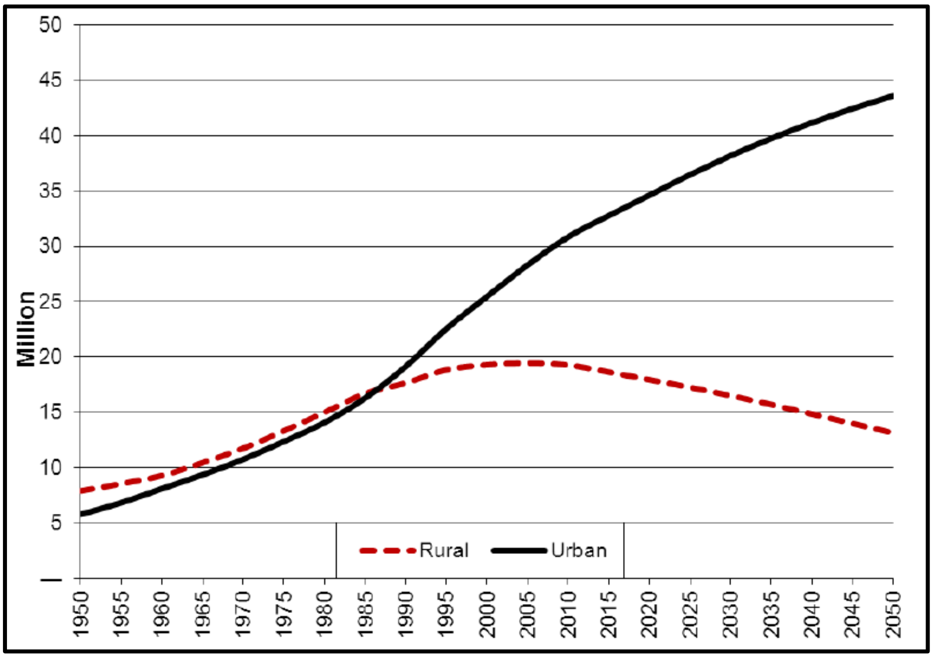


Figure 2.5: South African population living in urban and rural areas (1950–2050)

Source: UN Population Division (2020)

South Africa's urban configuration also differs between cities and social amenities (Ivan, 2012; Balie & Horn, 2021). The diversity of their spatial shape reflects their distinct physical topographies, key transportation axes, social and cultural mix, and the rate and nature of economic development and demographic increase. The dispersed nature of urban development in each of the metropolitan cities in South Africa is unique (National Treasury, 2018; Turok, 2012). Duminy et al. (2020) and Marais et al. (2021) acknowledged that physical topographies, major transportation arteries, social and cultural compositions, and character of economic development and demographic growth are all reflected in the spatial form or urban development in each major urban centre in South Africa.

2.2.3 Development in Mangaung Metropolitan Municipality

The Orange Free State republic was founded in 1854, with Bloemfontein as its capital. Bloemfontein has been a stronghold of Afrikaner heritage since its foundation (Twala & Barnard, 2006). As a result, the city has hosted the headquarters of the first Free State republic, the Orange Free State Province (1911–1993), and the Free State Provincial Government since 1994. Bloemfontein's administrative role was also crucial in the founding of Grey College in 1855, the first school north of the Orange River. It became Grey University College in 1904, then the University College of the Orange Free State, and finally the University of the Free State. The Free State Technikon now the Central University of Technology was founded in the early 1980s. In the late 1960s, the University of the Free State established a School of Medicine which attracted migration of students and resulted in large public and private medical facilities in the province. Many health research firms have since been founded in the city due to this development (OECD, 2012). During apartheid, the administrative route resulted in the significant expansion of military outposts, although their significance has reduced during the democratic period.

Apartheid planning had a significant influence on Mangaung as well as the Thaba 'Nchu Municipal District, which, along with Thaba 'Nchu, formed part of *grand apartheid* (a term commonly used to describe macro-apartheid planning that aimed to divide South Africa into ethnic states or homelands). It was effectively integrated into Bophuthatswana, a homeland for the Setswana-speaking population, but never recognised by the international community. The history of displacement urbanisation of Bloemfontein to Thaba 'Nchu and Botshabelo has been extensively recorded. From 1968 to 1979, black urbanisation in Bloemfontein was redirected to Thaba 'Nchu and Botshabelo, with no further extensions authorised. (See Figure 2.6.)

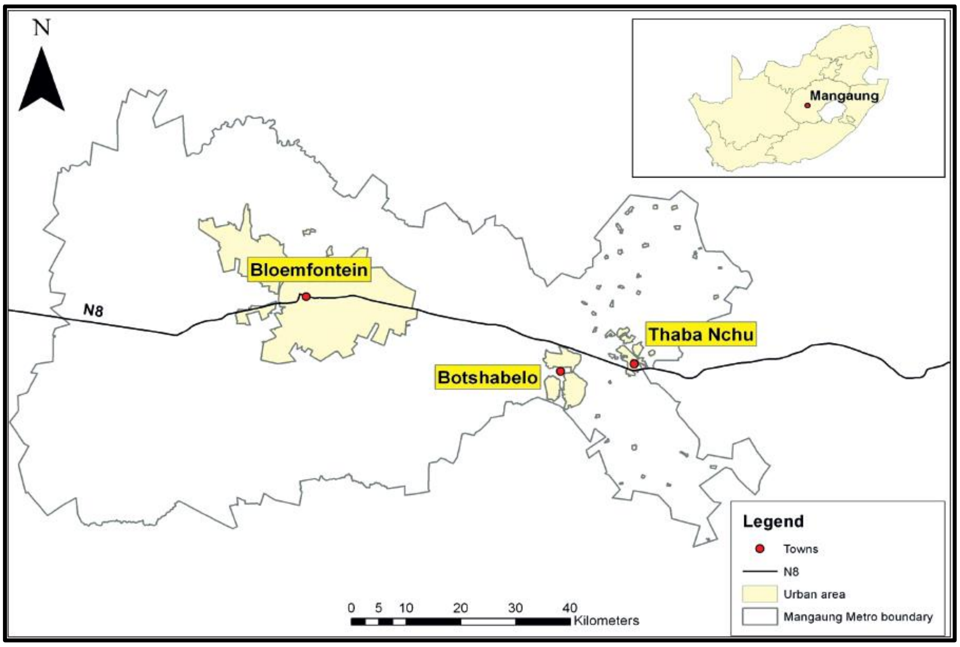


Figure 2.6: Location of Mangaung Metropolitan Municipality before the merger with Naledi Local Municipality

Source*:* Marais et al. (2014)

Botshabelo was supposed to be part of the QwaQwa homeland for Sesotho speakers during apartheid. It was comparable to the reasoning underlying the absorption of Thaba 'Nchu into Bophuthatswana (Twala & Barnard, 2006). Bloemfontein was not to develop, and all expansion should occur in Botshabelo. The apartheid administration devised three economic measures to support Botshabelo and Thaba 'Nchu. First, a heavily subsidised bus system was created, reducing the cost of travelling between Botshabelo and Bloemfontein by up to 60%. Moreover, at its height in the late 1980s, 14 500 people commuted daily between Bloemfontein and Botshabelo (Van Wyk, 2014).

In the late 1980s, 57 industrial plants were estimated to be in production, creating 10 000 jobs. The relative exploitation of female workers and the misappropriation of available subsidies were noted. Nearly all of the stands were filled ten years later, even if the industrial component had reduced (Marais et al., 2005). Bloemdustria, with approximately 140 industrial stands, was declared a deconcentration point in 1998, halfway between Botshabelo and Bloemfontein (Van Wyk, 2014). Until the 1990s, most of the planning was based on apartheid ideology, which kept black urbanisation at a distance. The city's public administration was conservative and predominantly white and Afrikaner. Mainstream schools and colleges were primarily reserved for white South Africans as required by apartheid legislation. However, apartheid had a social and economic cost due to many individuals from Botshabelo and Thaba 'Nchu attempting to relocate to Bloemfontein to be closer to areas of employment; the strategy of orderly urbanisation was abolished (Marais & Ntema, 2013). It also ended decentralisation subsidies.

The lack of further incentives for the industrial deconcentration locations in Botshabelo and Bloemdustria made local jobs tougher to come by. Meanwhile, South Africa's economy re-entered the global market and struggled to compete. Because Botshabelo's economy was mainly based on textiles, it was exceedingly difficult to compete with inexpensive imports from the East (as was the case in the rest of South Africa). By 2012, manufacturing employment in Botshabelo had dropped from over 10 000 in the early 1990s to around 6 100 (MMM, 2014).

In recent years, Bloemfontein has developed in a similar way as most South African urban centres (Chobokoane & Horn, 2015). The urban development in Mangaung formed in terms of its informants of historic urban form as well as past and current spatial development policies (Stats SA, 2016). This exhibited an urban form very similar to other South African cities and consequently faced the same challenges to achieve compaction as most South African urban areas. According to the Mangaung Spatial Development Framework (2013), there has been a lot of building activities in Bloemfontein and other major urbanising centres in the municipality. In Bloemfontein, new residential area and township establishments in the Grasslands, Woodland Hills and Vista Park areas, Phases 2 to 10, Dinaweng and Hillside View are recently developed townships and surburb that signify urban expansion and growth in this area (Chobokoane & Horn, 2015; SPDF, 2020).

Furthermore, offices and retail buildings, largely in the western suburbs, mixed land use development in the eastern area, major retail development at the Loch Logan Waterfront, and the spread of high density walled townhouse complexes west of the N1. However, investment in Thaba 'Nchu and Botshabelo had been modest (C40 Cities, 2020; CDP, 2019). The urban expansion in terms of residential and industrial activities in Mangaung has led to the deterioration of infrastructure, poor water quality and environmental degradation. This chapter highlights African urbanisation patterns and its impact on the environmental ecosystem. Furthermore, the relationship between urbanisation and climate change are discussed.

2.3 Sources of urban environmental contamination

Human activities influence the environment and exhibit consequences through land, water and air, referred to as ecological, hydrological and meteorological effect. Soil and water contaminations are an impact of human activities in the environment. Also, variants of the urban activities have triggered temperature increase, wetland disappearance and storm surges (Carmin et al., 2012).

Increasingly changing temperatures often lead to excessive heat loss and depletion of the ozone layer, which result in health crises (Bigelow et al., 2017). Over the years, urban expansion has produced pronounced pollution, health-related risks and other environmentally related threats in urban areas, compared to the rural environment (Arnfield, 2003). The air-induced environmental consequences are connected with the emission of harmful gasses that are contributing to health threats. The World Meteorological Organization (1996) indicated that urban industrial and commercial activities are major contributors to the rising greenhouse gases due to their intensive use of energy. The narratives of the phenomenon can be observed in a city with a population of one million, where about 25 000 tons of carbon dioxide and 300 000 tons of wastewater are discharged every day.

Traffic problems result in the increase in congestion and pollution, high unemployment, social environmental complications, CO_2 emissions as a result of gas flaring and power generation. Details on the component of urban activities and its impact on our planet are discussed in section 2.4 below.

Urbanisation is one of the most apparent and intrusive human-caused changes in the world today (UN, 2019). Urban regions are mainly responsible for excessive resource use and hazardous substance emissions due to industrial and commercial activities (Luo et al., 2017; Smichowski, 2008). These affect the environment and, in certain circumstances, threaten life and livelihoods. Urbanisation, population growth, associated activities, and the environmental implications have therefore become essential concerns in recent decades.

Various factors, including urban activities, are vital sources of growing greenhouse gas emissions due to their high energy use. According to the World Meteorological Organization (1996), a million-person metropolis emits 25 000 tons of carbon dioxide and 300 000 tons of wastewater every day. Some cities have seen substantial changes in the frequency and severity of extreme weather events; some have seen temperature rises, while others have seen coastline erosion, wetland loss, and storm surges (Carmin et al., 2012). The ozone layer in urban areas inhibits sun radiation and may be harmful to humans and animals. Urbanisation has resulted in marked warming in urban regions compared to rural areas (Arnfield, 2003; Carmin et al., 2012). Human actions affect the environment in three primary ways: land, water, and air. As a result, the impact of urbanisation is investigated through these three human–environmental interactive mediums.

The urban activities are collections of actions performed by dwellers within a city in a given locality. These actions are primarily intended to meet their basic or non-basic needs for a sustainable lifestyle and may sometimes be performed as individual or collective actions. Urban activities are often contrasted with the rural way of lifestyle. Hence, these has led to rural–urban migration in the twenty-first century without considering the impact of rapid urbanisation on the present ecosystem. An uncontrolled growing population is a major activity in the global urban centres today.

2.3.1 Urban slums

Slum settlements are typically developed on previously uninhabited or undesirable wastelands, as they are sometimes the only locations near economic possibilities and access to the urban areas (IPSOS, 2019). However, these locations, particularly wetlands, riverbanks, and steep slopes, are increasingly recognised as having an intrinsic disaster mitigation potential (Ajibade & McBean, 2014). In their natural condition, wetlands act as a natural sponge to absorb and release surface water (Renaud et al., 2013). Wetland ecosystems and those in the surrounding areas are affected by human activities on the natural environmental system (Ajibade & McBean, 2014). The difficult living conditions of slum residents limit their capacity to advocate for a healthier climate, prolonging and aggravating environmental concerns. In reality, marginal land possesses unrecognised critical environmental services lost via unplanned and haphazard slums.

More than three-quarters of the world's low- and middle-income urban inhabitants are living in slums with varying demographics, livelihoods, and size (UN-Habitat, 2018). Slums are the most apparent type of urban poverty, yet slum residents are not all equally destitute. Most slum inhabitants find work in the informal economy, leading to unstable earnings based on transitory, low-paying labour (Erdogan et al., 2020). However, some people who work in the official sector (e.g., teachers) are excluded from the formal housing market (Erdogan et al., 2020). Furthermore, self-employed people who do not fall under the low income category to live in slum communities (Erdogan et al., 2020). Poor earnings, low human capital, low social capital, and low financial capital all contribute to poverty (UN-Habitat, 2018). The extent of deprivation varies by age, gender, and health. As the impoverished population grows in metropolitan environments, vulnerable populations are severely disadvantaged.

Slum communities are characterised by an excessive population density and overcrowding in general. Lack of access to better water sources means water must be gathered directly from a well or river. The need for affordable, durable housing material leads to trees being chopped down to construct houses (Disasters Environment Working Group for Asia, 2008). The more congested people are in an urban area, the greater the pressure on limited resources. Slum dwellers are unique in that they have limited access to natural resources due to their urban surroundings. The majority of slum dwellings use urban canals or rivers for drinking water, cooking, washing, and trash disposal. Although urban rivers and coastal regions may provide livelihoods for fishermen, many rivers in cities are becoming or are already "biologically dead" (Ballesteros, 2010). Slum residents repurpose rubbish for home foundations and buildings (Ajibade & McBean, 2014), or reinforce decrepit structures (UN-Habitat, 2004). It adds to high vacancy rates in substandard homes with poor structural conditions (UN-Habitat, 2004). Slum inhabitants' resources are distinctive because of their urban environment, city location, and contact with other urban residents.

Human waste may quickly degrade both the environment and human health in high-density areas. If there is no waste management system in place, such as in slum communities lacking sanitation, vital water supplies may become polluted. Water sources are contaminated by slum dwellers who use them to dispose of human waste (Porio, 2015), by mixing groundwater with open defecation sewage (Moffat & Finnis, 2005), or by leaching pit latrine waste (Moffat & Finnis, 2005; Nyenje et al., 2013). The trash increases river siltation, causing more frequent flash floods (Porio, 2015). Water-borne and vector-borne illnesses are more likely to spread when existing toilets get blocked, and people are forced to discharge themselves directly in the river, resulting in a downward circle of continuous human and environmental degradation (Porio, 2015). Strong household waste is often a problem for slum residents. Toxic contaminants can leak into the atmosphere and offer refuge for disease-spreading vectors such as rodents and mosquitoes (Davis, 2006). Waste from other urban inhabitants is occasionally dumped in slums, a clear case of social and environmental injustice (Davis, 2006).

2.3.2 Wastewater plant

A wastewater plant is an important urban infrastructure; however, it is also a major source of known and unknown emerging contaminants in rivers and streams (Haley et al., 2019). Water and sanitation systems influence urban economic activity and energy needs and the rural–urban water balance (Gober et al., 2010). The wastewater plant is a host of human waste, food scraps, oils, soaps and agricultural chemical substances. The urban environment and water system are at risk if wastewater is not properly managed at the plant; this further impact the environment and human health. These impacts can include harm to river habitat, urban populace, water insecurity and other restrictions on recreational water use and contamination of drinking water (UNICEF, 2019).

The United Nations Conference on the Human Environment (1972) provided characteristics of pollutants that can be found in wastewater and the potential harmful effects on ecosystems and human health:

- Decaying organic debris in rivers depletes dissolved oxygen in a river, in which the aquatic habitat cannot live on.
- Excess phosphorus (P) and nitrogen (N), including ammonia (NH_3), can cause eutrophication, or over-fertilisation, of receiving waters, which can be toxic to aquatic organisms, promote excessive plant growth, reduce available oxygen, harm spawning grounds, alter habitat, and lead to the extinction of certain species.
- Chlorine compounds and inorganic chloramines can poison aquatic animals, algae, and fish.

- Bacteria, viruses, and pathogens that cause disease can pollute beaches and taint shellfish populations, limiting human recreation, drinking water intake, and shellfish consumption.
- Heavy metals such as mercury (Hg), lead (Pd), cadmium (Cd), chromium (Cr), and arsenic (As) can be hazardous to species in both acute and chronic doses.
- Emerging contaminants, such as some pharmaceutical and personal care items, which reach the environment mostly through wastewater effluents, may also endanger human health, aquatic life, and wildlife.

2.3.3 Traffic and carbon dioxide emissions

The effect of human activities is accelerated by the amount of greenhouse gases generated. Greenhouse gases trap heat and make the planet warmer (UN COP 26). Greenhouse gases in the atmosphere over the last decades have been known to exacerbated by human activities. The main source of greenhouse gas emissions from human activities worldwide is the combustion of fossil fuels, followed by carbon dioxide (CO_2) emissions from transportation and industrial facilities (Sims et al., 2014).

Transportation contributed to 29% of greenhouse gas emissions in the United States in 2019 (Figure 2.7). Across the globe, the transportation sector generates the largest share of greenhouse gas emissions, which in turn accelerate global warming and climate change (IPCC, 2020). Transportation-related greenhouse gas emissions are mostly caused by the use of fossil fuels in automobiles, trucks, ships, trains, and planes. Over 90% of transportation fuel is petroleum-based, which includes gasoline and diesel.

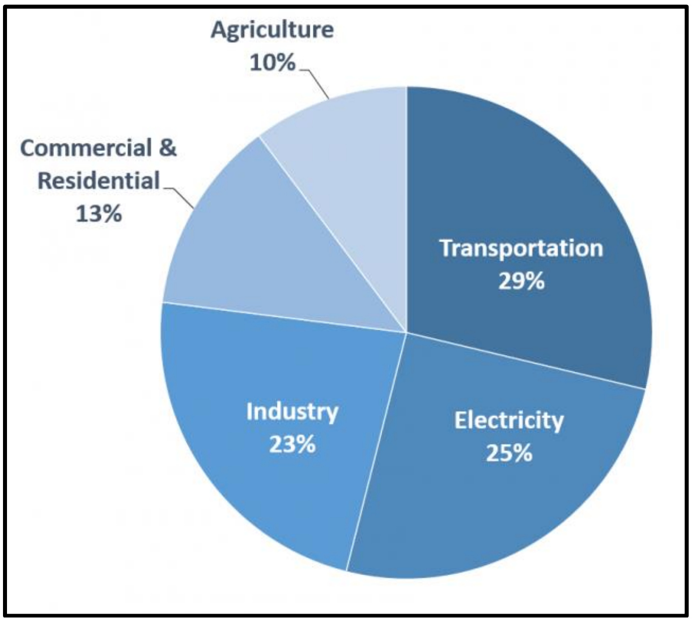


Figure 2.7: Total greenhouse gas emissions by urban sector in 2019

Source: IPCC (2020)

Furthermore, on the highway, exhaust particles are generally 0.1 µ in size, but urban driving creates coarser particles of up to 5 µ. Vehicular sources have contributed significantly to ambient lead, ranging from 40% absolute lead (Pb) content with minimal contribution from diesel traffic to 4% when diesel traffic is significant (due to the diluting effects of carbonaceous particles (Adachi & Tainosho 2004).

The advent of multi-element analytical methods such as inductively coupled plasma atomic emission spectroscopy (ICP-AES) led to the discovery that platinum group elements or metals such as platinum (Pt), palladium (Pd), rodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os) have begun to accumulate in the environment. Emissions from car catalytic converters have been estimated at up to 1.4 tons per year, according to Barbante et al. (2001). All of these components bioaccumulate and are delivered in ultrafine particles (0.39 µ). Finally, urban traffic and combustion of coal can accelerate air quality pollution, which generate acid rain.

2.3.4 Agriculture

Historically, humans were hunter-gatherers with individual small-scale agricultural farming before the advent of urbanisation (Cox, 2012). Humans fished in the sea, hunted on land, and harvested fruits, seeds, and plants that grew wild. Modern agriculture emerged in recent years, when we began to cultivate wild wheat and barley on fertile ground. Agriculture revolutionised our way of living by providing more consistent food sources, allowing civilisations to thrive, and supporting an exponential increase in human population growth.

Agriculture has experienced great horizontal growth due to fast urbanisation throughout thousands of years, implying that humans have set aside more and more land to grow food. Between 1700 and 1980, the quantity of land used for agriculture increased roughly six-fold. We have also dramatically industrialised agricultural practices and generated more hardy and productive crop species in recent decades. This increase in productivity, also known as vertical expansion, has been credited with increasing yields and lowering food costs. However, many of the instruments that enable this high-input, high-volume agricultural commodity have also contributed significantly to environmental damage.

According to some estimates, industrialised farming produces greenhouse gas emissions, pollutes air and water, and destroys wildlife (United Nations Environment Programme [UNEP], 2020). From fertiliser runoff to methane emissions, large-scale industrial agricultural pollution takes a toll on the environment and contributes to soil and water pollution. The pollution from industrial agricultural activities to meet the demand of rapid population growth is nothing but a disaster on our environmental ecosystem.

2.3.5 Unregulated land use pattern

Land use, urbanisation and environment are closely connected because of the fascinating benefits and underlying issues attached to their co-movement (Wei & Ye, 2014). The increasing trend of urbanisation and urban activities exhibit noticeable impact on land and its resources. Land use and agriculture are products of urbanisation (Junfeng Jiao, 2021). Kalnay and Cai (2003) speculated that the estimate of 0.27 °C mean surface warming in a century as a result of land use changes in the United States is twice as high as former estimates based on urbanisation.

In developing countries, unaffordable property rights hinder urbanisation, but expensive land prices often lead to exponential growth in informal settlements, resulting in contamination of water and soil (Cai et al., 2018). Urbanisation increases jobs, housing, education and other technology-based opportunities. It creates havoc due to the need for road expansions and overstretched existing services (Thuo, 2013). The rapid urbanisation rate globally creates more pressure on land utilisation. Evidence in China shows that the increased urbanisation rate, coupled with economic boost, caused inadequate land for agriculture and vegetation over the last two decades (Chen, 2007). Unplanned urbanisation has caused a tremendous increase in built-up areas and a decline on agricultural use as well as shortage of quality water sources (Sajjad & Iqbal, 2012).

2.4 Impact of urbanisation on environmental ecosystems

Urbanisation is a noticeable and invasive human-driven modification to the planet in the current world of industrialisation. It has fascinating values with a series of environmental and health issues all over the world (Gu, 2019). Developing countries are prominently captured in the web of the unimaginable changes by rapid urbanisation (Yuan & Guanghua, 2015; Zhang, 2017). The ripple effects of rapid urbanisation are evidently responsible for excessive consumption of the earth's resources and emission of harmful substances (Yu & Li, 2011). The harmful industrial substances and industrial activities in urban areas alter the environment and, in many cases, constitute threat to lives and livelihood (Yu & Li, 2011). Against this backdrop, the subject of urbanisation, population increase, climate change, accompanying activities and the resultant consequences on the environment have therefore been a topical and discursive research agenda among researchers.

2.4.1 Water pollution and contamination

Research have unfolded that the amount, quality and distribution of water on the earth has been affected by human activities, especially in urban areas (Hasan Rashid et al., 2018). In developing countries, uncontrollable urban growth and activities did not only make water unsuitable but also shortened the quantity of distribution from the major rivers (Hasan Rashid et al., 2018). Turok and McGranahan (2019) indicated that rapid urbanisation are associated with the declining of water quality and quantity. Inadequate infrastructure due to geographical and financial limitations is central to urban human activities that triggered both natural and engineered water complexities and affected quantity and quality dynamics of freshwater systems (McDonald et al., 2014). In Africa where groundwater serves as a major source of water supply, the rapidly growing population resulted in depletion of groundwater, rise in water demand and violation of pricing rule, which triggered the need for regulation and planning for sustainable water systems (Arfanuzzaman & Rahman, 2017).

Evidence shows that urbanisation alters the hydrological cycle that controls the energy and material flows in the environment (DeFries & Eshleman, 2004). Due to population growth, rapid land use change and climate change, water supplies in urban environments around the world are increasingly strained (Sun et al., 2008). The availability of water has severely restricted environmental, social, and economic growth in many parts of the world (Falkenmark, et al., 2007; McDonald et al., 2011). In fast-growing population centres, in particular, where water requirements are high and water quality is generally poor, water stress is especially a challenge (Oki & Kanae, 2006).

2.4.2 Soil contamination

Urban activities generate enormous wastes, chemicals, metals and other known and unknown contaminants. The contaminants are held and stored up in the soil and land surface, resulting in soil contamination (Sajjad & Iqbal, 2012; Zgłobicki & Telecka, 2021). As urbanisation processes change natural and agricultural areas, the ecological responsibilities of soils shift from biomass production to pollutant storage. Thus, the area of impermeable land surface and population density are determined by urbanisation.

Excessive application of pesticides and fertilisers from agriculture pollute the soil in an urban setting. Furthermore, the use of untreated wastewater for irrigation, and use of manure and sewage sludge containing high levels of antibiotics, antimicrobial-resistant bacteria, and heavy metals are all contributing factors to soil pollution in agriculture and livestock operations.

Domestic heating systems, manufacturing facilities, building activities, municipal waste treatment plants, and hospitals also enhance urban soil contamination. Traffic is acknowledged as a critical source of element enrichment in urban soils (Adachi & Tainosho, 2004; Zereini et al., 2012). Besides exhaust emissions, metals and metalloids are emitted from cars in non-exhaust emissions, such as road surface erosion and vehicle component attrition (Harrison et al., 2012). Copper (Cu) and Antimony (Sb) have been found in brake lining materials, particularly in places with high braking rates, such as traffic junctions (Adachi & Tainosho, 2004; Harrison et al., 2012). Increase in transportation in an urban area emits

Pb through the usage of wheel weights and yellow paint for road marking (Adachi & Tainosho, 2004; Agnan et al., 2016).

2.4.3 Air pollution

According to the most current assessment of 4 300+ cities worldwide, just 20% of the urban population examined live in regions that meet the air quality threshold for particulate matter ($PM_{2.5}$) (WHO, 2015). In many developing cities, average particle air pollution levels can be four to fifteen times higher than the WHO air quality guideline levels, placing many people at risk of long-term health concerns (WHO, 2015). Unfortunately, air pollution has an adverse impact on millions of people's health and the erratic nature of the weather. Cardiovascular disease, lung cancer, and respiratory illnesses are all caused by pollution in the air (UN COP 26, 2021). Concerns over the quality of urban air have led to legal limitations and reduction on emissions by the world leaders at the Glasgow climate change conference in 2021. These concentrated on emission sources, commencing in the UK with the "London smogs" of the 1950s (Saghir & Santoro (2018). In order to distinguish between natural and human contributions to suspended air particles, a considerable number of studies have tried to discriminate between natural and urban sources. Van Dingenen et al. (2004) reported that the size distribution of urban suspended particles is bimodal, with the coarsest component being a particulate matter of natural origin (resuspended soil and mineral particles) and the finer fraction being anthropogenic (combustion). The sub-micron particle size is prevalent in many cities.

Particulate matter such as PM_{10} and $PM_{2.5}$ is considered inhalable and may penetrate the alveoli of the lung and cause irritation and terminal disease. The coarsest particles of this fraction are lodged in the nose, and mouth. It is therefore linked to harmful health consequences such as asthma and even death.

The health consequences of ultra-fine particles have been debated, although most studies have focused on the tiniest fraction. As, Cd, Cr, Hg, magnesium (Mn), nickle (Ni), Pb and vanadium (V) are toxicologically essential trace elements present in these tiny particles known as particulate matter. Occupational exposure to these components may cause sinusitis, asthma, chronic bronchitis, pneumonia, lung haemorrhage, lung cancer, and brain haemorrhage (Choi et al., 2009). The potential toxicity has sparked many studies on their origins and quantities in urban environments. The emissions of suspended particles from various urban operations, such as heating, fuel burning and industrial processes are major drivers of global warming and climate change (Maponya & Rampedi, 2013).

2.5 Health risks of urban contamination

Environmental geochemists are particular about the health impacts of urban pollution. Increase levels of hazardous components in street dust, soil, water and air pose major health risk to the majority of the urban populace (Banerjee, 2003; Tessier et al., 2014). Bioassays can be used to assess the ecotoxicological relevance of trace components in roadway dust. Risk assessment methodologies widely employed by regulatory bodies to determine soil screening levels or soil guideline values must be utilised to assess the relevance in terms of health impacts of hazardous elements and compounds in urban matrices.

This adoption is subject to the peculiarities of urban environments (Granero & Domingo, 2002). Ongoing reviews of carcinogen and noncarcinogen toxicity levels are given as point estimates indicating the uncertainty associated with their determination, generally one order of magnitude. In the end, risk assessors use these toxicity values to estimate the degree of exposure as an average daily chronic or lifetime dose (in milligrams of contaminant per unit of body weight and per unit of time).

Four categories of factors impact the dosage acquired in the urban particulate matter, namely:

- Rate of contact.
- The extent of exposure.
- Length of exposure.
- The body weight of the prospective exposed population.

Estimates of these variables are further affected by the degree of variable uncertainty. Given the fact that these factors are all population-specific, determining the exact contribution of each exposure's medium to total risk is problematic. Despite these difficulties, risk assessment has shown to be a beneficial tool for determining the real impact of trace element concentrations in urban environments and human health.

Non-communicable disease risks associated with outdoor and interior air pollution are exacerbated by unplanned urban expansion. Additionally, urban sprawl is linked to road traffic injuries and physical inactivity-related dangers, such as obesity, as well as other health issues.

2.5.1 Climate change risk on urban areas

The climate change dilemma driven by urbanisation has been an important subject in the twentieth and twenty-first centuries across the globe (IPCC, 2021; UNFCCC, 2020). Climate change is caused by human-induced factors on the earth surface. Various human activities are accelerating climate change; urbanisation is the foremost driving factor in this era of modernisation and industrialisation (Nerem et al., 2018). Climate change is one of the common disasters facing human kind across the planet. In recent decades, climate change has impacted natural and human ecosystems globally (IPCC, 2014).

The rural–urban migration leads to over-population, and rapid urban development thereby results in pollution and poor sanitation that are detrimental to the environment. Socio-economic factors in an urban centre act as a pulling factor to people causing an increase in rural–urban migration; unfortunately, an increase in the population in an urban centre often comes at the cost of the local environment (Chan, 2017; Sim, 2016). Climate change and urbanisation are intricately related as change in any one will affect the other, which can also lead to potential environmental consequences if not guided by smart and sustainable environmental policies.

Unplanned rapid urban development can bring about deforestation, habitat destruction and increase in CO_2 emissions which generate greenhouse gases (Dash & Mallick, 2017; Murshed & Saadat, 2018). Urban growth drives commercialisation and industrialisation, which increase the use of fossil fuels. Meanwhile, an increase in the use of fossil fuels accelerate global warming and climate change (Cohen, 2019). In many urban cities across the globe, forest and vegetated land are destroyed to create housing and infrastructure to the growing population in urban cities. The vegetated and forest area being one of the biologically diverse ecosystems when destroyed, can accelerate climate change.

Extensive deforestation reduces the number of trees; thus, decreased oxygen supply, rain and increased carbon dioxide in the atmosphere. Consequently, those environmental factors lead to higher humidity that can accelerate global warming and climate change (Homan et al., 2020; Tadić & Biraud, 2020). According to the ASEAN Biodiversity Outlook report (2021), the biological diversity in the Philippines, Indonesia and Malaysia will be greatly eroded by 2100 if the destruction of the environment continues. The same scenario applies to many rapidly urbanising centres across the globe.

Urbanisation has in many ways promoted global warming, climate change, environmental degradation and depletion of natural resources (UN, 2019). Urbanisation in Tokyo caused change in the water cycle due to reducing of forest land and vegetated areas converted to residential areas (Homan et al., 2020; Nakao & Tanimoto, 1997; Okata & Murayama, 2011; Quah & Roth, 2012). According to Nunes et al. (2020), surface runoff in major cities has increased in recent years through paving and sealing due to urbanisation. Furthermore, natural retention water storages such as lakes and wetlands were filled and replaced as impervious surface. Hence, the remaining rivers in urban areas are not capable and overflow can occur in urban centres leading to flooding, as we experience in our metropolitan cities such as KwaZulu-Natal in South Africa and Lagos in Nigeria. It is no doubt that acknowledging the reality of climate change and the enormous cost, are often associated with the impact on our present day. Reports on global climate change, according to Lin et al. (2016) and Garner et al. (2017), revealed an alarming trend of climate change and the resultant effects on environmental sustainability. However, global and national discourse have attracted attention and urgency to issues of climate change, thereby prioritising it above other critical economic and environmental challenges confronting human existence (Ahmed et al., 2018; UN COP 2021).

Davenport et al. (2015) noted that over 70 member states of the United Nations overwhelmingly prioritised climate change as contained in their statements in the Paris conference of 2015. World leaders have virtually attributed the various environmental, economic and political problems to climate change. Schäfer (2013) was of the opinion that most countries face economic, food and water insecurity, and social environmental adversity resulting from the consequences caused by climate change, which is triggered by rapid and sudden urban development. Corroborating this statement, Aronoff (2015) and Oloke et al. (2021) reported that countries such as Turkey, Brazil, Egypt, Iraq, Nigeria and other sub-Sahara Africa countries are faced by extreme weather conditions leading to frequent flooding and droughts. According to Oloke et al (2021), the effects of climate change caused by urbanisation can be addressed by promoting the use of green technologies, improving efficiency in the use of fossil fuels, reducing traffic congestion and CO_2 emissions.

2.5.2 Managing environmental disasters in a changing climate

The global impact of climate-related disasters is growing. The impact of climate-related catastrophes in cities may be amplified by interactions between climate change and urban infrastructure systems, expanding urban populations and economic activity (Oloke et al., 2021). The majority of the world's population now lives in cities, and this figure is expected to rise in the next decades (Adachi et al., 2012). According to Ahmed et al. (2018), cities should pay more attention to climate-related calamities such as heat waves, floods, and droughts. In order to fully handle emerging and escalating risks in a changing climate, a new decision-making framework is required. This necessitates a paradigm shift away from impact assessments that concentrate on singular climate dangers based on historical events. The new paradigm necessitates integrated, system-based risk assessments that take into account both existing and prospective threats across large metropolitan regions (Bounoua et al., 2020).

Disaster risk reduction and climate change adaptation are critical components of making cities resilient to climate change. In order to integrate these operations with a city's development vision, a new systems-orientated approach to risk assessment and planning is required. Furthermore, because previous experiences cannot inform decision-makers about emerging and escalating climate hazards, systems-based risk assessments must include the present conditions as well as future forecasts for entire metropolitan regions. A paradigm shift of this magnitude will necessitate decision-makers and stakeholders, increasing the capacity of communities and institutions to organise, strategise, and implement risk-reduction plans and disaster responses. Bounoua et al. (2020) established the importance of developing multi-level, multi-sectoral, and multi-stakeholder integration.

Urban planners and decision-makers must coordinate efforts to reduce the causes of climate change and adapt to shifting weather patterns (Carmin et al., 2012; Chan, 2017). Solutions are provided by actions that support both climate change mitigation and environmental sustainability. Decision-makers must sometimes negotiate trade-offs and reduce conflicts between competing agendas. A better knowledge of the interconnections between mitigation and adaptation can offer new opportunities for urban areas (Cappiella et al., 2012). Strategies such as reducing the urban heat island effect, improving air quality, and increasing resource efficiency in the built environment and energy systems are examples. Enhancing carbon storage through land use and urban forestry is likely to reduce greenhouse gas emissions while boosting a city's resilience. Specific adaptation and mitigation strategies should be chosen in the context of other sustainable development goals, taking into account the city's actual resources and technological capabilities, as well as inhabitants'demands.

2.6 Basic methods of environmental sustainability assessment

Individuals in numerous professions have been grappling with the definition and significance of environmental sustainability for more than a decade. There has been no consensus between those who advocate a three-legged strategy (i.e., simultaneously benefiting the economy, society, and environment) and those who perceive it as a relationship between human society and nature (Morelli, 2011). Ultimately, protecting global ecosystems for the sake of humanity and aquatic life are the key component of environmental sustainability. Different methods have been proposed and applied to the mapping of environmental sustainability in various forms. Some of these methods have been accepted and adopted by government and international organisations such as the United Nations, the WHO and private institutions.

Sustainable environment has become one of the most prominent policy buzzwords. Nearly all governments have committed to the sustainable development goal by integrating economic welfare, environmental quality, and social cohesion. As a result, there is a robust political urge for a complete examination of economic, environmental, and social (including institutional) conditions: It will be challenging to improve a problem that cannot be quantified. The United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992, called on individual countries, as well as international governmental and non-governmental organisations, to "develop and identify indicators of SD [sustainable development] in order to improve the information basis for decision-making at all levels" (UNCED, 1992, Agenda 21). Indicator lists have been established since the early 1990s. The Sustainable Development Indicator Initiatives Compendium lists almost 500 initiatives (Parris & Kates, 2003).

The multiplicity of sustainable development indicators poses tremendous difficulty for policymakers, mainly because they require an aggregate index that can be easily interpreted and disseminated to the general public (Dalal-Clayton & Bass, 2002; Hammond et al., 1995). According to Nordhaus and Zolotas (1981), the production of aggregate sustainable development indexes has a lengthy history in 1985.

For better understanding, a brief description of some major and common environmental sustainability methodologies will be attempted. The methods will approach all aspects of the environment and natural resources. The following basic methods of environmental sustainability are further highlighted in this chapter:

- The Living Planet Index (LPI).
- Ecological Footprint (EF).
- City Development Index (CDI).
- Human Development Index (HDI).
- Environmental Sustainability Index (ESI).
- Environmental Performance Index (EPI).
- Environmental Vulnerability Index (EVI).
- Environmental Well-Being Index (EWBI).
- Comprehensive Environmental Pollution Index (CEPI).

2.6.1 Living Planet Index

The LPI measures trends in vertebrate populations around the world as a measure of global biological diversity. The biodiversity indicator LPI was developed by the World Wide Fund for Nature (1998) and was adopted by Loh et al. (2000) and Collen et al. (2009). It has been used to track over 2 000 populations of over 1 100 vertebrate species in terrestrial, fresh-water, and marine environments. The LPI has sub-indices for each of the three spheres. Every species within a sphere has its population ratio computed in successive years. The geometric mean of these species' quotients multiplied by the previous year's index value yields the biodiversity index for the relevant sphere (1970 serves as a base-year with the index value for 1970 scaled to unity). The LPI is the geometric mean of these indices. All variables reflect changes in species counts, no normalisation is done, and all ratios are equally weighted.

A generalised additive modelling framework was utilised to determine the underlying trend in each population time-series while calculating the LPI (Collen et al., 2009; Loh et al., 2005). After that, average rates of change are computed and aggregated to the species level. The method of aggregation for the global LPI has recently been altered to include a weighting scheme that provides trends from more species-rich systems and realms, and groups more weight in the final index (McRae et al., 2017):

$$d_t = \frac{1}{n_t}\sum_{i=1}^{n_t} d_{it}$$ *Equation 1*

Where:

n_t = the number of specie populations; and

d_t = the annual rate of change for a population in a given year, given by

$$d_t = log_{10}\left(\frac{N_t}{N_{t-1}}\right)$$ *Equation 2*

Where:

N = the population measure; and

T = the year.

It is then converted back to index values by:

$$I_t = I_{t-1} * 10^{d_t}, \quad I_0 = 1$$ *Equation 3*

2.6.1.1 Strengths of the Living Planet Index method

The population time-series data of the LIP is supplemented with information about the population's taxonomy, location, and ecology, allowing for trend analysis at multiple scales and for different habitats in the aquatic ecosystem. The method also demonstrates the trends in temperate and tropical regions and different biogeographic realms.

In addition, subsets LPI population trend can

- assist in tracking progress on multilateral accords such as the Convention on the Conservation of Migratory Species;
- build an index of biodiversity trends in a certain environment;
- be used to investigate trends in specific groupings of species; and
- create regional and global indices representing certain habitats or biomes.

2.6.2 Ecological footprint

The EF is regarded as the impact of human activities measured in terms of the area of biologically productive land and water required to maintain a sustainable environment from the consumable product and to conform with the wastes generated by humans.

The EF (Rees & Wackernagel, 1994) is based on the quantifiable land and water needs to indefinitely sustain a national living standard, assuming that specific efficiency increases. The ratio of necessary to available resources is regarded as a measure of ecological sustainability. Modern living standards would contradict the principles of sustainable development if they exceeded the one-to-one ratio. The EF is derived from national consumption statistics. Thus, the EF relies heavily on normalization as any consumption is converted in land use. All land and water needs are summed together, with weighting implied in the conversion parameter. The MIPS (Material-Input-Per-Service) idea, the Sustainable Process Index (Gassner & Narodoslawsky, 2004; Narodoslawsky & Krotscheck, 2000) or the Ecoindex^{TM} are all comparable methods (Chambers & Lewis, 2001).

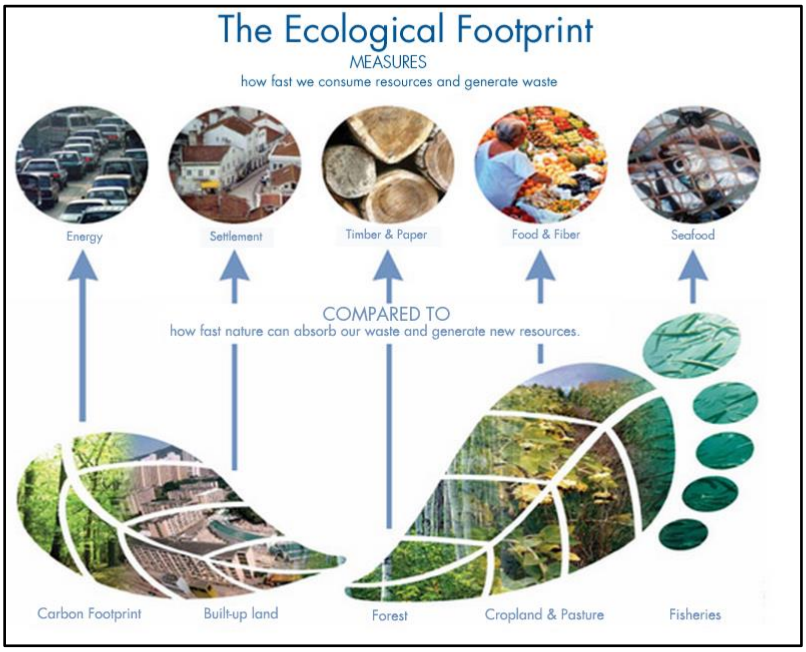


Figure 2.8: Diagram of the ecological footprint method, measure parameter and impact on the environment

Source: Rees and Wackernagel (1994)

The ecological footprint considers many variables as shown in Figure 2.8 to calculate the ecological footprint of a nation, the equation found in Rees and Wackernagel (1994) and Gallie et al. (2007):

$$EF = \frac{\sum T_i}{Y_w} \; X \; EQF_i \qquad \text{Equation 4}$$

Where:

T_i = annual tons of variables i that are consumed in an area,

Y_w = annual global average yield of product i,

EQF_i = equality factor for each product i.

2.6.2.1 Limitations and factors of the ecological footprint

The calculation of the ecological footprint takes the following factors into account:

- The Earth's biocapacity, namely the planet's capacity to produce resources.
- Human activity and its ecological impact, namely the resources consumed by humans and their waste.
- The EF focuses on food security and does not account for biodiversity, toxicity, pollution and other traditional environmental concerns.

2.6.3 City Development Index

The CDI was developed by Dunteman (1989) to rank cities according to level of development and environmental sustainability. The UN Habitat for humanity's CDI consists of five sub-indices. These sub-indices include city product, infrastructure, garbage, health, and education (UN-Habitat, 2006). The infrastructure index is based on four equally weighted factors such as the percentage of households with access to clean water, canalisation, electricity, and a phone network without mobiles. In addition, it has a two-fold equally weighted waste index based on the percentage of untreated sewage in total wastewater and the percentage of solid waste disposal in total solid wastes. Finally, this index method considers a two-fold diversely weighted health score, which measures life expectancy and infant mortality. An education index is produced by combining the percentages of literacy and enrolment. Therefore, a city product index is based on the logarithmic value of the city's gross domestic product (GDP).

The CDI uses a standard normalisation technique for variables where absolute values Ix are converted according to the UN-Habitat (1996).

$$\frac{x_i - \underline{x}}{\overline{x} - \underline{x}} \qquad \text{Equation 5}$$

with $\overline{x}$ ($\underline{x}$) representing exogenous maximum (minimum) goal values.

The indicators are weighted using a multivariate statistical approach (Principal Components Analysis by Dunteman, 1989). The five sub-indices are averaged to get the CDI. The formulae used to calculate the CDI are presented in Table 2.1. The weighing scheme is derived using the principal components analysis.

Table 2.1: Summary of the City Development Index calculation by UN-Habitat

Factor	Formula
Infrastructure	25 × H_2O connections + 25 × sewerage + 25 × energy + 25 × mobile
Waste	Treated wastewater × 50 + formal waste disposal site × 50
Health	(Life expectancy – 25) × 50/60 + (32 – child mortality) × 50/31.92
Education	Literacy × 25 + combined enrolment × 25
Product	(Log city product – 4.61) × 100/5.99
City Development Index	(Infrastructure index + waste index + education index + health index + city product index) / 5

Source: UN-Habitat (1996)

2.6.3.1 City Development Index – initiative of the Asian Development Bank

The Asian Development Bank (ADB) began an initiative in 1999 under regional technical assistance for the construction of a city development index for the Asian and Pacific Region. The ADB addressed the need for enhanced sustainable data, indicators, and benchmarking in managing the fast-growing cities across the region. The ADB database considers the factors on three indexes presented below.

- City Development Index (CDI).
- Congestion Index.
- Connectivity Index.

Table 2.2 gives the formulae for the three indices. The weighing scheme is derived using the principal component analysis.

Table 2.2: Calculation of the City Development Index by the Asian Development Bank

Index	Formula
Infrastructure	25 × water connections + 25 × sewerage + 25 x energy + 25 × mobile
Waste	Treated wastewater × 50 + waste disposal site × 50
Health	(Life expectation – 25) × 50/60 + (32 – child deaths) × 50/31.92
Education	Literacy × 25 + principal enrolment × 25 + secondary enrolment × 25 + graduates/350 × 25
Product	(Log city product – log 400) × 30/2.71 + (log of residential density – 1.98) × 30/4.86 + 40 × (log population – 2.78)/6.7

Index	Formula
City development	(Infrastructure index + waste index + education index + health index + city product index)/5
Congestion	(Log travel time – 2.08) × 30/2.71 + (log of residential density – 1.98) × 30/4.86 + 40 × (log population-2.78)/6.7
Connectivity	(Log Internet + 0.71/6.34) + log corporations/6.7 + (log tourism – 3.42)/5.75 + (log flights – 4.33)/5.27 – 0.07/3.3

Source: ADB (2001)

2.6.4 Human Development Index

The HDI has been reported yearly since 1990 as part of the Human Development Report of the United Nations Development Programme (UNDP, 2007). HDI comprises three equally-weighted sub-indices, namely life expectancy index, education index and Gini index. The HDI emphasises the social dimension of sustainable development. It can be assumed that x(x) indicates the exogenous maximum (minimum) value and the dimension index denotes the actual value in a nation or locality.

Table 2.3: The component value indicators for the Human Development Index

Dimension	Indicator	Minimum	Maximum
Health	Life expectancy (years)	20	85
Education	Expected years of schooling	0	18
	Mean years of schooling	0	15
Standard of living	GINI per capita (2017 purchasing power parities in dollar)	100	75 000

Source: Foster et al. (2005)

There are two steps to calculating HDI values, namely:

Creating the dimension indices:

Minimum and maximum values are set in order to transform the indicators as expressed in different units into indices between 0 and 1.

$$Dimension\ Index = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$ *Equation 6*

Aggregating the dimensional indices:

The HDI is the geometric mean of the three-dimensional indices:

$$HDI = (I_{health} * I_{education} * I_{income})^{\frac{1}{3}}$$ *Equation 7*

Figure 2.9 presents factors and indicators considered to calculate the HDI.

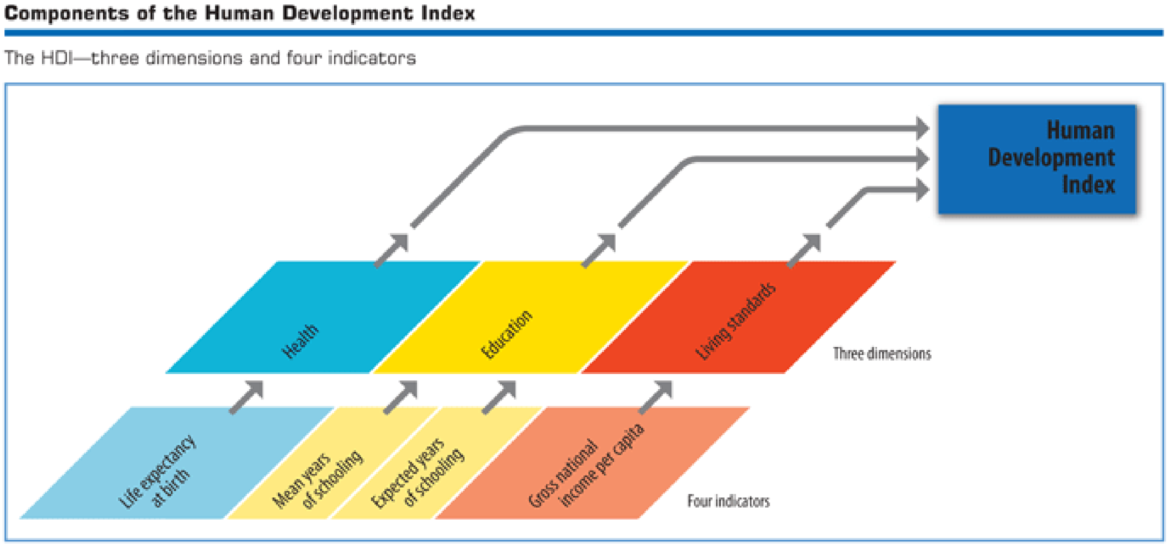


Figure 2.9: Graphical presentation for calculating the human development indices

Source: UNDP (2020)

2.6.4.1 Strengths of the Human Development Index

The HDI is a summary assessment of average success in characterising human development towards sustainability. The HDI factor takes into account the living and healthy lifestyle, literacy, and having a decent standard of living in a rapidly urbanising region.

2.6.4.2 Limitations of the Human Development Index

- HDI has a huge variance within countries. For example, countries like China and Kenya have widely different HDI scores depending on the region investigated (for example, north China is poorer than south-east China).
- HDI reflects long-term changes (for example, life expectancy) and may not respond to recent short-term changes.
- Higher national wealth values does not indicate welfare. The gross national income (GNI) may not necessarily increase economic welfare; it depends on how it is spent. For example, if a country spends more on military spending then it is reflected in a higher GNI, but welfare could actually be lower.
- Also, higher GNI per capita may hide widespread inequality within a country. Some countries with a higher real GNI per capita have high levels of inequality (for example, Russia and Saudi Arabia).
- However, HDI can highlight countries with similar GNI per capita but different levels of economic development.
- Economic welfare depends on several other factors, such as threats of war, levels of pollution and access to clean drinking water.

2.6.5 Human Well-being Index

The United States Environmental Protection Agency (USEPA) has created an integrated approach to assessing human well-being. An index of human well-being has been constructed at several levels and is known as the Human Well-being Index (HWI). In order to investigate the impact of social, economic, and environmental service relation on the eight areas of human development, the HWI employs a variety of variables (Figure 2.10). Prescott-Allen's (2001) well-being assessment assumes that a healthy environment is required for healthy individuals. The Well-being Index is the arithmetic mean of the HWI and the Ecosystem Well-Being Index (EWI). HWI and EWI have five sub-indices each. The HWI includes indexes for health and population, welfare, knowledge, culture, and society, as well as an equity index. The EWI includes indexes for land, water, air, species, genes, and resource deployment (Figure 2.10). The five dimensions of the HWI are based on 36 indications and that of the EWI on 51. Each of these dimensions is aggregated by a weighted arithmetic mean of sub-indices or variables, which are normalised again by a proximity-to-target technique utilising targets of related indicators (Prescott-Allen, 2001).

First, metrics are combined to create an indicator (k) score for a spatial area ($\overline{xk}$) using the following equation:

$$\overline{xk} = \frac{\sum_{m=1}^{n_n} \cdot \sum_{i=1}^{n_c} w_i \, x_{mi}}{n_m} \qquad \textit{Equation 8}$$

Where:

n_c = the number of locations in an area;

n_m = the number of metrics;

w_i = the population weight for location I; and

x_{mi} = the metric cost for location i and metric m combination.

A domain (d) is scored for a given area ($\overline{xk}$) as follows:

$$\overline{xk} = \frac{\sum_{k=1}^{n_k} \bar{x}_k}{n_k} \qquad \textit{Equation 9}$$

Where:

k represents an indicator;

$\overline{xk}$ refers to the indicator score; and

n_k is the total number of indicators.

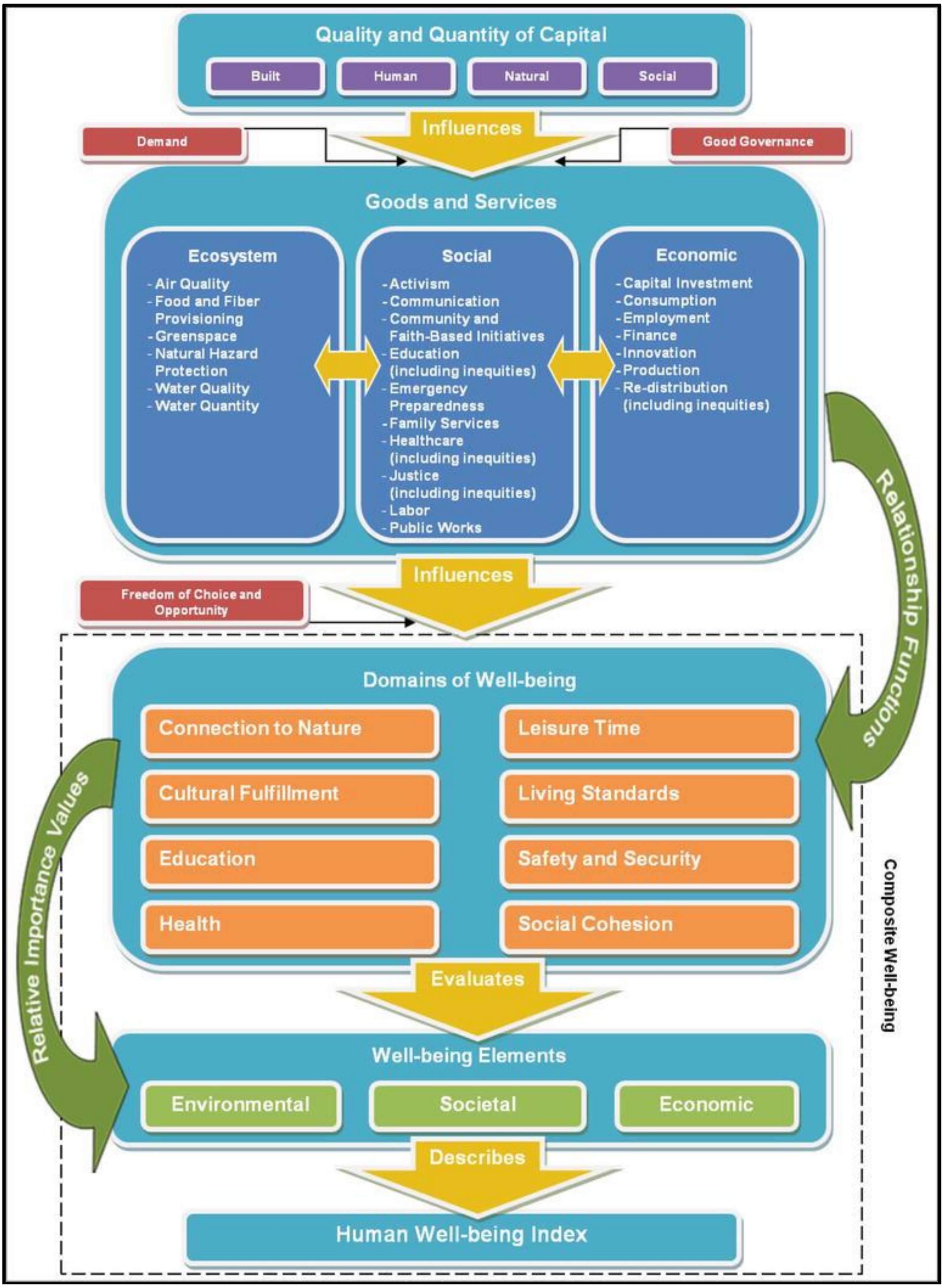


Figure 2.10: ***Theoretical framework for evaluating the effect of human activities on well-being***

Source: USEPA (2015)

Economic, environmental, and social well-being element values (e) are calculated by taking the geometric mean of all domains and multiplying it by a relative importance value assigned to each element. Equation 10 gives the total element scoring for a given area:

$$\bar{x}_e = \prod_{d=1}^{8} \bar{x}_d^{\,RIV\,(d,e)} \qquad \textit{Equation 10}$$

where $RIV_{(d,\ e)}$ is the relative importance value between domain *d* and element *e*.

Finally, the Human Well-being Index is calculated using a relative importance factor for each element-to-overall well-being relationship as shown below:

$$HWBI = RIV_{eco\bar{x}_{eco}} + RIV_{env\bar{x}_{env}} + RIV_{soc\bar{x}_{soc}} \qquad \textit{Equation 11}$$

where RIV_{eco}, RIV_{env}, RIV_{soc}, and $\bar{x}_{eco}$, $\bar{x}_{env}$, $\bar{x}_{soc}$ are the relative importance values and scores for the economic, environmental, and social elements, respectively.

2.6.6 Environmental Vulnerability Index

According to UNEP, the South Pacific Applied Geoscience Commission (SOPAC), the EVI measures how vulnerable different countries and regions are to various forms of environmental problems. The results of the EVI are utilised to focus on planned solutions to environmental concerns, while also supporting sustainable development.

The EVI consists of 32 hazards, 8 resistances, and 10 damage indicators (SOPAC, 2005). The normalising EVI scale goes from 1 (*high resilience/low vulnerability*) to 7 (*poor resilience/ high vulnerability*). The 50 indicators (Figure 2.11) are weighed equally and then averaged.

INDICATORS	TYPES	ASPECTS	SUB-INDICES						
1 Wind	W&C	Hazards	CC	D				CCD	
2 Dry	W&C	Hazards	CC	D		AF	W	CCD	
3 Wet	W&C	Hazards	CC	D		AF	W	CCD	
4 Hot	W&C	Hazards	CC	D				CCD	
5 Cold	W&C	Hazards		D				CCD	
6 SST	W&C	Hazards	CC			AF			CBD
7 Volcano	G	Hazards		D					
8 Earthquake	G	Hazards		D					
9 Tsunami	G	Hazards		D					
10 Slides	G	Hazards		D					
11 Land	Gph	Resistance	CC						CBD
12 Dispersion	Gph	Resistance	CC						CBD
13 Isolation	Gph	Resistance							CBD
14 Relief	Gph	Resistance	CC					CCD	CBD
15 Lowlands	Gph	Resistance	CC					CCD	CBD
16 Borders	Gph	Resistance							CBD
17 Imbalance	R&S	Damage				AF			CBD
18 Openness	R&S	Hazards				AF			CBD
19 Migratory	R&S	Resistance				AF			CBD
20 Endemics	R&S	Resistance							CBD
21 Introductions	R&S	Damage				AF			CBD
22 Endangered	R&S	Damage							CBD
23 Extinctions	R&S	Damage							CBD
24 Vegetation	R&S	Damage	CC			AF	W	CCD	CBD
25 Loss Veg	R&S	Hazards				AF	W	CCD	CBD
26 Fragmentation	R&S	Damage				AF			CBD
27 Degradation	R&S	Damage				AF	W	CCD	
28 Reserves	R&S	Hazards					W		CBD
29 MPAs	R&S	Hazards				AF			CBD
30 Farming	R&S	Hazards				AF			
31 Fertilisers	R&S	Hazards			HH	AF	W		
32 Pesticides	R&S	Hazards			HH	AF	W		
33 Biotech	R&S	Hazards				AF			
34 Productivity overfishing	R&S	Hazards				AF			
35 Fishing Effort	R&S	Hazards				AF			
36 Water	R&S	Hazards	CC		HH	AF	W	CCD	
37 SO2	R&S	Hazards			HH				
38 Waste	R&S	Hazards							
39 Treatment	R&S	Hazards			HH		W		
40 Industry	R&S	Hazards							
41 Spills	R&S	Hazards							
42 Mining	R&S	Hazards							
43 Sanitation	R&S	Hazards			HH		W		
44 Vehicles	R&S	Hazards							
45 Density	H	Damage	CC	D			W		
46 Growth	H	Hazards					W		
47 Tourists	H	Hazards							
48 Coastal	H	Damage	CC	D					
49 Agreements	H	Hazards							
50 Conflicts	H	Damage							

Figure 2.11: Summary of indicators selected for the Environmental Vulnerability Index and their allocation to policy-relevant sub-indices

Source: SOPAC (2005)

2.6.6.1 Strengths and weaknesses of the Environmental Vulnerability Index

The EVI, like all methods of summarising and modelling data, is connected with conditions, strengths, and weaknesses that must be recognised in order for it to be properly applied. Researchers and expert evaluations identified a set of strengths and flaws that were added to those established by the SOPAC.

The **strengths** of the EVI have been identified as follows:

- The EVI is a convenient measurement of environmental vulnerability assessment.
- This method is based on a theoretical framework that prompted the EVI team to find indicators for all identified aspects of vulnerability in the environment.
- The method identifies conditions that are contributing to environmental vulnerability of a given country or nation.
- The method allows countries to study their environment and how it changes through time.
- It stimulates debate at the science / policy interface at national and international levels and among disciplines.
- It is able to incorporate a range of data types on different response scales and nonlinearities.
- The EVI method is applicable to all regions across the globe.
- The EVI could be used for awareness in an unsustainable environment.
- It identifies areas of environmental concern which could provide a focus for new or improved data collection.

The **weaknesses** of the EVI were identified as follows:

- Some complex environmental features could not be measured directly.
- The EVI is affected by the specific environmental factors chosen and the results obtained may differ for different environmental factors.
- The EVI is subject to difficulties with differences in quality of environmental data and the interpretation.
- Inaccessibility to some environmental data.

2.6.7 Environmental Performance Index

The EPI was an initial effort to rate nations on 21 metrics and 76 environmental sustainability components. The ESI has a broad scope; therefore, the Yale-Columbia research team created the EPI in 2006. The EPI, on the other hand, tracks outcome-orientated indicators based on best available data. The research team also established measures that allow policymakers, environmental scientists, and others to compare their country's performance to other countries published in 2006, 2008, 2010 and 2012.

In addition to the EPI, a Pilot Trend Environmental Performance Index (Trend EPI) has been in place since 2012. On the one hand, countries may be compared, while on the other hand, global environmental policy goals can be appraised. Countries are ranked on their environmental performance during the previous decade. It illustrates which countries improve and which decline over time.

These policy categories track two major environmental goals:

- Environmental health: minimising environmental health risks.
- Protecting ecosystems and natural resources.

These two goals have long-term goals on international treaties, norms set by non-governmental groups and scientific consensus, namely the EPI objectives, policy areas, and indicators. Input data for the 2012 EPI came from a variety of sources, such as governments and non-profit organisations (Table 2.4). Sources include government statistics and data produced by international and research organisations.

Table 2.4: Policy categories and indicators of the 2012 Environmental Performance Index

Objectives	Policy categories	Indicators
Environmental health	Air pollution (effects on humans)	Indoor air pollution Particulate matter
	Water (effects on humans)	Access to drinking water Access to sanitation
	Environmental burden of disease	Child mortality
Ecosystem vitality	Air pollution (ecosystem effects)	SO_2 emissions per capita SO_2 emissions per GDP
	Water (ecosystem effects)	Change in water quantity
	Biodiversity and habitat	Biome protection Marine protection Critical habitat protection
	Forests	Forest loss Forest cover change Growing stock change
	Fisheries	Coastal shelf fishing pressure Fish stocks overexploited
	Agriculture	Agricultural subsidies Pesticide regulation
	Climate change	CO_2 emissions per capita CO_2 emissions per GDP CO_2 emissions per electricity generation Renewable electricity

Source: Emerson et al. (2012)

2.6.8 Environmental Sustainability Index

The ESI assesses a country's progress towards environmental sustainability. As a composite index, it measures and influences environmental sustainability at the national level. As part of the Environmental Performance Measurement project, the Yale Centre for Environmental Law and Policy, Columbia University's Centre for International Earth Science Information Network, the World Economic Forum, and the European Commission's Joint Research Centre collaborated on the ESI. Through environmental indicators and data, the Environmental Performance Measurement Project seeks to improve environmental decision-making (Table 2.5). The Environmental Performance Index (EPI) preceded the ESI. The ESI records national environmental sustainability indicators, whereas the EPI assesses important environmental policy outcomes using trend analysis and performance objectives. The ESI was published in 2000, 2001, 2002, and 2005. The ESI analyses environmental performance across countries (Table 2.5). The environmental performance is evaluated using 21 indicators derived from 76 data sets. The ESI seeks to provide a tool for measuring national environmental performance, such as natural resource endowments, environmental management activities, and pollution levels. The initiative promotes the Millennium Development Goals, especially Goal 7, "Ensuring Environmental Sustainability". A high ESI score implies that a country has achieved a high level of environmental sustainability and enhanced its capacity to maintain environmental conditions in the future. A low ESI score reflects a country's environmental sustainability challenges. In 2005, the top five nations were Finland, Norway, Uruguay, Sweden, and Iceland, and the worst five were North Korea, Iraq, Taiwan, Turkmenistan, and Uzbekistan. The compilation of 21 metrics permits comparisons across five aspects of sustainability:

- Reducing environmental stresses.
- Reducing human vulnerability to environmental stresses.
- Societal and institutional capacity to respond to environmental challenges.
- The ESI is a policy instrument to make environmental decision-making more empirically standardised. It is a valuable tool for comparing environmental stewardship across countries.
- The ESI rating provides a relative and approximate measure of a country's environmental sustainability. It is a snapshot of environmental performance, encompassing pollution control, natural resource management, and social problem-solving capabilities.

Table 2.5: Indicators and variables of the 2005 Environmental Sustainability Index

Component	Indicator	Variable
Environmental system	Air quality	• Urban population weighted NO_2 concentration • Urban population weighted SO_2 concentration • Indoor air pollution from solid fuel use
	Biodiversity	• Percentage of country's territory in threatened ecoregions • Threatened bird species as percentage of known breeding bird species in each country • Threatened mammal species as percentage of known mammal species in each country • Threatened amphibian species as percentage of known amphibian species in each country • National Biodiversity Index
	Land	• Percentage of total land area (including inland waters) having very low anthropogenic impact • Percentage of total land area (including inland waters) having very high anthropogenic impact
	Water quality	• Dissolved oxygen concentration • Electrical conductivity • Phosphorus concentration • Suspended solids
	Water quantity	• Freshwater availabilities per capita • Internal groundwater availability per capita
Reducing environmental stresses	Reducing air pollution	• Coal consumption per populated land area • Anthropogenic NOx emissions per populated land area • Anthropogenic SO_2 emissions per populated land area • Anthropogenic volatile organic compound emissions per populated land area • Vehicles in use per populated land area
	Reducing ecosystem stresses	• Annual average forest cover change rates from 1990 to 2000 • Acidification exceedance from anthropogenic sulphur deposition
	Reducing population pressure	• Percentage change in projected population 2004–2050 • Total fertility rate
	Reducing waste and consumption pressures	• Ecological footprint per capita • Waste recycling rates • Generation of hazardous waste
	Reducing water stress	• Industrial organic water pollutant (biochemical oxygen demand) emissions per available freshwater • Fertiliser consumption per hectare of arable land • Pesticide consumption per hectare of arable land • Percentage of country under severe water stress

Component	Indicator	Variable
	Natural resource management	• Productivity over fishing • Percentage of total forest area that is certified for sustainable management • World Economic Forum Survey on subsidies • Salinised area due to irrigation as percentage of total arable land • Agricultural subsidies
Reducing human vulnerability	Environmental health	• Death rate from intestinal infectious diseases • Child death rate from respiratory diseases • Children under five mortality rates per 1 000 live births
	Basic human sustenance	• Percentage of malnourished in total population • Percentage of population with access to improved drinking water sources
	Reducing environment-related natural disaster vulnerability	• Average number of deaths per million inhabitants from floods, tropical cyclones, and droughts • Environmental Hazard Exposure Index

Source: Esty et al. (2005)

2.6.9 Comprehensive Environmental Pollution Index

The CEPI provides inclusive evidence on the extent of pollution caused by human and industrial activities. This can be used to identify appropriate mitigation measures to environmental pollution (Rajamanickam & Nagan, 2018). The CEPI technique is a source–pathway–receptor method that considers an ecosystem affected by a polluting media (Figure 2.12). This index is a quantitative method for understanding impacts caused by human activities on the environment.

The quantification scope of the updated index has been expanded; nonetheless, CEPI will not represent reality unless effective data collection and continuous data flow are ensured. Cumulative Impact Assessment is gaining popularity as industrial activity in global cities grows. CEPI is a useful approach for numerically representing the extensive and diverse consequences of environmental pollution.

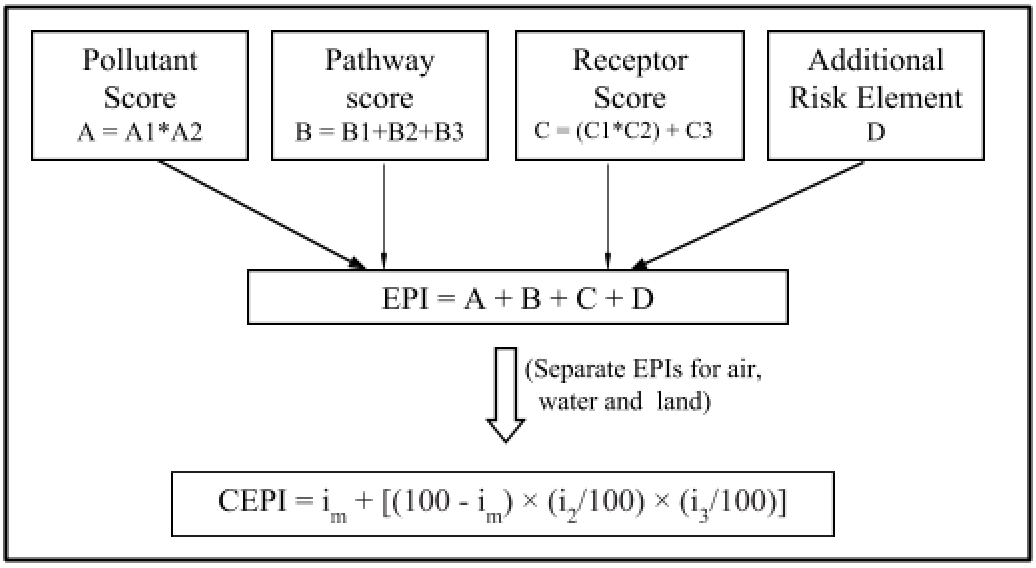


Figure 2.12: Simplified CEPI model chart

Source: Rajamanickam and Nagan (2018)

Table 2.6: Sustainability indices about scale, normalisation, weighting, and aggregation

Index	Normalisation	Weighting	Aggregation
Living Planet Index	$\left(\frac{x_{i,t}}{x_{i,t-1}}\right)$	Equal	$\sqrt[N]{\prod_{i=1}^{N} \frac{x_{i,t}}{x_{i,t-1}}}$
Ecological Footprint	Transformation in square kilometre	Equal	$\sum_{I=1}^{N} x_i$
City Development Index	$\frac{x_i - \underline{x}}{\overline{x} - \underline{x}}$	Two steps Principal component analysis and experts	$\frac{1}{N}\sum_{i=1}^{N} w_i x_i$
Human Development Index	$\frac{x_i - \underline{x}}{\overline{x} - \underline{x}}$	Equal	$\frac{1}{N}\sum_{i=1}^{N} x_i$
Environmental Sustainability Index 2005	Standard deviation	Equal/experts	$\frac{1}{N}\sum_{i=1}^{N} x_i$
Environmental Performance Index	Best = 100 Worst = 0	Principal component analysis and experts	$\sum_{i=1}^{N} w_i x_i$
Environmental Vulnerability Index	Aim = 1 Worst = 7	Equal	$\frac{1}{N}\sum_{i=1}^{N} x_i$
Well-being Index	Best = 100 Worst = 0	Subjective	$\frac{1}{N}\sum_{i=1}^{N} (w_i) x_i$

Source: Böhringer and Jochem (2007)

2.7 Gap of the sustainability indices evaluation

In section 2.6 above, a review of the current environmental sustainability indices was presented. However, there are substantial gaps in the eight indices. The parameters of each index do not represent the comprehensive character of UHS. The choice of parameters of each index is clearly influenced by the availability of data focusing on different aspects of the environment. In addition, the correct selection of parameters may vary per region due to different sustainability criteria (Booysen, 2002). Conversely, this compromises the UHS, as urbanisation has continued to increase since the Industrial Revolution.

Second, there is no universally recognised method for the weighting and scoring of all the indices. Some methods are rated subjectively (LPI and EFP), while others are measured objectively (EVI and CEPI) (Parris & Kates, 2003; Rajamanikan & Nagan, 2018; SOPAC, 2005). The scoring and thresholds for urban sustainability parameters are based on the best available information; therefore, the weighting and scoring system requires improvement as a new set of parameters are collected globally and the limit of sustainability becomes better understood. Therefore, the general weighing and scoring of urban sustainability vary based on the targeted urban environment and the parameters used in those assessments.

The scientific aggregation rules developed by Ebert and Welsch (2004) do not apply to all but one index, which accounted for population species in the ecosystem (Table 2.6). The LPI is based on populations of particular species and thus serve as an inadequate example of a weighting and scoring system in urban sustainability assessment, even though it uses a geometric mean for aggregations.

Finally, all the environmental health sustainability indices discussed in section 2.6 included various parameters, and components of the ecosystem lacked human health indices. The inclusion of human health sustainability due to changing climate conditions and rapid urbanisation was important. Therefore, there is a need to develop a model that will consider parameters for human environmental sustainability. The developed UHS in this study includes parameters for urban sprawl and other environmental activities that contribute to loss of biodiversity and poor environmental conditions in terms of water, vegetation, and extreme weather.

Chapter 3

GEOLOGICAL, HYDROLOGICAL AND CLIMATIC CHARACTERISATION OF THE MANGAUNG METROPOLITAN MUNICIPALITY

3.1 Introduction

This chapter characterises the local municipality in terms of its geology, climate variability, hydrology and water resources. Mangaung has a total land area of 9 886 km^2 and comprises three major urban centres, namely Bloemfontein, Botshabelo, and Thaba 'Nchu, as well as rural areas with small towns such as Dewetsdorp, Wepener, Van Stadensrus, and Soutpan /Stats SA, 2020). The city of Bloemfontein is the capital of Mangaung. The rural region accounts for the vast majority (97.1%) of the entire municipal territory and is characterised by considerable commercial farming in the west, which consists primarily of mixed crop production and livestock farming, as well as a number of small farms. The MMM is distinguished by three distinct land use forms, which are formalised stands in urban areas, smallholdings, and farms. Furthermore, the Barolong tribal authority is in charge of 37 communities scattered throughout the tribal region. The tribal region is divided into two parts: the north, which contains 21 villages, and the south, which contains 16 villages. The rural areas in between the communities are distinguished by wide swaths of community grazing land used for cattle grazing.

The population of the MMM has increased from 853 141 in 2018 to 861 651 in 2019 (Figure 3.1), although the growth rate has been declining from 1.6% in 2011 to 1.0% in 2019 (Stats SA, 2019). The major population of the MMM is concentrated in Bloemfontein with 63%, Botshabelo 24%, Thaba 'Nchu 9%, Dewetsdorp and Wepener 1.5%, Soutpan 0.8% and Van Stadensrus 0.2% (Stats SA, 2016). The Mangaung population is made up of 86% black Africans, 11% whites, and 4% coloured (Stats SA, 2016). Therefore, the black African demography accounts for the vast majority of the total population of Mangaung. In addition, females in Mangaung account for 51.07% of the total population, while males account for 48.9% of the total population in the municipality.

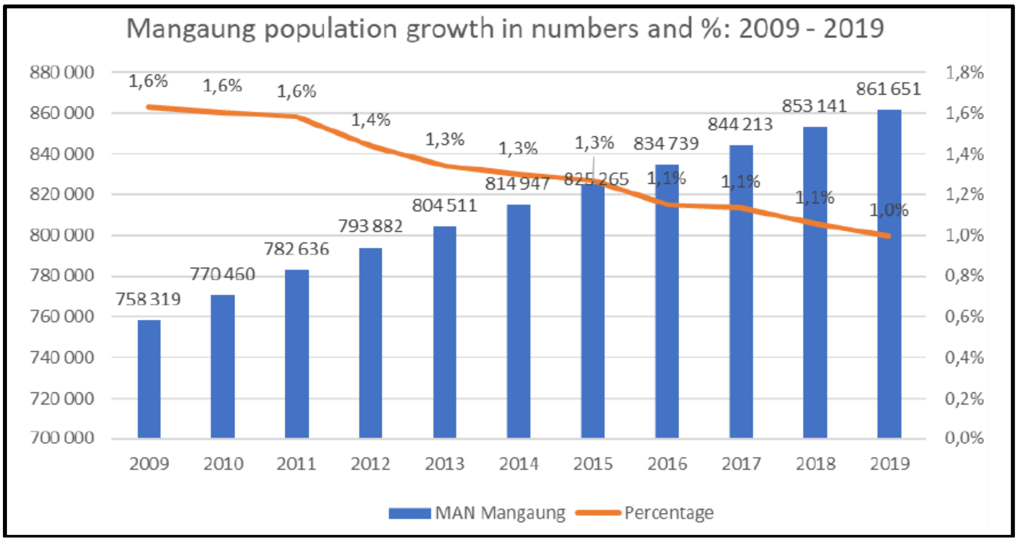


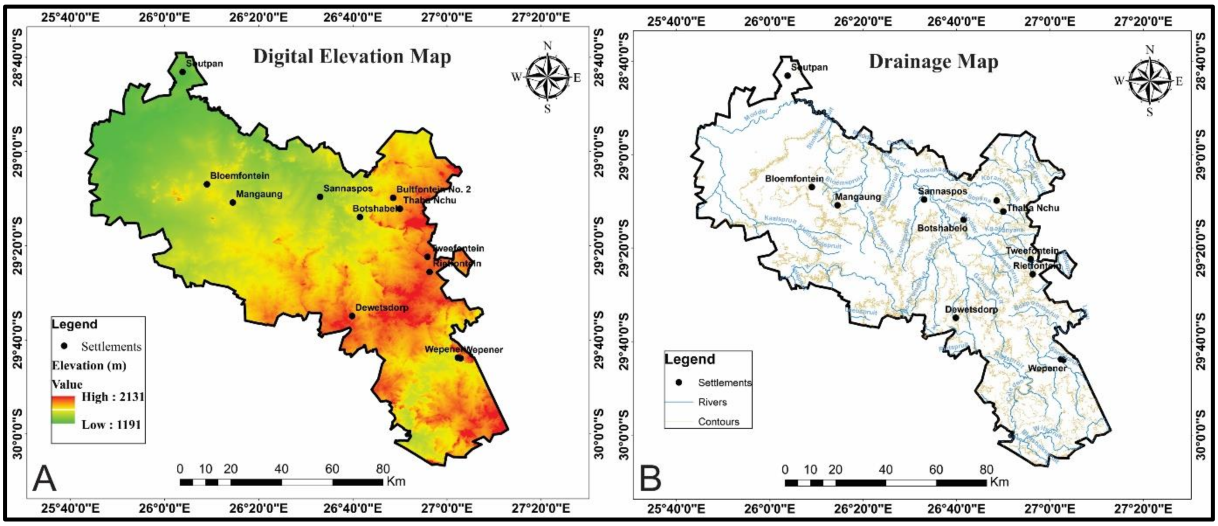
Figure 3.1: Population growth in Mangaung between 2009 and 2019

Source: Stats SA (2019)

3.2 Physiographic settings of the study area

3.2.1 Drainage and topography of the area

The topography of the area is uneven with an undulating terrain where the southern region is higher than the northern region in several places. The study area has an elevation ranging from 1 200 m to 2 200 m (Figure 3.2a). The south-eastern region of the municipality is relatively higher than the north-western region. This suggests the flow direction is SE–NW as shown in Figure 3.2a. Furthermore, the Modder River serves as a major source of water supply in the Bloemfontein, Botshabelo, and Thaba 'Nchu region.



Note: (A) Digital elevation map; (B) showing the drainage map of the area displaying major river and tributaries (Author's own, 2022).

Figure 3.2: Physiographic map of the Mangaung Metropolitan Municipality

The Digital Elevation Model (DEM) was systematically derived from high-resolution lidar and LANDSAT data. The WGS_1984_UTM zone 35S was adopted as the projected coordinate system, while GCS_WGS_1984 was used for the geographic coordinates system for the modification of the DEM map. The World Geodetic System (WGS) of 1984 is an ellipsoid and spheroid used to determine the surface shape and size of a geographic coordinate system (GCS) while the Universal Transverse Mercator (UTM) was adopted as the projected coordinate. Based on the geographic coordinate system, projected coordinates are defined on a flat, two-dimensional surface. Two parallels are used to eliminate some of the distortion of a single parallel projection in the Albers Equal Area Conic scheme (2004). From the tertiary Modder River catchment, DEM was generated for the quaternary Caledon–Modder River subcatchment covering the MMM (Figure 3.2a)

The main tributaries of the Modder River are the Kaal, Os, Doring, Renoster, Koranna, Sepane, Klein Modder, Krom, and Gannaspruit rivers (Figure 3.2b). The Modder River has its source near Dewetsdorp and flows in a north-westerly direction and then turns in a westerly direction until it joins the Riet River at Ritchie (Oke & Alowo, 2021; Seaman et al., 2001; Tetsoane, 2013). The Renosterspruit and Bloemspruit rivers run through Bloemfontein, while the Kgabanyane River and Klein-Modder River is connected to Botshabelo (Figure 3.2b). Furthermore, the Sepane River passes though Thaba 'Nchu. Also, the Dewetsdorp and Glen communities release their waste into the Rustfontein Dam and Modder River, which are further transported into the larger Modder River (Department of Environmental Affairs [DEA], 2016).

3.2.2 Climate variation, temperature, and rainfall

The study area falls within a semi-arid climate condition and the vegetation is highveld grassland (Oke & Alowo, 2021; Welderufael et al., 2013). Like other parts of South Africa, the MMM experiences four climate weather conditions: summer, winter, autumn and spring (South African Weather Service [SAWS], 2018). The summer runs between the months of December to February, while winter runs between June to August. Furthermore, autumn and spring spans through the months of March to May and September to November, respectively. The rainfall in the area varies significantly throughout the year. The wetter season stretches between August to May with an average annual rainfall of 550 mm (Dingaan & Du Preez, 2013). Consequently, the highest daily mean temperature of 31 °C (Figure 3.3) during summer and the lowest daily mean temperature of -10 °C during winter (SAWS, 2020).

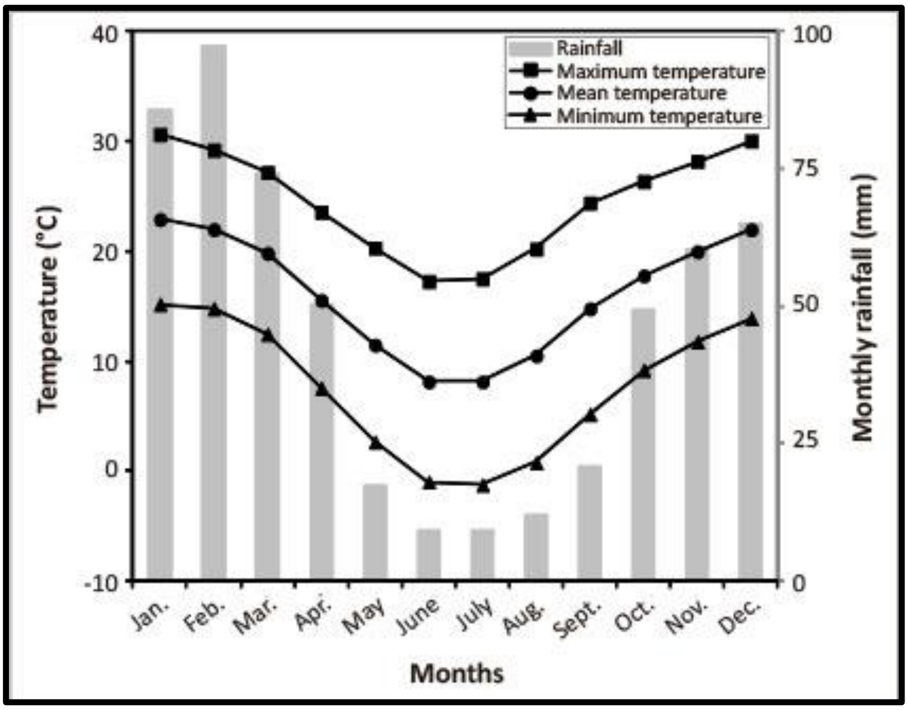


Figure 3.3: Average rainfall and temperature data of Mangaung, Free State

Source: SAWS (2020)

3.3 Geology of Mangaung Metropolitan Municipality

The Karoo Sequence rocks constitute the geology of the MMM, which is inserted into the Karoo Formation (Figure 3.4). Sedimentary rocks from the Karoo Supergroup, which were created before the Gondwana breakup, dominate the geology of the catchment (Alowo, 2021; Bicca et al., 2017). The Karoo Supergroup makes up about 66% of South Africa's land area. Throughout its history, it has preserved a succession of glacial-marine to terrestrial strata. Permo-Carboniferous (280 Ma) began and early Jurassic (100 Ma) ended this period. Up to 12 km of mixed silt were accumulated in some areas. Lesotho's basaltic magmas, which are 1,4 km thick, are the underlying layer. A retro-circular segmented basin, known as the Karoo Basin, was used to collect these specimens.

Plate assembly, subduction, and development along Gondwana's south-western Palaeo-Pacific boundary began the Late Palaeozoic Era. There is a 100 km-wide syntaxis zone in the western end of the Cape Fold Belt, which is formed by an east–west striking southern branch with north-skirting folds and a north–south striking western open folds. Ordovician-Carboniferous Cape Supergroup is where the mountain ranges are located, with an aggregate thickness of 8 000 m (Wickens, 1992).

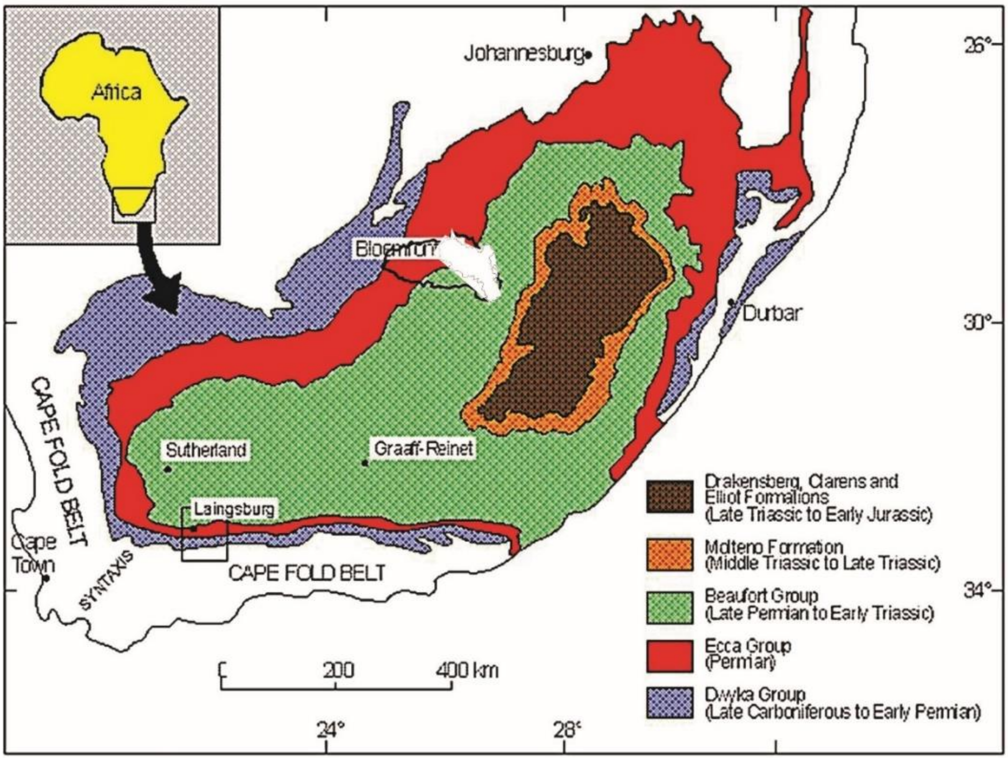


Figure 3.4: Regional geology of the Karoo Basin

Source: Modified after Alowo (2021)

3.3.1 Stratigraphy and deposition of the Karoo Basin

The stratigraphy of the Karoo Basin consists of sediment of the Ecca Group and Karoo Supergroup (Mosavel & Cole, 2019). The study area constitutes a retro-arc foreland basin, while the rest are intracratonic sag basins or rift basins. The formation of the Karoo started after a brief period of hiatus at the Cape/Karoo Supergroup border, the Karoo Supergroup was deposited. The melting water left behind a wide sea after the glacier. The Lower Ecca Group's clays and muds were gathered. Mountains to the south were raised and disintegrated due to basin deformation to the south. Due to neighbouring Cape Fold Belt thrust sheets, the basin was rapidly down-warped (Mosavel & Cole, 2019). The Cape Fold Belt syntaxis divided the Karoo Basin into the Laingsburg and Tanqua sub-basins in the southwest (Wickens, 1992). A thick submarine fan and deltaic sediment from the Upper Ecca Group filled the subbasins during deltaic progradation.

Sedimentation was outpacing subsidence throughout the Late Permian period, resulting in shallowing of the forearc. Backward succession slowed down the creation of the Beaufort Group because of its broad magnitude (Horsthemke et al., 1990). The Cape Fold Belt deposition in the Karoo Basin is lifted by the Early Triassic. The Triassic Molteno, Elliot, and Clarens Formations' fluvial, alluvial, and aeolian detritus was concentrated in a small area of the Karoo Basin (Figure 3.5). North and south of the Beaufort Group and east of the Ecca and the Dwyka Group lies the MMM (Figure 3.4).

The Transvaal Basin is home to the Rooiberg Group–Loskop Formation, which represents the final stage of volcanic evolution. At the time, most of the Kaapvaal Craton was covered by the carbonate stage of the Campbellrand–Malmani Group. In both Malmani and Campbellrand Subgroups, it is more than a kilometre thick. Dolomite and chert make up the Malmani Subgroup, which is located northwest of Johannesburg and has only minimal clastic residue.

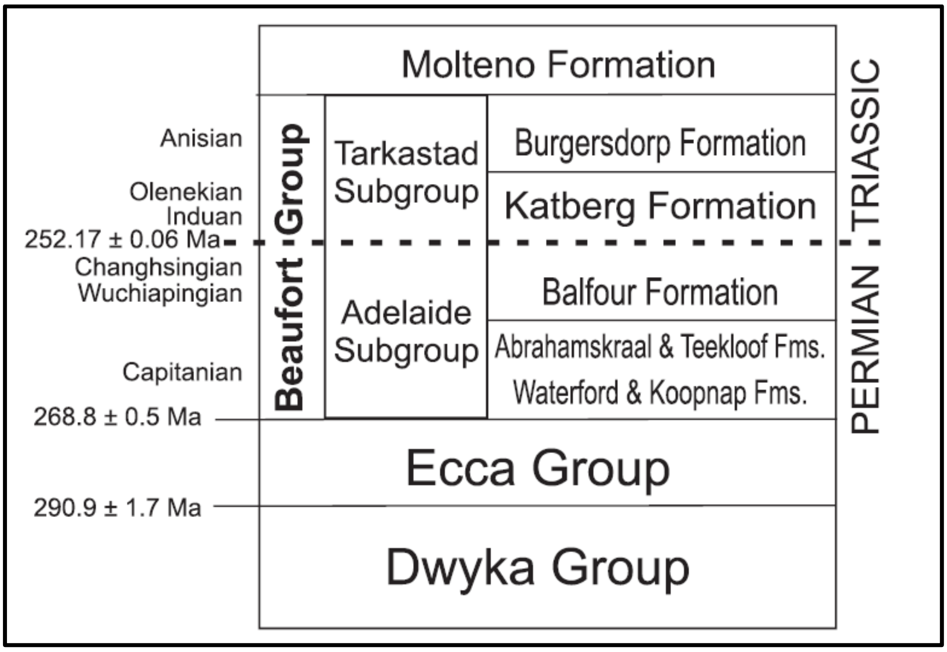


Figure 3.5: Generalised stratigraphy of the Karoo Supergroup

Source: Gastaldo et al. (2013); Stollhofen et al. (2008)

3.3.2 Local geology of the Mangaung Metropolitan Municipality

The geology of MMM consists mainly of rocks of the Karoo Sequence, intruded in places with dolerite dykes (Figures 3.6). Most of the study area has outcrops of the Beaufort Formation belonging to the Karoo Sequence. This formation consists of Intercalated Arinaceous sandstone, siltstone and Argillaceous mudstone and claystone strata in the west (Figure 3.6).

Five Karoo-aged rocks and Transvaal rocks are located in the catchment area, according to the local geology observed by various authors the available geological information pieces spanning the MMM. Figure 3.6 shows typical idealised rocks from the Beaufort, Dwyka, and Ecca Groups, as well as dolerite intrusive rocks, which are thought to be Karoo-age. Within the basin, the Karoo intrusive mafic rocks (dykes and sills) may be found, including the MMM area. The intrusive rocks are particularly visible on the north-eastern side near Bloemfontein and Wepener.

The Dwyka Group sediments consist mainly of diamictite (tillite) that is generally immense, with little jointing, which may be stratified in a few places (Woodford & Chevallier, 2002). The Ecca Group (Tierberg) consists of undifferentiated shales, with interbedded siltstone between Bloemfontein and Kimberley, while Transvaal calcareous limestone and calcarenite rocks are exposed. A small exposure of Transvaal Ventersdorp lava is found south of Kimberley.

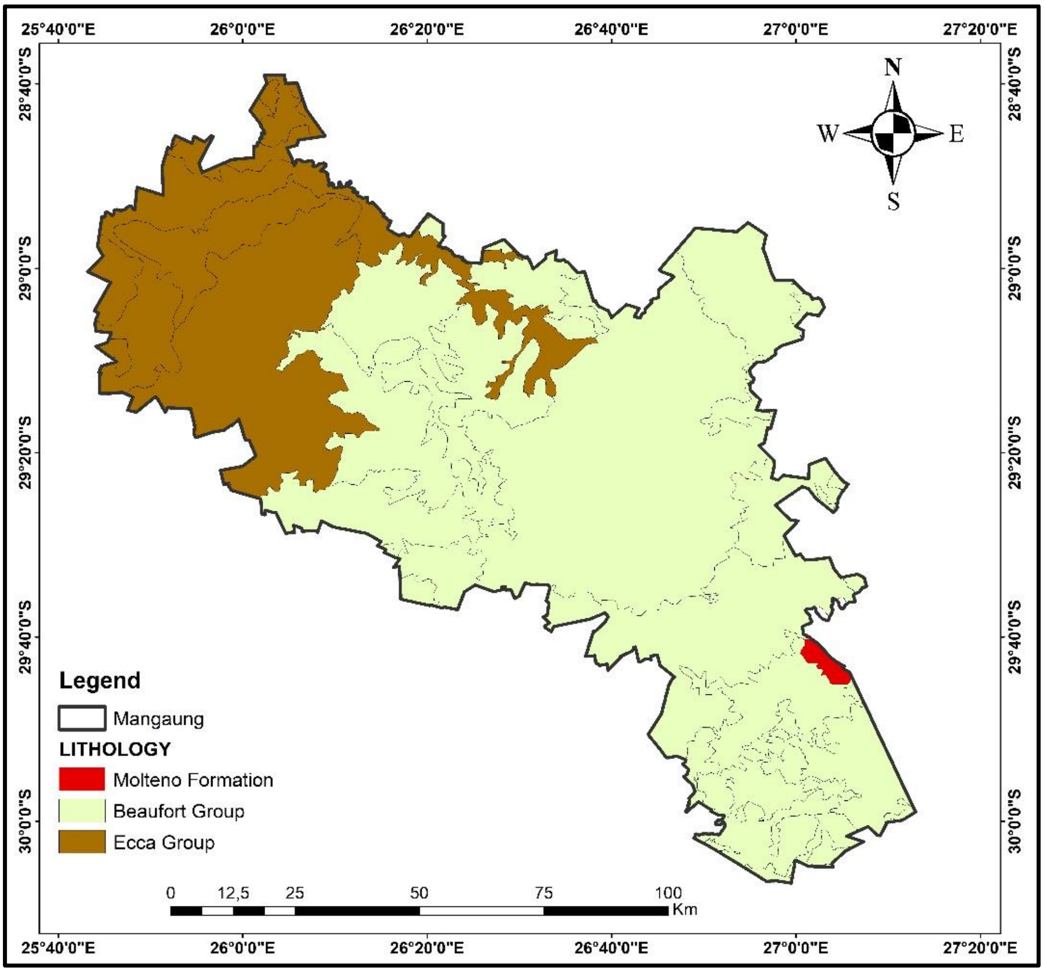


Figure 3.6: Local lithological map observed in the Mangaung Metropolitan Municipality

3.3.3 Soil characterisation of the Mangaung Metropolitan Municipality

Soil is made up of microorganisms, water, particles, and air (Sparks, 2003). The chemical interactions of soil particles and soil solution affect plant development and water quality (Vasanthavigar et al., 2010). Soil reacts chemically in several ways. These reactions impact pollutant solubility, mobility, and speciation. Adsorption of pesticides and other contaminants into soil determines their discharge into water systems.

Runoff and other external variables may determine the flow of intermediate chemicals (Erdogan et al., 2020). The texture, structure and moisture of the soil, as well as concentration of organic matter, may affect chemical leaching and runoff (Zalidis et al., 2002). As a result, harmful substances such as fertilisers and pesticides are carried by water through the soil. This filthy water eventually finds its way into streams and rivers via aquifers or erosion from land surface (Sparks, 2003). Soil in the MMM was classified using the global soil classification system of the Food and Agriculture Organization of the United Nations (FAO).

The FAO designates eight soil groups, namely Cambisol, Chernozem, Fluvisol, Gleysol, Kastanozem, Phaeozem, Umbrisol, and Vertisol as having a high inherent soil fertility. Soils in MMM vary from moderate to deep clayey loams found in the exceptionally flat central region of the MMM (Figure 3.7). In the western part of the catchment the soil has a light texture as confirmed by the Department of Water Affairs and Forestry (1999). This could be because large amounts of sediment are transported into the area by westerly winds. In the middle section, farming is mostly dairy and mixed farming with sheep farming in the south-east. Land use in the area is predominantly urban and irrigated agriculture. The land cover of the Modder River is mostly grassland (Senbore & Oke, 2021).

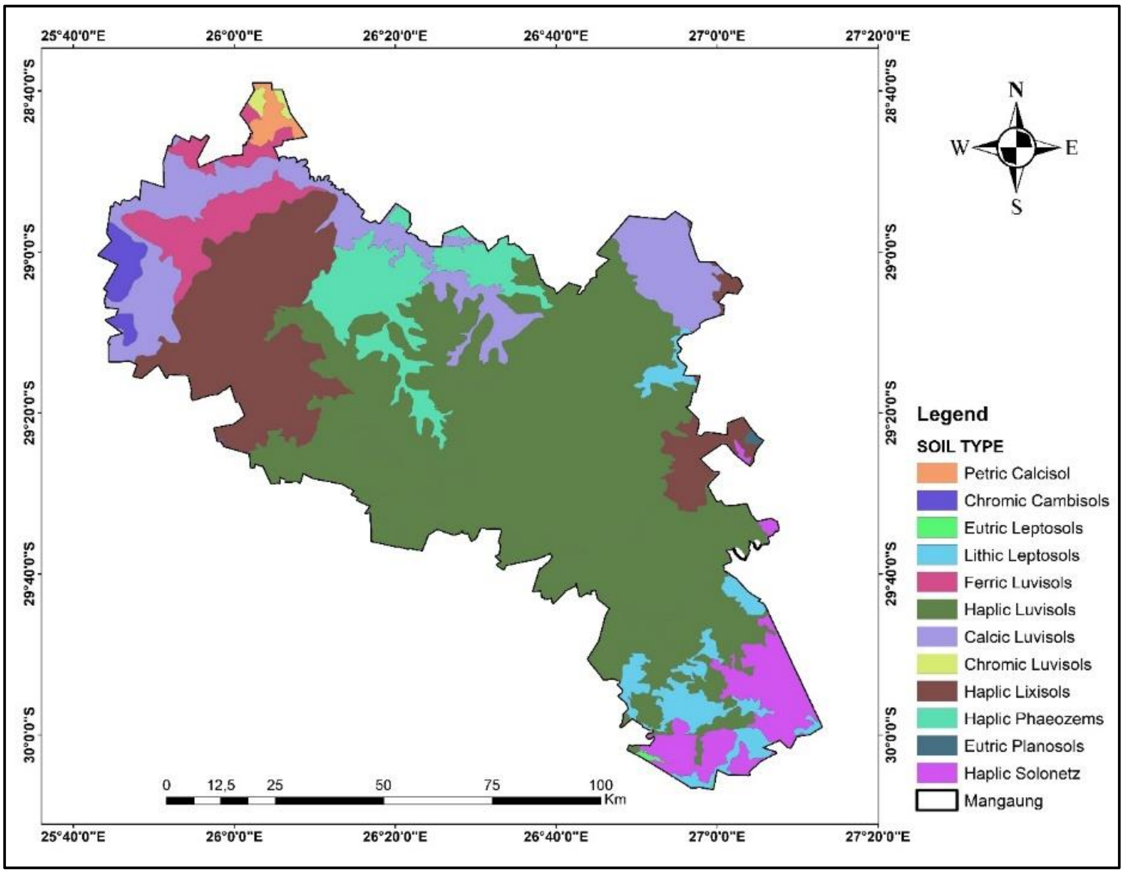


Figure 3.7: Soil classification map of the study area

Source: FAO (2020)

3.4 Hydrology and water resources of the Mangaung Metropolitan Municipality

The first step in comprehending the challenges in water quality and water provision in Mangaung is to examine the status of water resources in the MMM in relation to its climatic variability. The municipal supplied water resources in the MMM lies on the Caledon–Modder subsystem that is affected by climate variability. Assessing the effects of climate change and variability on the region is to determine the status of the hydrology and water resources available in the region. Distinct time scales have different impacts on hydrology and water resources when it comes to climate change unpredictability. A changing climate necessitates an ongoing assessment of basin hydrology and water resources to ensure their availability and quality. As a result of this, adaption and mitigation methods are recommended.

The Modder River Basin that serves the MMM is divided into three main river sections that make up the river's course: the Upper Modder, Middle Modder and Lower Modder rivers and is all referred to as the C52 catchment. Furthermore, the southern part of Mangaung lies on the Caledon River catchment which has been grouped into D23 and D24. The Mockes, Maselspoort, Rustfontein and Welbedacht dams are the largest man-made reservoirs in the municipality. It is necessary to continuously monitor and evaluate water resources in these reservoirs due to the impact of urbanisation surrounding these reservoirs that have contributed to the quality of the water and influence temporal and spatial climate variability on the locality. Water shortages in the Modder River are getting worse as a result of the consequences of climate change. Extreme weather events such as floods and droughts have occurred far more frequently in the last decade, reducing the amount of water that was available over both time and area (DWS, 2016).

In the Southern African Development Community (SADC) region at large, several economies have been negatively impacted by drought (South African Research and Documentation Centre, 2010). The consequences are well-felt and include a decrease in agricultural production as well as an increase in temperature, bad ecosystems and other environmental issues. It is possible to get detailed information on the influence of climate change on water supplies by using regional climate modelling, water availability models and projections that require an understanding of current hydrology and water resources in the study area (Ndhlovu, 2019), as well as their relationship to climatic variability.

The MMM has some water treatment plants at Maselspoort, Soutpan and Wepener that feed from the Modder and Caledon rivers. The MMM purchases 70% of its water from Bloemwater, an initiative of the DWS (Figure 3.8). The municipality and Bloemwater supply water to all the towns in the municipality (DWS, 2017).

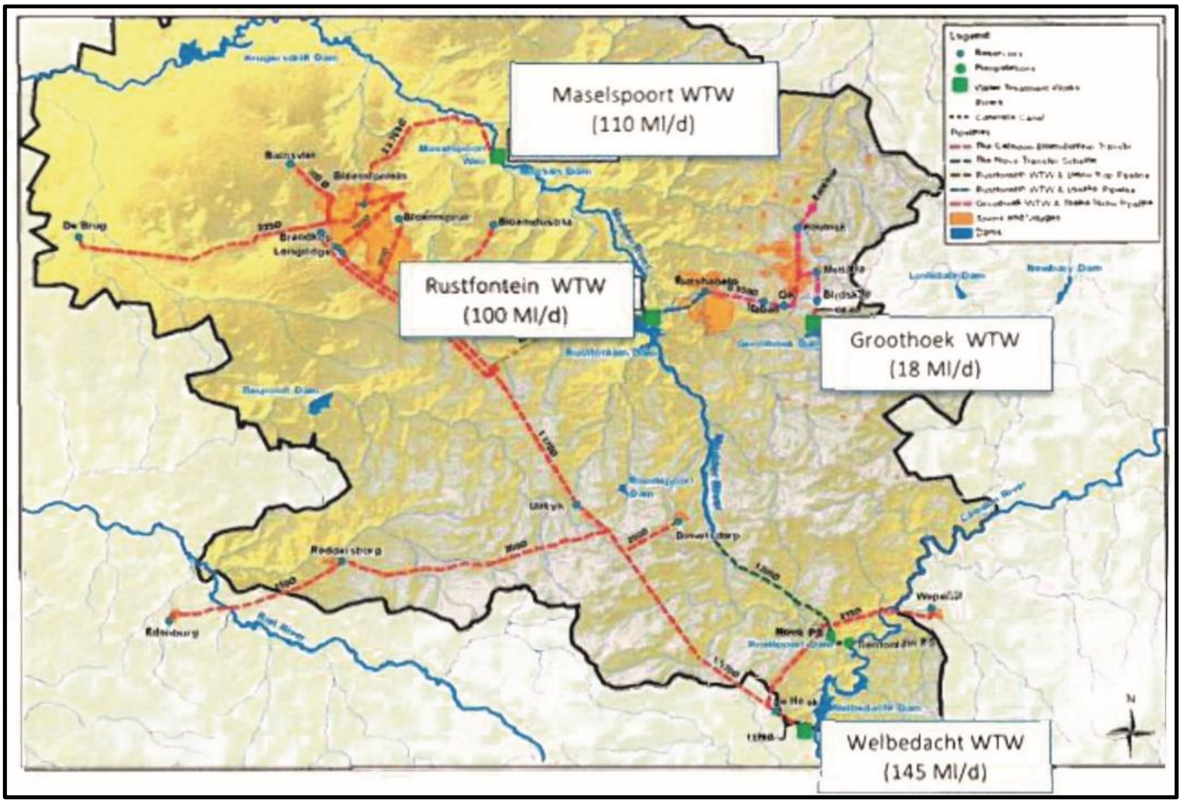


Figure 3.8:** **Water resources and infrastructure system in the Caledon–Modder River subsystem

Source: DWS (2017)

3.4.1 Catchment delineation of the Caledon–Modder river subsystem

The MMM area covers the C52, D23 and D24 subcatchment (Figure 3.9). The water in the Modder River originates in the Maluti highlands. The water supply in the upper and middle parts of the Modder River is stabilised at the Mockes and Rustfontein dams, while to the west of Bloemfontein, the river is stabilised at the Krugersdrift Dam. Figure 3.9 shows the quaternary catchment as a sub-catchment in the upper-middle orange tertiary catchment.

The watershed delineation was based on surface water morphology and zoning as nationally delineated by the DWS. Surface water sources (streams and rivers) that contribute to flows into a larger river were used to delineate the Caledon–Modder river subcatchment in this study. The study area watershed delineation took into account a variety of characteristics, including topography, elevation and river flow directions. The surface water delineation across South Africa currently defines the boundaries for various municipalities for accessibility to water.

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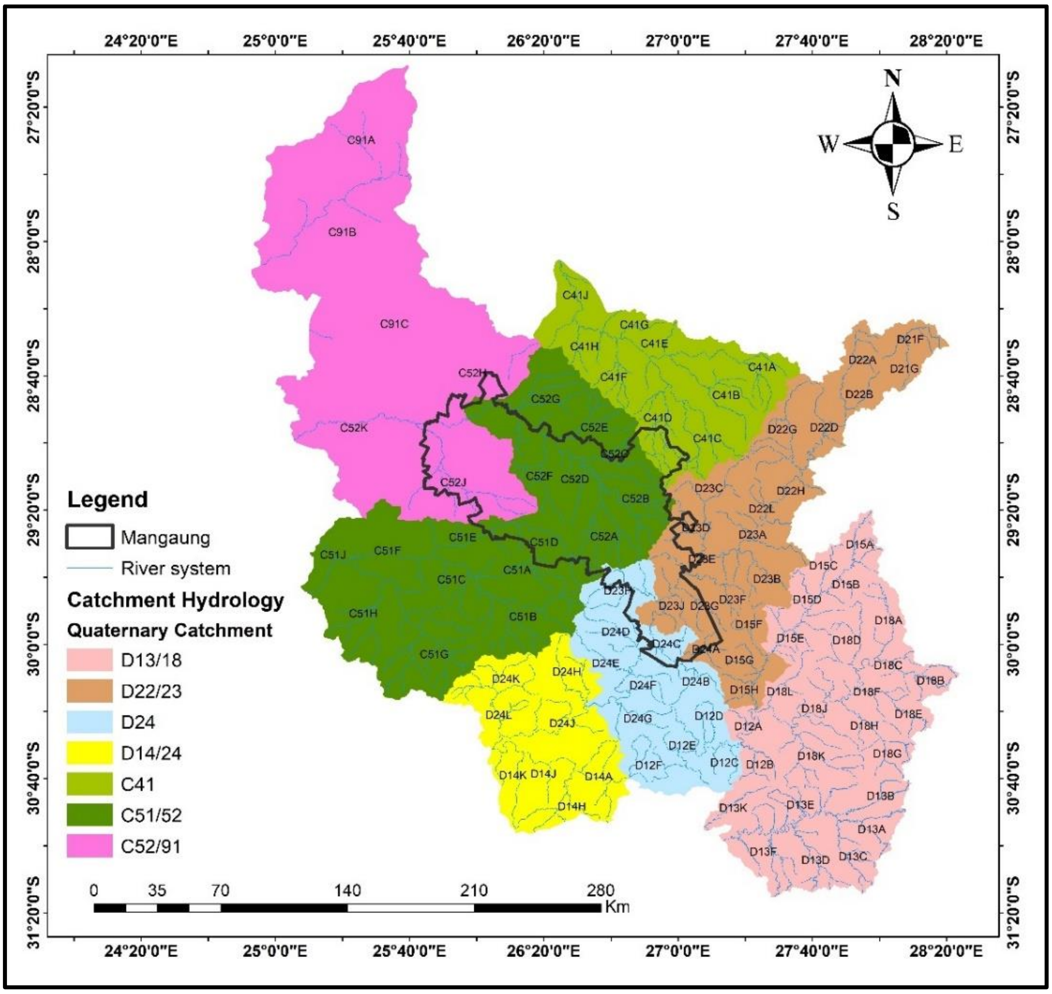

Figure 3.9: Delineation of the Caledon–Modder River catchment within the upper-middle Orange River

Source: Modified after DWA (2022)

A user-friendly ArcGIS interface makes it possible to outline a watershed catchment using several spatial discretisation strategies (Alowo 2021; Di Luzio et al., 2002, 2004; Tetsoane, 2013) and manual delineation systems. The study area was manually delineated using several ArcGIS tools for delineation of a watershed in a given study area. Delineation for the Caledon–Modder subcatchment was carried out by the process of watershed segmentation supported by the acquisition of the Southern Africa watershed shapefile and was further processed into segmentation into discrete land and channel segments, to allow for analysis of C52 watershed behaviour. The study area watershed catchments C52, D23, and D24 were delineated and digitised primarily using two methods:

- The boundaries of water streams that run downhill on a grid cell-based technique were finalised by geographic information system (GIS) techniques using the DEM, stream definition (outlet and inlet definition), as shown in Figure 3.2a.

- In manual delineation for watersheds were drawn by tapping a guide. Because of the need for precision, it necessitated only the basic details about a single control point or outlet.

The main tributaries of the Caledon–Modder subcatchment are the Kaal River, Os River, Doring River, Renosterspruit, Koranna River, Sepane River, Klein Modder River, Krom River, and Gannaspruit (Figure 3.2b). The Modder River flows in a north–west direction with its source near Dewetsdorp and then joins the Riet River at Ritchie (Oke & Alowo, 2021; Seaman et al., 2001; Tetsoane, 2013). The topography in the study area is relatively flat with elevation ranging from 1 200 m to 2 200 m (Figure 3.2a). The southeastern region of the municipality is relatively higher than the north-western region. This suggests the flow direction is south-east to north-west.

3.4.2 Water demand and adaptation in the Mangaung Metropolitan Municipality

The Department of Water and Sanitation in South Africa is responsible for the water catchment including dams and river systems (DWS, 2015). The MMM provides water to its residents in Bloemfontein, Thaba 'Nchu, Dewetsdorp, Botshabelo, Van Stadensrus, Soutpan and Wepener. The MMM water service providers are Bloemwater and Orange–Riet Water Users' Association. Bloemwater supplies water to Bloemfontein, Botshabelo, Thaba 'Nchu, Dewetsdorp and Wepener through the MMM. The MMM experienced drought in 2016 (DWS, 2016). The drought recorded in Mangaung was the most severe water challenges in the history of the MMM (DWS, 2016). The drought is caused by extreme climate weather conditions accelerated by urbanisation and environmental factors which pose a threat to water supply in the municipality. Therefore, the authorities campaigned for water savings up to 30% across major urban and suburban centres in Bloemfontein, Botshabelo and Thaba 'Nchu of up to 170 Ml per day, while Dewetsdorp up to 1.96 Ml per day, and Wepener; 0.017 million cubic metres per day. However, while the MMM was allocated 170 Ml per day to meet its water demand across the municipality, it consumed an average of 200 Ml per day (DWS, 2016). Therefore, the MMM imposed water restrictions in line with the council resolution in 2015 to combat the water situation in the MMM (DWS, 2016).

The MMM populace in recent times is grappling with accessibility to quality water supply, which is a fundamental right of the urban populace to water resources by all (South African Local Government Association, 2011). As part of the National Water Conservation and Demand Management Programme, the MMM has developed a campaign to educate the public on various water conservation topics. To this end, the populace was encouraged to install more efficient plumbing items, such as shower heads, dual flush toilets, and drip irrigation systems in their homes and gardens to reduce water consumption (DWS, 2016).

3.5 Climate variability in Mangaung Metropolitan Municipality

The MMM lies in the semi-arid climate condition in the southern region of Africa (Oke & Alowo, 2021). MMM experiences four climate weather conditions, namely summer, winter, autumn, and spring (SAWS, 2018). Daily weather data, such as measured precipitation, humidity, maximum temperature, and minimum temperature data for a 40-year period (1978 to 2018) were obtained from the SAWS. In this study, global weather data by the National Aeronautics and Space Administration Weather Service was used to generate various weather parameters to patch areas where data was missing.

3.5.1 Rainfall

The rainfall in the area varied significantly throughout the 40-year period, with the highest amount of rainfall in 1978. The mean average rainfall of 720 mm was recorded in 1978 and 419 mm in 2018. Quantitative estimation of the rainfall spatial distribution within the MMM is presented in Figure 3.10. The rainfall data is an important climate data in environmental and climate variation monitoring. This importance of rainfall monitoring includes hydrologic modelling, flood forecasting, water resources management, climate change evaluation, water balance, soil moisture modelling for crop production and irrigation scheduling (Basistha et al., 2008).

The rainfall data in MMM is captured by rain gauge stations spread all over the Caledon–Modder subcatchments. The assessment of the average annual rainfall over an area at several measuring stations is an important phase in climatic variation measurement (Bastin et al., 1984; Chua & Bras, 1982; Pardo-Igúzquiza, 1998). Dirks et al. (1998) reported that problems facing meteorologists and hydrologists studying spatial rainfall patterns are the interpolation of data from irregularly spaced rain gauges in order to characterise rainfall variability within a catchment. Different interpolation methods and applications exist in the literature (Basistha et al., 2008; Bargaoui & Chebbi, 2009; Dirks et al., 1998; Ruelland et al., 2008; Wilk et al., 2006). In this study, an inverse distance weighted and Kriging interpolation method were employed for the study of the spatial rainfall in the MMM.

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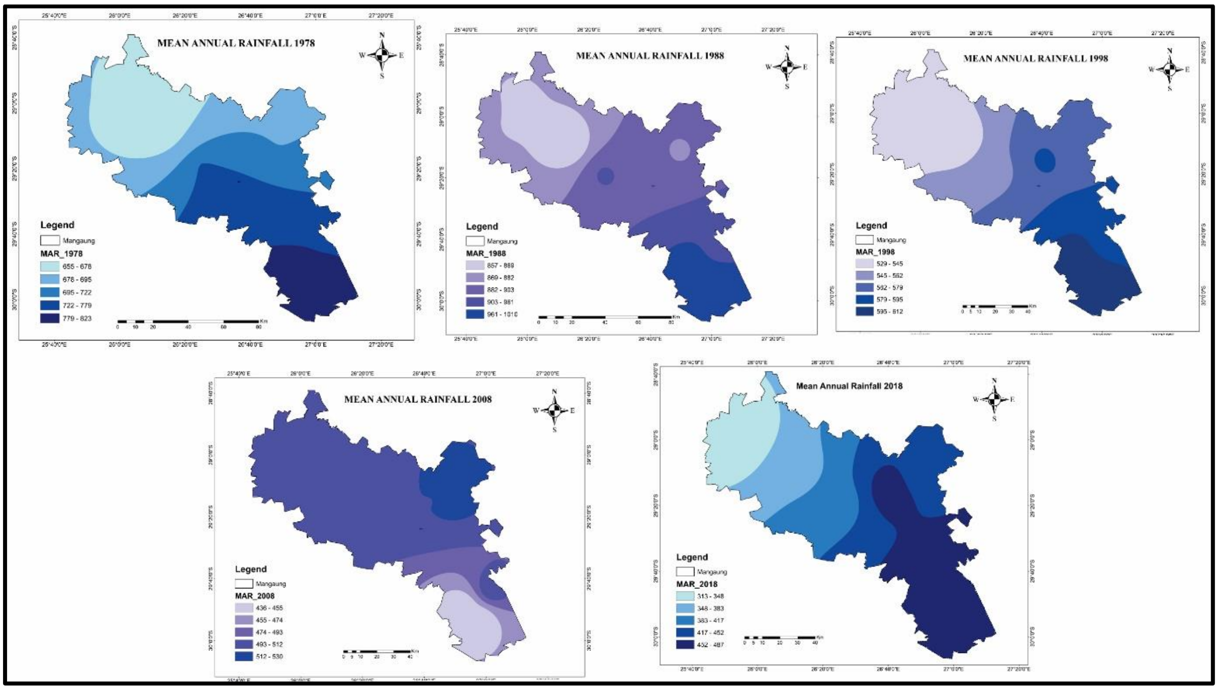

Figure 3.10: ***Spatial annual precipitation map of Mangaung Metropolitan Municipality for the period 1978–2018***

3.5.2 Temperature and evapotranspiration

The temperature differs significantly across the MMM, which lies in the Caledon–Modder subcatchment in accordance with topography. The coldest months are from June to July, with mean monthly temperatures of less than 14 °C, while January is the hottest month with mean daily temperatures of 31 °C. Temperature is higher in the southern part of the Mangaung. Consequently, the highest daily mean temperature of 37 °C during summer and the lowest daily mean temperature of -10 °C during winter was observed (SAWS, 2020).

The Potential Evapotranspiration (P_{ET}) also varied considerably across the study area from more than 1 700 mm in 1978 to 1 400 mm in 2018 (Figure 3.11). The P_{ET} in the Caledon–Modder subcatchment was higher in 2018 as against the precipitation in 2018. However, the temperature was higher in 2018, which could give rise to the increase in evapotranspiration. This scenario may give rise to water loss in the study area (Ndhlovu, 2019; Southern African News Features, 2015).

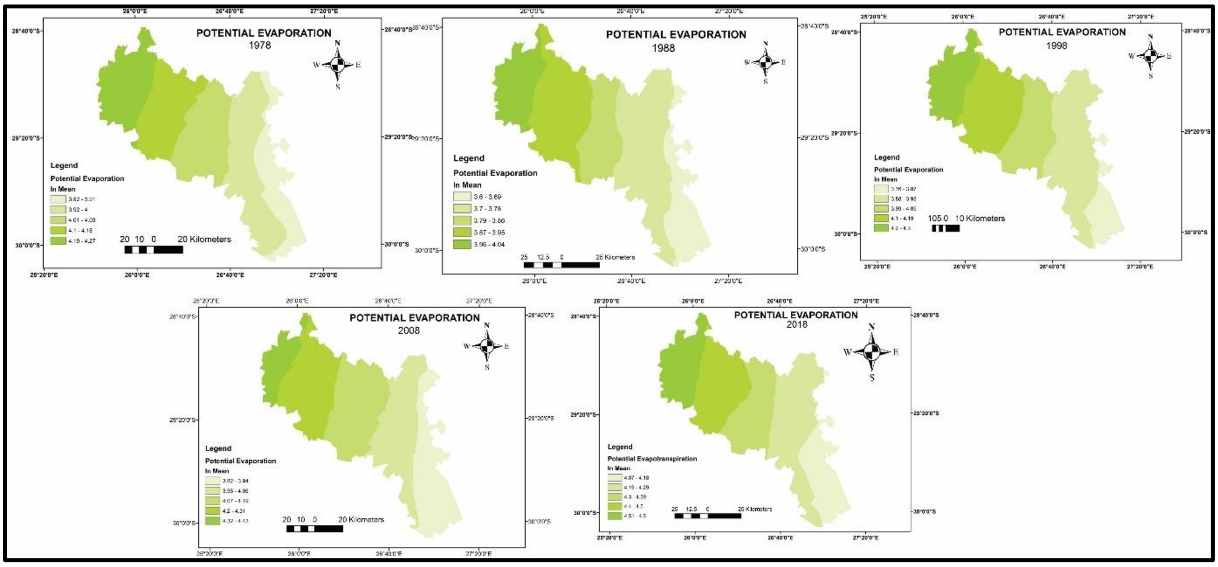

Figure 3.11: Spatial annual potential evapotranspiration map of the Mangaung Metropolitan Municipality for the period 1978–2018

3.5.3 Humidity and cloud cover

Another characteristic of the weather that cannot be seen but can be felt is humidity. Humidity has a substantial impact on weather conditions, but it also affects our environmental health in diverse ways. During the 40-year period observed in this study, the highest annual average relative humidity was recorded in 1988, while the lowest annual relative humidity was in 2018. It was observed that the highest yearly average rainfall values correspond with the highest relative humidity values on a comparative scale. High relative humidity provides a moist environment and favours increase in insect pests and diseases. Generally, across the study area, a decline in mean relative humidity was observed during the 40-year period of data investigated. For instance a decrease in relative humidity would increase the growth of leaf miners.

It is no secret that clouds are an excellent indicator of both the current weather conditions and future conditions for a healthy environmental assessment. Using scientific instruments to dig deeper and get a better sense of the current and historical air conditions, was quite beneficial in this study to understand the environmental health conditions of the MMM. The highest and lowest mean cloud cover in 1978 were 36.15 and 27.81, while the highest and lowest mean cloud cover in 2018 were 93.25 and 61.21, respectively (Figure 3.12). The cloud cover represents a proportion of the indoor and outdoor dust and other atmospheric pollutants in this study. This study revealed a high concentration of cloudiness in 2018 as compared to the cloudiness recorded in 1978. The high concentration of cloud cover was attributed to the rapid urban growth, thus and increase in transport activities, road dust and other emissions generated from households and industries.

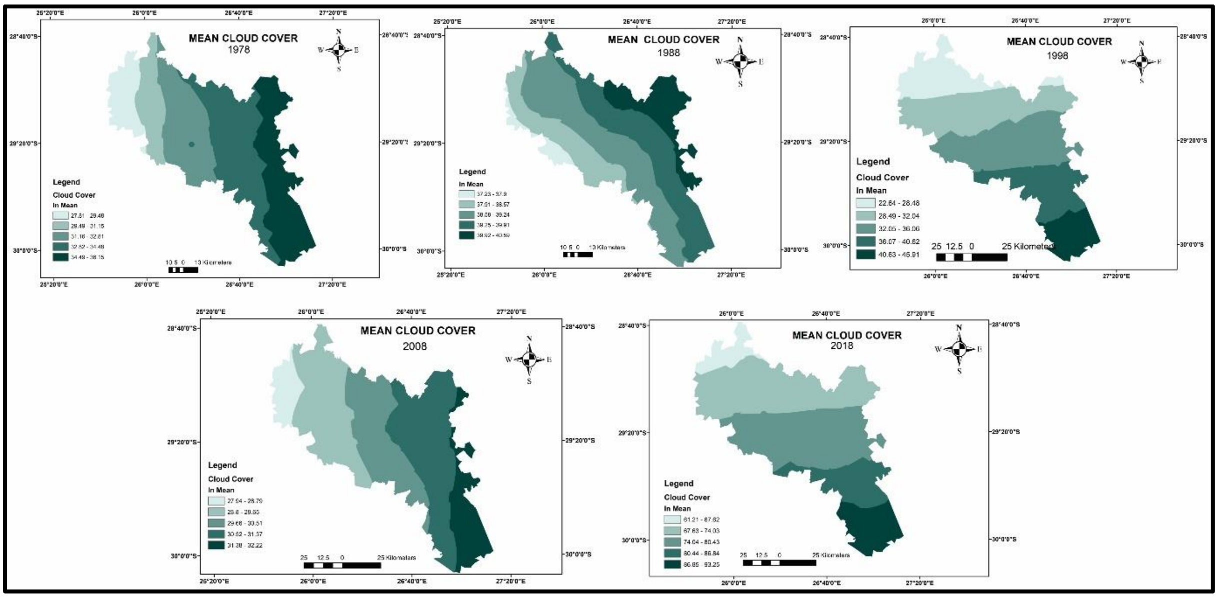

Figure 3.12: ***Spatial annual cloud cover map of Mangaung Metropolitan Municipality for the period 1978–2018***

Chapter 4

ENVIRONMENTAL HEALTH SUSTAINABILITY ASSESSMENT PROCEDURE

4.1 Introduction

This section provides the scientific approach employed in this research to investigate the impact of urban development on water sources and environmental health sustainability in the MMM. Land use / land cover (LULC) classification using remote sensing and GIS techniques, historical water quality data, and other parameters of climate variability were analysed. Furthermore, an analytical and statistical study pertinent to urban development and environmental sustainability was carried out. Historical land use data and hydrologic information with long-term water quality data were investigated. Finally, the UHS model was developed to determine the current impact of urban growth and to predict the future impact of urbanisation on environmental health sustainability of the MMM.

4.2 Remote sensing and geographic information systems

Remotely-sensed Landsat images of the MMM for the years 1978 to 2018 were acquired on the United States Geological Survey (USGS) Earth Explorer system (Figure 4.1). The Landsat satellite imagery was used because of its improved radiometric precision that better characterised land cover images (USGS, 2019).

The study of LULC mapping, urban density and the urban development effect on an environmental ecosystem over time intervals, were deduced using remote sensing and GIS in this study. Spatial data from remote sensing provided timely, reliable, and accurate information on vegetation, water, built-up areas at chosen intervals for environmental monitoring and management (Ahmad, 2013; Chen & Wang, 2017; Orimoloye et al., 2018; Sansare & Mhaske, 2020). For this study, a Landsat sensor with Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced TM Plus (ETM+), and Landsat-8 Operational Land Imager provided various satellite data that played a significant role in detecting changes in LULC, Normalised Difference Water Index (NDWI), Normalised Difference Vegetation Index (NDVI), Normalised Difference Moisture Index (NDMI) and Normalised Difference Built-up Index (NDBI) from 1978 to 2018 in the MMM. Furthermore, the shapefile map of the MMM was adopted from the database of the Department of Environmental Affairs. The dataset and its descriptions are summarised in Table 4.1.

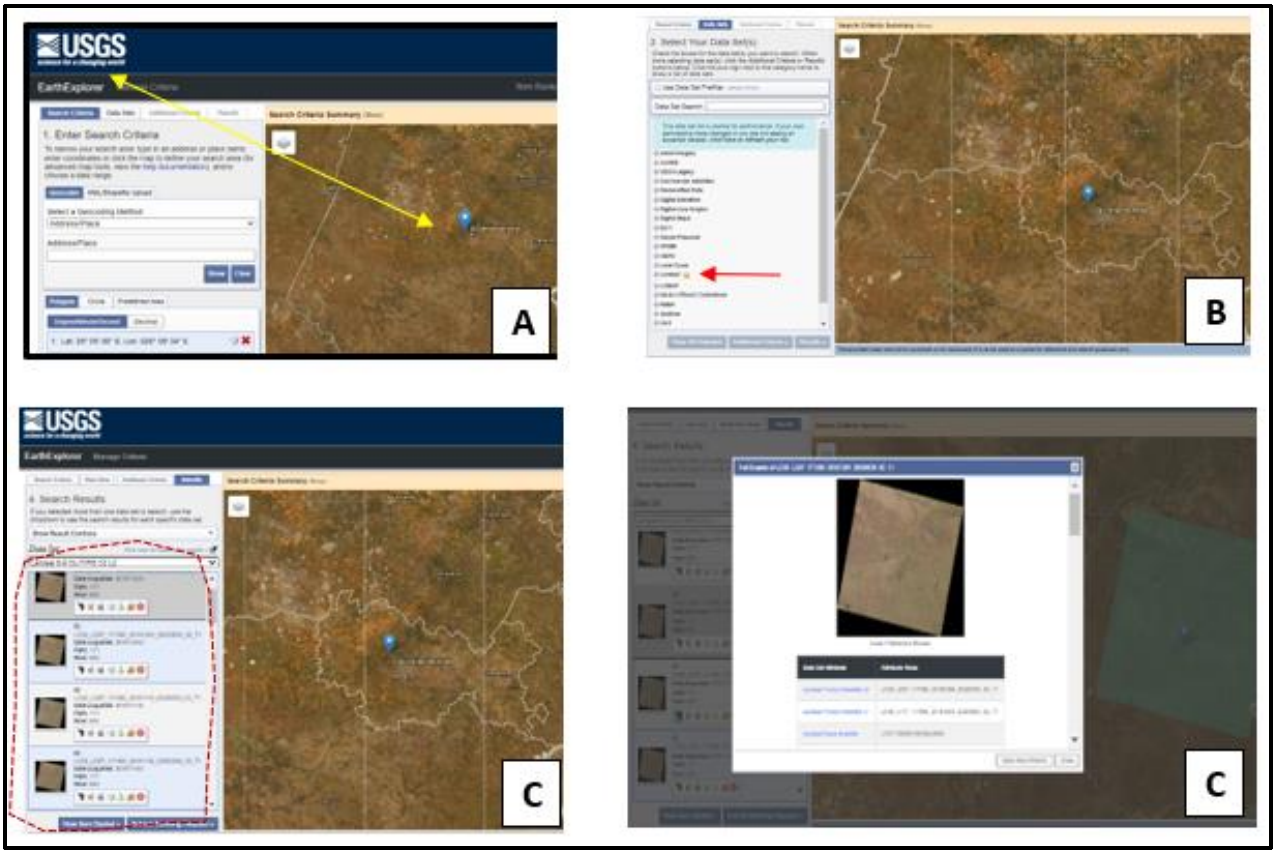

Figure 4.1: Methodical acquisition of Landsat data from the USGS Earth Explorer System

Table 4.1: Description of remote sensing/GIS datasets and their characteristics

Satellite imagery	Sensor	Path/Row	Resolution (m)	Date of acquisition	Cloud cover
Landsat	Thematic Mapper	182/080 182/081	30	1978-06-17 1978-06-17	1.0
Landsat 4	Thematic Mapper	170/080 170/081 171/080	30	1988-03-21 1988-03-21 1988-03-28	14.0
Landsat 5	Thematic Mapper	170/081 171/080	30	1998-11-04 1998-11-04	0.0
Landsat 7	Enhanced Thematic Mapper Plus	170/081 171/080	30	2008-01-08 2008-01-31	23.0 0.0
Landsat 8	Operational Land Imager and Thermal Infrared Sensor	170/081 171/080	30	2018-12-13 2018-12-20	6.12 0.01
Shapefile of the study area	Digital Map				

4.2.1 NDVI and NDWI characterisation

The NDVI was used in the MMM to assess the level of environmental degradation, focusing on vegetation and biodiversity. The NDVI is given as follows:

$$NDVI = \frac{NIR - Red}{NIR + Red} \qquad \textit{Equation 12}$$

Where NIR is near infrared and R is red.

Negative values simply refer to areas without healthy vegetation. For the Landsat TM 1978 and Landsat ETM+ 2008, Bands 4 and 3 were imputed as NIR and R bands, respectively. For Landsat 8, Bands 5 and 4 were imputed as NIR and R bands, respectively. NDVI is an imagery presentation used to evaluate the healthiness of vegetation. In general, values ranging between (−1) correspond to water (−0.1 to 0.1) correspond to barren areas of rock and sand. Furthermore, low, positive values represent shrub and grassland (0.2 to 0.4), while high values indicate temperate and tropical rainforests (values approaching 1).

In this study, the vegetation cover was identified from each of the years using the polygon tool. The polygon shapefile was used to extract the vegetation from the composite of each year. Likewise, the extracted features were analysed using the NDVI in ArcGIS 10.7. Band 4 (NIR band) and Band 3 (Red band) were used in computing the NDVI for Landsat TM and Landsat ETM+, while Band 5 (NIR band) and Band 4 (red band) were used to compute the NDVI for Landsat 8.

Furthermore, NDWI measures the change in water content by using the near infrared (NIR) and the short-wave infrared (SWIR) bands. This is because NDWI is sensitive to water content of plants as well as bodies of water, it is often used for drought monitoring, recording yield reductions, and reservoir discharge. The NDWI makes use of the reflected near-infrared radiation and visible green light was used to provide estimations on available surface water in the study area. The NDWI uses the formula in Equation 14:

$$NDWI = \frac{Green - NIR}{Green + NIR} \qquad \textit{Equation 13}$$

Values for waterbodies are larger than 0.5. Vegetation has much smaller values, which makes distinguishing between vegetation and waterbodies easier. Built-up features have positive values between zero and 0.2 (Sentinel-hub, 2018).

4.2.2 Normalised Difference Moisture Index

The NDMI is used to determine vegetation water content (USGS, 2021). It is calculated as a ratio between the NIR and SWIR values in traditional fashion (Wilson & Sader, 2002). The NDMI is sensitive to the moisture levels in vegetation. It is used to monitor droughts as well as monitor fuel levels in fire-prone areas.

$$NDMI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$ *Equation 14*

4.2.3 Normalised Difference Built-up Index

Landsat satellite images are used in this study to analyse the built-up area of the Mangaung municipality (Table 4.1). Landsat images were collected from the USGS Earth Explorer, and Bands 5, 6 and 7 were stacked to form "false colour composite image". The standard false colour composite band distinguished various land covers such as built-up, water, vegetation and barren land. The minimum, maximum and standard deviation of each of the covers examined in the seven TM bands confirmed that these values are most distinctive from one another. Therefore, Bands 4 and 5 were the most useful bands in deducing a built-up index of an area using Landsat images. The NDBI is given in Equation 15:

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$ *Equation 15*

Where:

SWIR = short-wave infrared band and

NIR = near-infrared band

Furthermore, the built-up area in this research were identified by using Equation 16.

$$Builtup\ area = NDBI - NDVI$$ *Equation 16*

4.3 Sampling and hydrochemical data processing

Hydrochemical monitoring data for the major water in MMM was acquired from the Department of Water and Sanitation (DWS, 2020) for the years 1978, 1988, 1998, 2008 and 2018. The purpose of the specific chosen years of data is to cover a 40-year period with intervals of 10 years, which gives better clarity in long-term changes in the water quality in the MMM. The monitoring stations for this study lay in the C52, D23 and D24 water catchment of South Africa (Table 4.2). The hydrochemical data was sorted and compared to the South African National Standard for water quality (SANS 241, 2015). The physicochemical data for

1978, 1988, 1998, 2008 and 2018, collected across the municipal area, were studied for hydrochemical characterisation, water quality and health risk assessment. Furthermore, site visits were conducted across the study area to check the current physical parameters of the rivers and dams along the river systems. In addition, ground truthing was established to validate the GIS and remote sensing analysis.

Table 4.2: Sampling stations along the Modder River C52, D23 and D24 catchment

Selected site on Caledon–Modder River catchment	Catchment	Description of location and land use types	Longitude (East)	Latitude (South)
Rustfontein	C52	Urban, wastewater from Thaba 'Nchu	26° 36’ 57.9’’ E	29° 16’16.6’’ S
Maselspoort	C52	Urban, wastewater from Bloemfontein City	26° 24’ 29.9’’ E	29° 01’45.0’’ S
Mockes Dam	C52	Urban, wastewater from Bloemfontein	26° 27’ 42.0’’ E	29° 03’ 02.0’’ S
Likatlong	C52	Agricultural wastewater	26° 34’ 23.9’’ E	29° 09’ 37.0’’ S
Renosterspruit @ Bishop Glen	C52	Residential and agricultural wastewater	26° 20’ 30.9’’ E	28° 59’ 04.9’’ S
Renosterspruit @ Shannon Valley	C52	Residential wastewater from Heidedal	26° 19’ 05.0’’ E	29° 08’ 39.9’’ S
Krugersdrift Dam	C52	Residential and agricultural wastewater from Soutpan	25° 57’ 01.0’’ E	28° 52’ 59.9’’ S
Stoomhoek	C52		26° 06’ 43.9’’ E	28° 48’ 27.0’’ S
Kgabanyane River	C52	Residential and agricultural wastewater from Bothsabelo	26° 55’ 43.9’’ E	29° 17’ 08.0’’ S
Cypress 89	C52		26° 19’ 15.5’’ E	28° 56’ 56.7’’ S
Welbedacht Dam	D24	Residential and agricultural wastewater	26° 51’ 38.0’’ E	29° 54’ 32.0’’ S
Rietspruit	D23		26° 53’ 20.9’’ E	29° 46’ 52.6’’ S

Figure 4.2: Water sampling and ground truthing of GIS analysis by student researcher

4.3.1 Hydrochemical characterisation

The geochemical source of water can be denoted by representing the concentration of cations and anions in the Piper trilinear and other relative diagrams. The historical hydrochemical data obtained were processed and analysed using Grapher geochemical software and then statistical analysis using SPSS software. The Piper diagram is a multi-layered plot where milliequivalents percentage concentrations of anions (HCO^{3-}, SO_4^{2-}, and Cl^-), and major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) are plotted on a trilinear diagram. On the other hand, the Gibb's diagram is the ratio of $Cl/(Cl+HCO_3)$ and $Na/(Na+Ca)$ as a function of total dissolved solids (TDS). This has been used by several researchers to measure the functional sources of dissolved chemicals such as precipitation, rocks and evaporation (Gibbs, 1970; Narsimha & Sudarshan, 2018). Anion and cation plots are used to decipher factors controlling water chemistry in this study. In order to determine the source rocks that contribute to the ionic components of the water, three parameters were taken into account in terms of TDS variation, as shown in Table 4.3.

Table 4.3: Ionic components defining source rock deduction

Serial number	Total dissolved solids (mg/l)	Source: Rocks
1	>500	Carbonate
2	<500	Silicate

Ionic ratios using Equations 17 and 18 were further used to predict a weathering dominance sources.

$$\frac{(Na + K - Cl)}{(Na + K - Cl + Ca)} \qquad \textit{Equation 17}$$

$$\frac{(Na)}{(Na + Cl)} \qquad \textit{Equation 18}$$

Where the results obtained from Equation 17 are > 0.2 and < 0.8, the plagioclase weathering can be concluded; however, if < 0.2 or > 0.8, then plagioclase weathering is unlikely (Adewumi & Laniyan, 2020; Oke, 2015). In addition, for Equation 18, if the ratio is > 0.5, a sodium source other than halite, albite and ionic exchange can be inferred; if it is equal to 0.5, halite solution is inferred. If it is < 0.5 with a TDS value of > 500 mg/l, then a reverse softening can be inferred. When it is < 0.5, with a TDS value of < 500 mg/l, an analysis error can be inferred. If it is < 0.5, with a TDS value of less than 50, then rainwater can be deduced.

4.3.2 Water Quality Index

The water quality index (WQI) was calculated following the SANS and drinking water quality standard recommended by the WHO. In this study, thirteen water parameters were chosen for the calculation of the water quality index. These parameters are physical parameters of pH, TDS and electrical conductivity (EC). Anions included Cl, F, NO_3, PO_4, SO_4 and HCO_3, while cations used are Ca, K, Mg and Na. Furthermore, index score and class were derived from Banda and Kumarasamy (2020) in Equation 19. The description of the index scores is given in Table 4.4.

$$WQI = \frac{1}{100}\left[\sum_{i=1}^{n}\right] f(S_i)W_i \quad \text{Equation 19}$$

Where:

WQI = the water quality index;

S_i = the sub-index value of the i^{th} water quality parameter;

W_i = the weight coefficient value of the i^{th} water parameter;

1 = the sum of all coefficients (w1 + w2 + w3 + … + wn = 1); and

n = the total number of sub-indices i.e., n = 13.

Table 4.4: Index score classification for the water quality index

Rating	Score	Description of rank and classification	Water quality status
1	<25	Water quality is protected with absence of threat	Excellent
2	25–50	Water quality is protected with a minor degree of threat	Good
3	50–75	Water quality is protected but recurrently threatened	Poor
4	75–100	Water quality is always threatened	Undesirable

4.3.3 Hydrochemical assessment for irrigation

The concentration of soluble salts in water determines its quality for irrigation (Ajala et al., 2016; Erdogan et al., 2020). The sodium adsorption ratio (SAR), Kelly ratio (KR), magnesium adsorption ratio (MAR), and soluble sodium percentage (SSP) were used to calculate the salinity of the water in this study. For the purpose of the irrigation water quality assessment, Equations 20–24 were considered to assess water quality for irrigation in the study (Erdogan et al., 2020; Jacobs et al., 2020; Krapivin et al., 2019; Todd 2001; Van Koppen et al., 2020). The score for SAR, SSP, KR and MAR is presented in Tables 4.5 to 4.8.

$$SAR = \frac{\mathrm{NA}}{\sqrt{\mathrm{Ca + Mg}/2}} \quad \text{Equation 20}$$

$$\%N = \frac{(Na^{+} + K^{+}) \text{ X } 100}{(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})} \quad \text{Equation 21}$$

$$KR = \frac{Na^{+}}{(Ca^{2+} + Mg^{2+})} \quad \text{Equation 22}$$

$$SSP = \frac{(Na^{+} + K^{+})}{(K^{+} + Na^{+} + Ca^{2+} + Mg^{+})} \times 100 \quad \text{Equation 23}$$

$$MAR = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100$$ *Equation 24*

NB: All ionic concentrations are expressed in mEq/l.

Table 4.5: Irrigation water quality classification based on sodium adsorption ratio

SAR class	Quality index
>26	Unsuitable
18–26	Fair
10–18	Good
0–10	Excellent

Table 4.6: Irrigation water quality classification based on sodium adsorption percentage

SSP class	Quality index
>80	Unsuitable
60–80	Fair
40–60	Permissible
20–40	Good
<20	Excellent

Table 4.7: Irrigation water quality classification based on Kelly ratio

KR class	Quality index
>1.0	Unsuitable
<1.0	Suitable

Table 4.8: Irrigation water quality classification based on magnesium adsorption ratio

MAR class	Quality index
>50	Unsafe
<50	Safe

4.3.4 Human health risk assessment

The human health risk assessment is characterised on the risk level concentration by carcinogenic and non-carcinogenic health factors (USEPA, 2009). Dermal contact and oral exposure were measured in this study. Furthermore, the average daily intake of toxic elements were evaluated using existing models by USEPA (1989) and Wu et al. (2013).

$$ADI_{oral} = \frac{(CW \times IR \times EF \times ED)}{(BW \times AT)}$$ *Equation 25*

$$ADI_{Dermal} = \frac{(CW \times SA \times Kp \times ET \times EF \times ED \times CF)}{(BW \times AT)}$$ *Equation 26*

Where:

ADI_{Oral} and ADI_{Dermal} is the exposure dose (mg/kg/day), via oral ingestion and dermal contact, which is calculated using the parameters presented in Table 4.8.

Furthermore, to evaluate the non-carcinogenic health risk for exposure to contaminants, risk quotient (RQ) was also calculated for both oral ingestion and dermal contact, according to USEPA (1989) and the WHO (2016). If the range of RQ > 1, there is an unacceptable risk of adverse non-carcinogenic effects on human health, while if the RQ is < 1, it was considered an acceptable level (Giri & Singh, 2015; Houtman et al., 2014; Jiang et al., 2014; USEPA, 2001; WHO, 2016).

RQ can be determined by using Equation 27:

$$RQ = \frac{ADI}{RfD}$$ *Equation 27*

where *RfD* is the reference dose of a specific contaminant (mg/kg/day) of NO_3 considered from a risk-based concentration table (WHO, 2016).

Finally, to observe the overall potential of non-carcinogenic impact on human health, the RQs calculated for each chemical were summed and expressed as Hazard Index (HI) (USEPA, 1989; WHO, 2016), which is represented in Equation 28:

$$HI = RQ_1 + RQ_2 + \cdots + RQ_n$$ *Equation 28*

Where HI value does not exceed unity, i.e. (HI < 1), no health risks were assumed and if HI > 1, it thus implies non-carcinogenic health risk (Bodrud-Doza et al., 2020; USEPA, 1989; Yang et al., 2012).

Table 4.9: Parameters for exposure assessment through oral ingestion and dermal absorption

Parameters	Unit	Oral values	Dermal values
ADI (Average daily intake)	mg/kg/day	–	–
CW (Concentration of metal in water)	Mg/l	–	–
IR (Ingestion rate)	Litre per day	2.2 (Adult) 1 (Child)	–
EF (Exposure frequency)	Days/Year	365	350
ED (Exposure duration)	Year	70 (Adult) 10 (Child)	30 (Adult) 6 (Child)
ET (Exposure time)	Hour per event	–	0.58 (Adult) 1.0 (Child)

Parameters	Unit	Oral values	Dermal values
BW (Body weight)	Kg	70 (Adult) 25 (Child)	70 (Adult) 25 (Child)
AT (Average time)	Days	25 550 (Adult) 3 650 (Child)	Noncarcinogenic effects ED × 365 = 10 950 (Adult) 2 190 (Child) Carcinogenic effects: AT = 70 × 365 = 25 550
SA (Skin–surface area)	cm^2	–	18 000 (Adult) 6 600 (Child)
K_p (Permeability coefficient)	cm/hr	–	1×10^{-3} (Fe), 1×10^{-3} (Mn), 6×10^{-4} (Zn), 1×10^{-3} (F^-), 1×10^{-3} (NO_{3-})
CF (Conversion factor)	l/cm^3	–	1/1 000

Source: Giri and Singh (2015); Rahman et al. (2017); USEPA (2004); WHO (2016)

4.4 Development of Urban Health Sustainability Index

The study adopted principles of environmental sustainability assessment (Esty et al., 2005) in the design of the study's UHS index. The ESI measures the overall progress of nations toward environmental sustainability to achieve the sustainable development goals of the UN (Schmiedeknecht, 2013). As a composite index, UHS index tracks a set of environmental, social environmental indicators that characterise and influence the environment on an urban scale.

The UHS index will be used for future projection on urban development trends as it affects its sustainability for the environment and water security. In developing a sustainability model, consideration of the factors requires parameters associated with the phenomenon (Alowo, 2021; Coccia, 2020; Oertwig et al., 2015; Oke, 2015). Therefore, the UHS index will factor in the climate, water quality, ecological and social environmental parameters. The UHS index is further extensively discussed in Chapter 6.

Furthermore, the UHS index was validated to test its accuracy in environmental health sustainability of any given area. The validation proposed in this study was carried out by comparing the results generated from the UHS index with other existing methods. The UHS methods, factors, scoring and weighting techniques are discussed extensively in Chapters 6 and 7.

4.5 Chapter summary

This section summarises the method followed in this research. The methodology employed was to achieve the objectives as aimed to evaluate the impact of rapid urbanisation on environmental health sustainability in the MMM. The application of remote sensing and GIS was employed to achieve a specific goal in this research. Hydrochemical and meteorological data were acquired at an accredited government agency. The data was processed and analysed to achieve its purpose in this study. The chapter also hinted on the methods to develop the UHS method and validation process.

Chapter 5

URBAN ENVIRONMENTAL ASSESSMENT OF THE MANGAUNG METROPOLITAN MUNICIPALITY

5.1 Introduction

Population growth is rapidly increasing with A high rate of urbanisation and industrialisation in South Africa. Rapid urbanisation in the MMM has resulted in rapid and large-scale alterations in land use (Senbore & Oke, 2021). Urbanisation, food insecurity, internal migration and environmental regulations are among the factors that accelerate land use patterns (Adnan et al., 2018; Ateeq-Ur-Rehman et al., 2018; Fahad & Bano, 2018; Hammad et al., 2019; Kamran et al., 2019; Khan, Tan, Afridi et al., 2017; Khan, Tan, Munsif et al., 2017; Qamar-Uz et al., 2017; Saud et al., 2017; Turan et al., 2018; Wajid et al., 2017; Yang et al., 2017; Zia et al., 2017; Zamin et al., 2019). Global climate change also accelerates global surface temperature causing an upsurge of surface temperature, which has been a major topic of discourse at the just concluded COP 26 in Scotland by the world leaders. According to an IPCC assessment report, there would be an increase in surface temperature of about 1.1–6.4 °C by the end of this century (Saud et al., 2017). Recently, global climate change has had great impacts on vegetation, water and environmental ecology (Zoungrana et al., 2018).

In South Africa and selected countries on the African continent, there has been a collapse in structural infrastructure because of the rapid population increase in urban cities. This led to houses being built on a flood plains, drainage systems filled with solid waste, encroachment into river channels, which has led to major causes of a natural disaster (Ajibade et al., 2013; Okaka & Odhiambo, 2018; Olajuyigbe et al., 2012; Serdeczny et al., 2017). Recent studies by De Villiers, (2007) and Cullis et al. (2019) in the Berg River catchment revealed the impact of urbanisation and climate change on water quality and scarcity, resulting from anthropogenic factors from agricultural runoff and effluent from an over-loaded municipal sewage system.

Remote sensing and GIS are powerful tools for studying the dimensions of rapidly sprawling urban centres (Oke & Ruzvidzo, 2021; Sansare & Mhaske, 2020; Senbore & Oke, 2021). Current analysis and monitoring of LULC changes are necessary for environmental sustainability in the MMM, following the discovery by Senbore and Oke (2021) in the three main urban metropolitan centres. Several factors have triggered rapid unplanned and uncontrolled changes to urban land cover in a few decades, such as population growth, urban expansion, uncontrollable internal emigration, vegetation loss, and climate change. Rapid LULC changes have resulted in deforestation, degradation, biodiversity loss, mismanagement of agricultural projects, natural disasters, and increased global warming (Hammad et al., 2018; Hussain et al., 2019; Zoungrana et al., 2018). In recent years, there has been an increasing interest in studying the land cover status at regional and global scales, as well as the assessment of land cover changes that is fundamental for sustainable environmental health and management of the natural ecosystem (Garg et al., 2019; Moniruzzaman et al., 2021; Psomiadis et al., 2020; Siddiqui et al., 2018).

It was therefore necessary to investigate the LULC for a better understanding of urban and environmental change variations by studying it during a known period of time as an objective of this research. LULC change is a common process, essentially induced by human activities and natural phenomena, which in turn make changes that would affect natural ecosystems (Bansod & Dandekar 2018; Hussain et al., 2019). Logical planning of urban land cover changes plays a significant role in climate change mitigation (Orimoloye et al., 2018; Sansare & Mhaske, 2020). Understanding local land cover patterns, changes, and interactions between natural phenomenon and human activities are necessary for quality environmental health sustainability and urban planning. Therefore, mapping urbanisation growth and its impact on environmental sustainability of the MMM is carried out using the following methods:

- Land use / land cover classification.
- Vegetation index analysis.
- Built-up index analysis.
- Water quality assessment for drinking and agricultural use.

5.2 Land use / land cover classification in the Mangaung Metropolitan Municipality

The supervised imaging classification was evaluated using the false colour composition of Bands 2, 3 and 4 for Landsat TM and Landsat ETM+, while Bands 3, 4 and 5 were combined for Landsat 8. The spectral signature of each class was obtained from the images using the ERDAS Imagine software by selecting the area of interest for each of the LULC categories. The area of interest helped in producing the map by defining areas in the map based on the training sites and the spectral homogeneity of the pixels of the chosen area.

The accuracy assessment was carried out in this study by comparing GIS classification with ground-truth data to evaluate how well the classification was representative of the present environmental condition. The accuracy assessment of the classes was examined to be sure of a high level of accuracy in pixel selection and classification obtained. The different LULC classes in MMM were categorised into five classes for easy analysis and assessment for change detection. The LULC classification observed in this study included the urban area (all infrastructure, road networks and settlements), waterbodies (dams, rivers, streams and lakes), vegetation (natural vegetation, forestry), agricultural lands (cultivated areas, farmland) and barren surface areas (unused land, open space, bare soil). LULC supervised classification showed significant changes in the study observed in the MMM (Figure 5.1) through the period 1978–2018. The results of LULC showed a 17% increase in the overall extent of urban areas from 1978 to 2018 in the MMM (Table 5.1).

Table 5.1: Distribution of land use / land cover classification through 1978 to 2018

Land use / land cover area distribution										
Land use / land cover classes	**1978**		**1988**		**1998**		**2008**		**2018**	
	Area (km^2)	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**
Built-up areas	865.5	8.8	1 024.4	10.4	1 499.4	15.2	2 098.1	21.2	2 545.7	25.8
Waterbodies	575.4	5.8	541.2	5.5	381.7	3.9	103.5	1.0	42.9	0.4
Vegetated areas	1 501.3	15.2	1 281.3	13.0	927.4	9.4	632.2	6.4	115.5	1.2
Agricultural areas	410.7	4.2	702.2	7.1	1 081.1	10.9	1 763.1	17.8	2 645.0	26.8
Barren surface areas	6 527.1	66.1	6 330.9	64.1	5 990.4	60.6	5 283.1	53.5	4 530.9	45.9
Total	**9 880**	**100**	**9 880**	**100**	**9 880**	**100**	**9 880**	**100**	**9 880**	**100**

Built-up area class occupied 8.8% of the total classes in 1978. In 1988, the built-up area increased from 8.8% to 10%. In the same increasing vein, built-up areas in 1998 and 2008 experienced a significant increase of up to 15.2% and 21.2%, respectively. Finally, in 2018, the built-up area has increased rapidly to cover 25.8% of the entire area. The waterbody consisted of 5.8% in 1978, but then decreased in 1988 and 1998 to 5.4% and 3.9%, respectively. The waterbody in 2008 and 2018 further decreased to 1% to 0.4%, respectively (Table 5.1), which could suggest the effect of urbanisation and climate change-related events experienced in the MMM. Waterbodies occupy the smallest class among all the classes observed in the MMM.

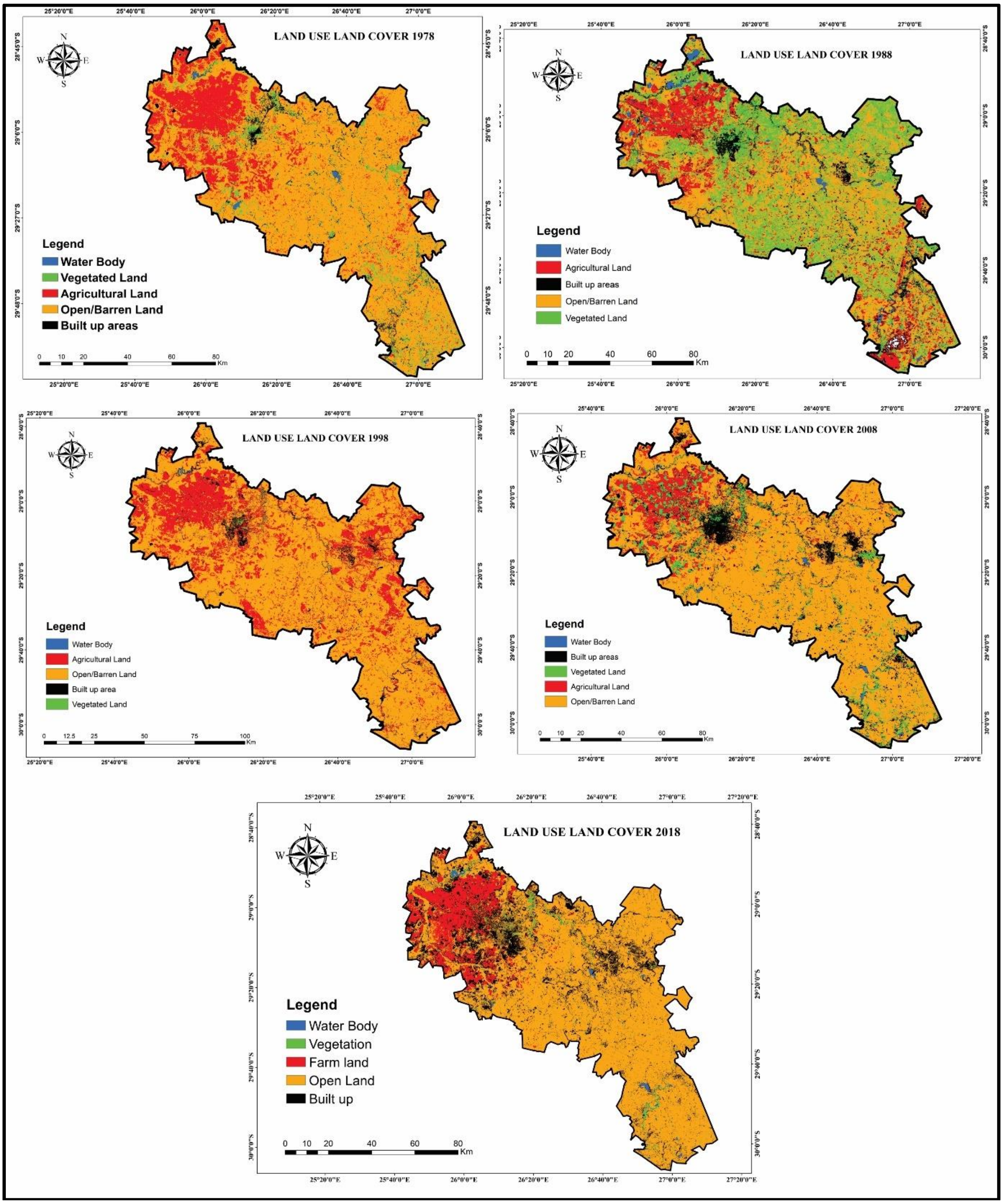

Figure 5.1: Land use / land cover maps of the study region in 1978, 1988, 1998, 2008 and 2018

Figure 5.1 reveals that barren or open land areas cover high proportions in the MMM; however, it also shows a decreasing trend as the built-up areas increased and agricultural land areas increased in the MMM. In 1978, 66% of the area was covered by open/barren surface areas, which decreased by almost 20% in 2018. The LULC analysis also revealed that vegetated areas in the study area decreased as the urban area increased by 15% to 1%, respectively, from 1978 to 2018. Major cities in Mangaung are growing annually due to the migration of people from rural areas to the city centres, resulting in a decrease of open land areas. The spatial and sequential changes in the LULC analysis have proceeded swiftly as a consequence of increased urban populations and urban activities (Zaidi et al., 2017; Zhang et al., 2018). It can be established that the rapid increase in urbanisation during the last 40 years, as evidenced in Figure 5.1, has ultimately resulted in an increase in agricultural activities and barren surface areas, with an increase in built-up areas.

5.2.1 Land use / land cover change detection analysis

The LULC change detection analysis was considered in this study to establish the change in classes of the LULC in the MMM between 1978 to 2018 (Table 5.2). The LULC classes with maximum and minimum changes used in the study were selected as lower and upper baselines to identify the maximum relative change during the aforementioned years in the MMM.

The change detection analysis has been observed between 1978 and 2018, the change analysis for "agricultural area" experienced a great increase with 22.6% in the area and this can be related to the increase in urban centres and population growth. Likewise, the increase in agricultural activities to meet the rapid population growth and urban expansion has contributed to an increase in contaminants that pollute the urban water systems in the study area (Senbore & Oke, 2021). It was also observed that open/barren land decreases yearly as the change analysis recorded in Table 5.2 revealed a decrease of −20.2% between 1978 to 2018. Furthermore, the waterbody, on the other hand, experienced a decrease of −5.4%; however, the study revealed loss of vegetation cover by −14% during the study period.

Table 5.2: Land use / land cover change detection analysis in Mangaung Metropolitan Municipality (1978, 1988, 1998, 2008 and 2018)

Change detection analysis in Mangaung Metropolitan Municipality										
Land use / land cover classes	1978–1988		1988–1998		1998–2008		2008–2018		1978–2018	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Built-up areas	158.9	1.6	475	4.8	598.7	6.1	447.6	4.5	1 680.2	17.0
Waterbodies	−34.2	−0.3	−159.5	−1.6	−278.2	−2.8	−60.6	−0.6	−532.5	−5.4
Vegetated areas	−220.0	−2.2	−353.9	−3.6	−295.2	−3.0	−516.7	−5.2	−1385.8	−14.0
Agricultural areas	291.5	3.0	378.9	3.8	682.0	6.9	881.9	8.9	2 234.3	22.6
Barren surface areas	−196.2	−2.0	−340.5	−3.4	−707.3	−7.2	−752.2	−7.6	−1 996.2	−20.2

Distinctively, the built-up area change detection observed experienced exponential change of about 17% increment. The total change detection observed from LULC ranged from 8.8% in 1978 to 25.8% in 2018. It is worthy to note that between 1978 and 2018 almost 14% of the vegetation area and 20% of open/barren land have been transformed into urban and agricultural areas in the MMM.

5.2.2 NDVI and NDWI characterisation

The NDVI and NDWI images in the MMM (Figures 5.2 and 5.3) for the period 1978 to 2018 indicates that the NDVI values ranged from −0.556 to +0.73 in 1978, −0.414 to +0.672 in 2008 and −0.213 to +0.598 in 2018, while the corresponding NDWI values ranged from −0.662 to +0.529 in 1988, −0.570 to +0.437 in 2008 and −0.542 to +0.237 in 2018. The highest NDVI value was observed in 1978 and the lowest in 2018. The higher values indicate the healthiest vegetated areas such as forests and crops, which significantly implies more rainfall and less impact of climate change. Similarly, lower values indicate less vegetated areas, water, bare soil and more built-up areas reducing the vegetation coverage.

In general, the NDVI values were lower in 2018, which is an indication of rapid urban sprawling; hence, forest areas, cropland or barren surface areas have been transformed into built-up areas. The NDVI values show the amount of chlorophyll content present in vegetation, where the greater NDVI value shows healthy and dense vegetation, but a lower NDVI value shows sparse vegetation (Hussain et al., 2019). The study shows that the area covered by vegetation in 1978 was 1 501.3 km^2, while the same area experienced a loss of vegetation cover within a 50-year period to 115.5 km^2 in 2018 (Table 5.2).

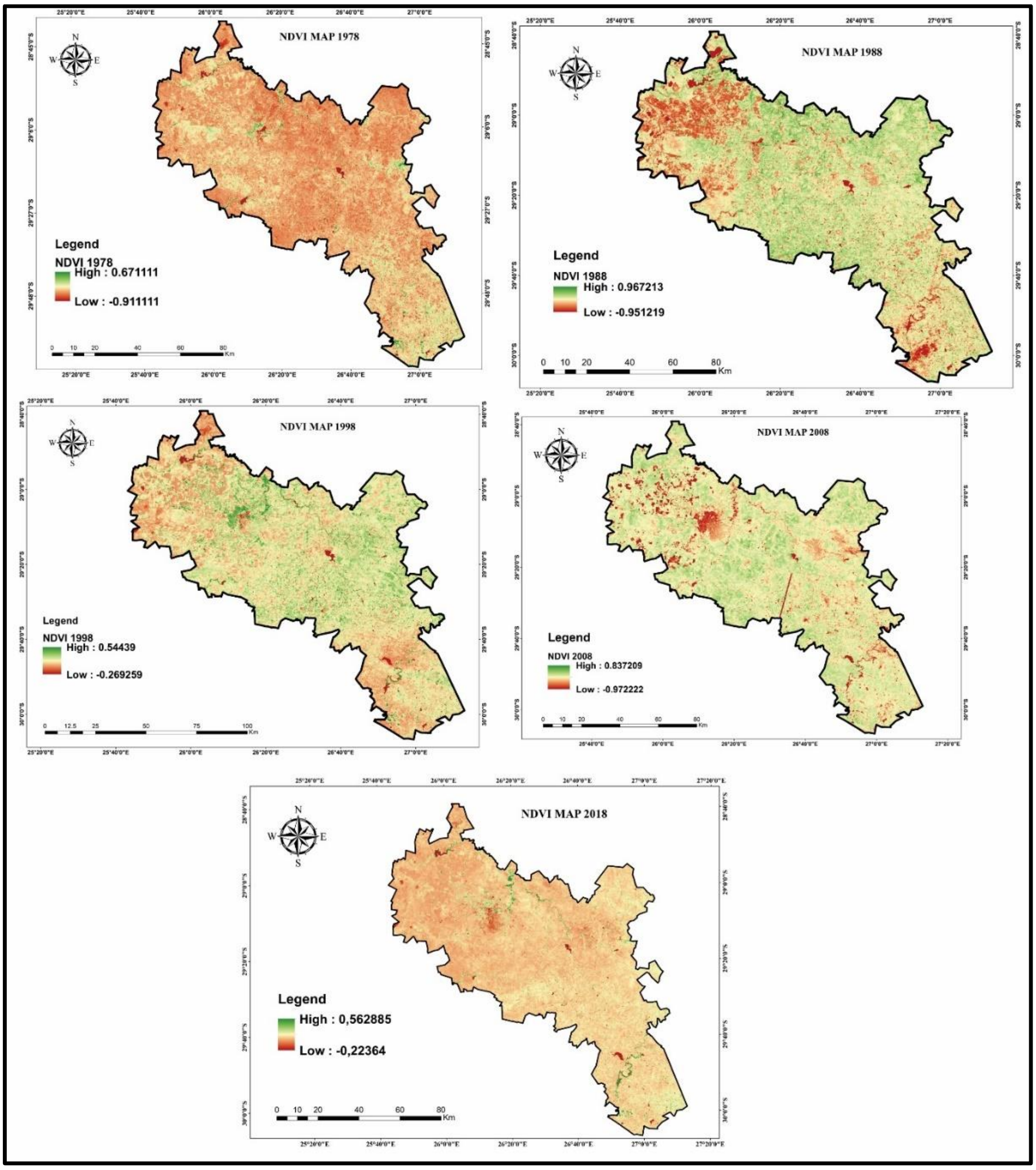

Figure 5.2: ***Normalised Difference Vegetation Index maps of the study area between the period 1978 and 2018***

In general, the NDVI values were lower in 2018, which is an indication of rapid urban sprawling; hence, forest areas, cropland or barren surface areas have been transformed into built-up areas. The NDVI values show the amount of chlorophyll content present in vegetation, where the greater NDVI value shows healthy and dense vegetation, but a lower NDVI value shows sparse vegetation (Hussain et al., 2019). The study shows that the area covered by vegetation in 1978 was 1 501.3 km^2, while the same area experienced a loss of vegetation cover within a 50-year period to 115.5 km^2 in 2018 (Table 5.2).

The NDWI was used to decipher the total surface area covered by water throughout the period of 1978–2018. The study shows that the area was covered by 575.4 km^2, 541.2 km^2, 381.7 km^2, 103.5 km^2 and 42.9 km^2 in 1978, 1988, 1998, 2008 and 2018, respectively (Table

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5.2) as estimated from the NDWI interpretation. It is evident that the water coverage area reduced by 5% between 1978 and 2018, with an exponential increase in urban coverage areas. As seen in Figure 5.3, more areas were prone to drought conditions in 1978 as compared to 2018.

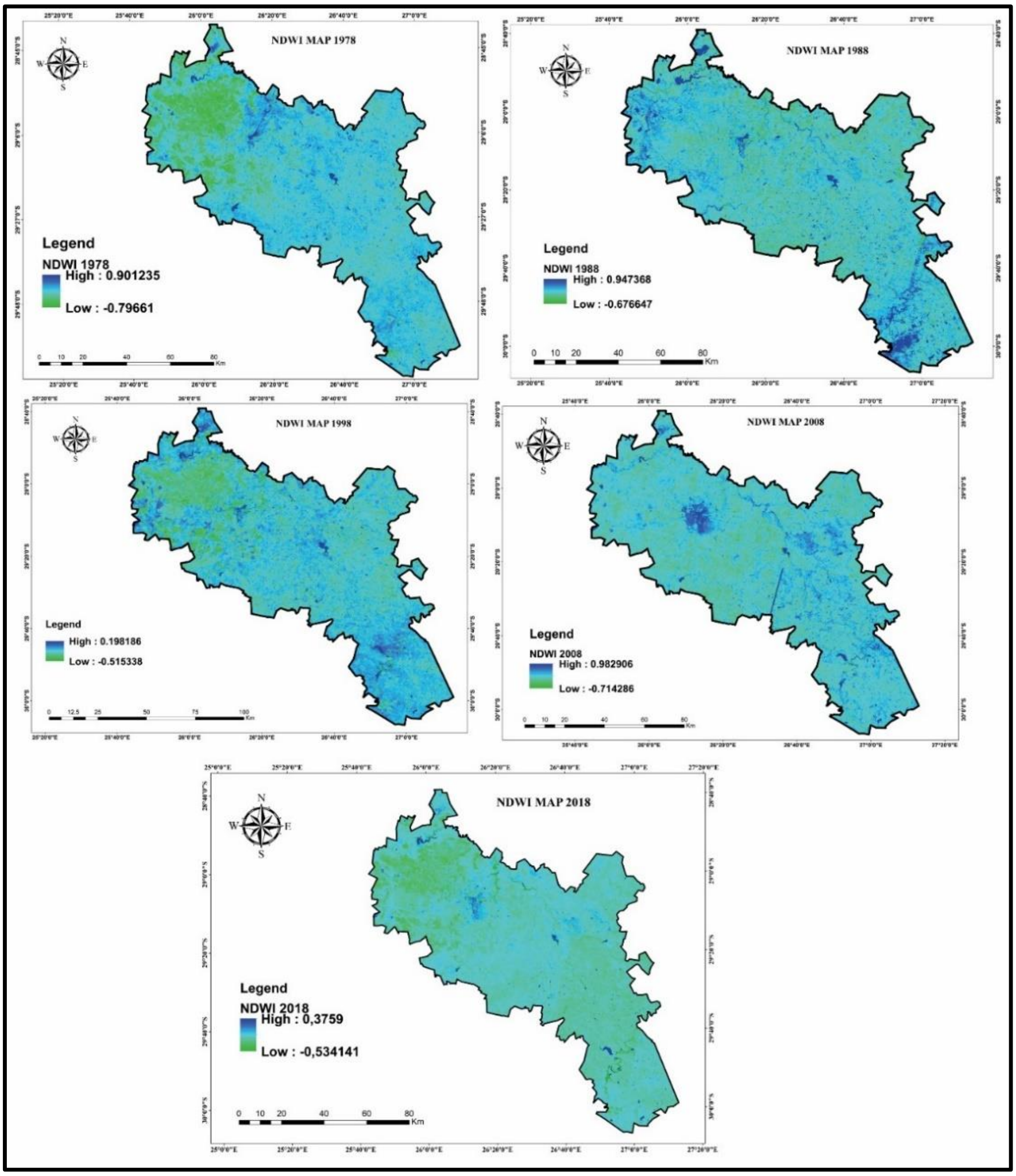

Figure 5.3: Normalised Difference Water Index maps of the study area between the period 1978 and 2018

5.2.3 Normalised Difference Moisture Index

The soil moisture environments during rainfall will affect the amount of runoff produced from that rainfall. Soils experience their high soil moisture condition during rainy seasons or after a rainfall event. If it rains when the soil moisture content is high, then less infiltration of water will occur and more runoff will be generated. Conversely, if the soil moisture condition is low, more rainfall will be absorbed by the soil, resulting in less runoff generation (Figure 5.4).

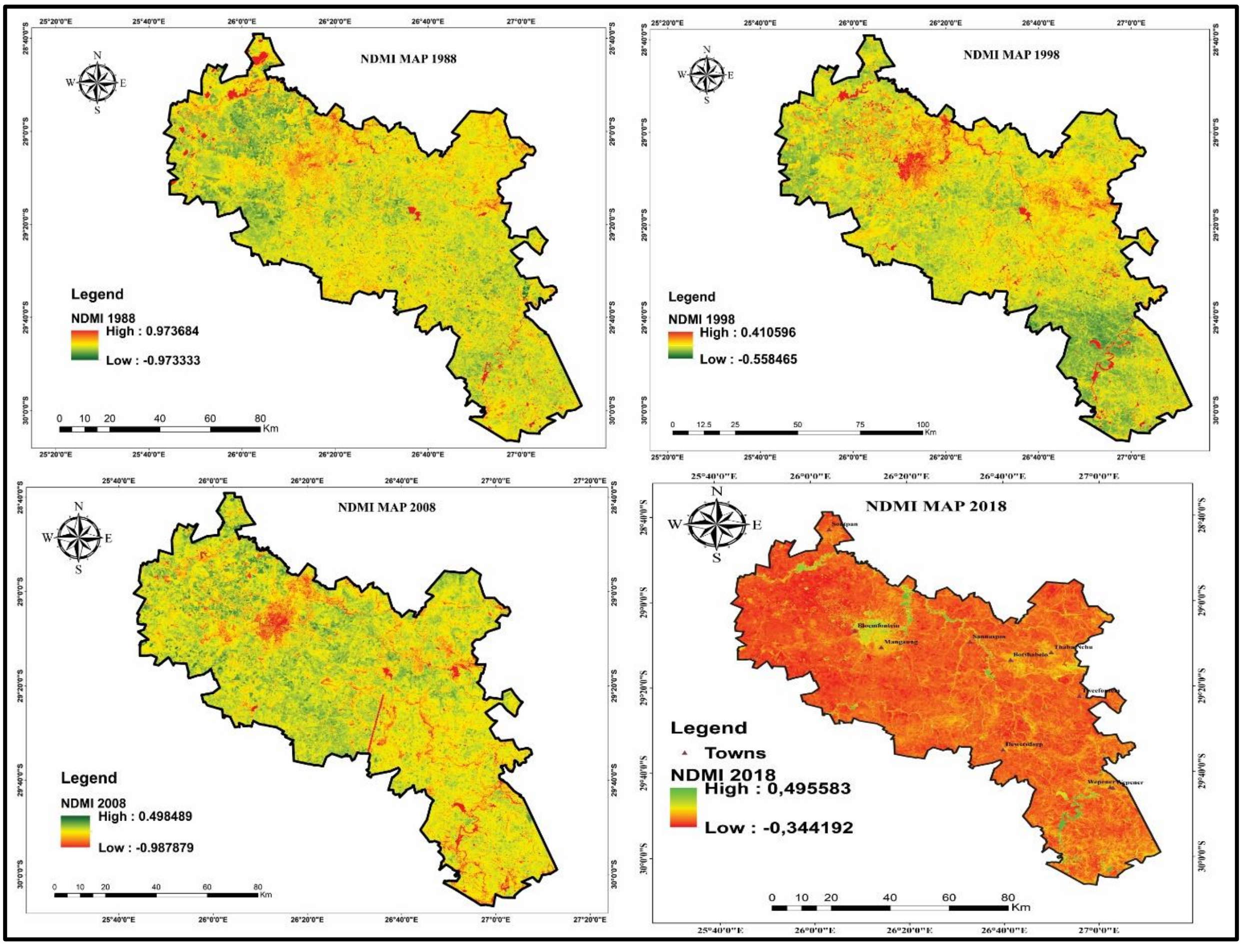

Figure 5.4: Normalised Difference Moisture Index maps of the study area between the period 1978 and 2018

5.2.4 Built-up and urban development change

The study concentrated on mapping of built-up areas. All the mapped land covers were categorised into five groups: built-up and all others in the study area of 9 880 km^2. Built-up areas account for nearly 26% of the entire study area. As implied previously, no further attempt was made to differentiate the specific uses of these areas.

The accuracy of the mapped built-up areas was assessed, both spatially and aspatially. The spatial discrepancy between the mapped and actual boundaries of built-up areas is graphically illustrated in Figure 5.5. It shows that the spatial expansion of the mapped built-up areas matches closely with the actual border of built-up areas in this part of the image (Figure 5.5). In order to provide a quantitative assessment of the accuracy for the entire urban area, their genuine identity on the ground was verified under the guidance of a global positioning system receiver in the field, according to their coordinates. It was found that of

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these checkpoints, 65% were correctly mapped as urban areas, resulting in an accuracy of 80%. Aspatially, the area of 9 880 km^2, derived from the NDBI method, closely resembles the area of 9 887 km^2 that was obtained from literature of the MMM report of 2020.

The spatial image used to generate the topographic map were taken, the urban area in Bloemfontein has expanded, resulting in a larger built-up area on the 2018 satellite image. The built-up areas have also been measured manually from the false colour composite. The manual result of the study area is similar to the NDBI derived for the study area (Figure 5.5).

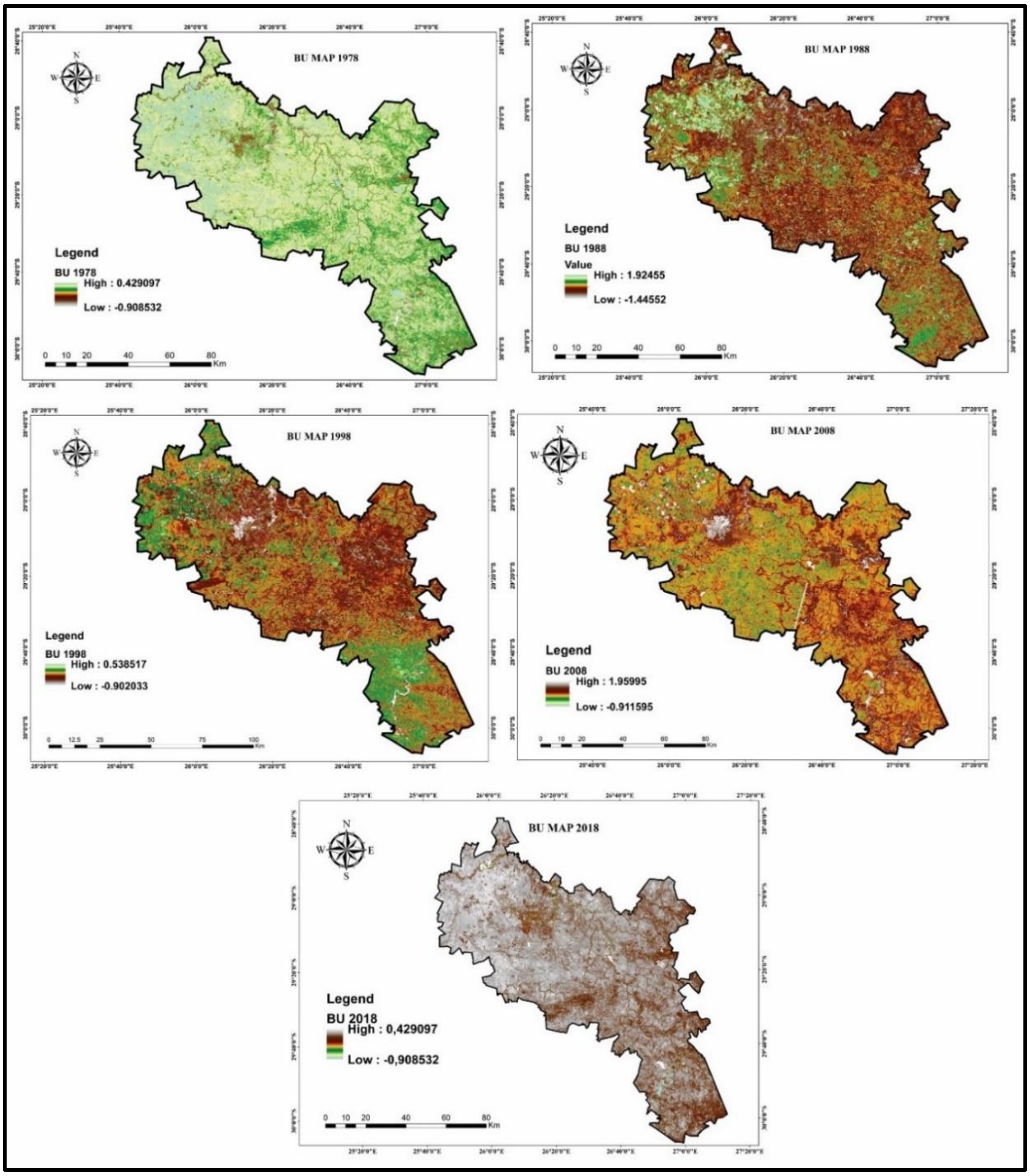


Figure 5.5: The NDBI density classes image classification for the years 1978 to 2018

Built-up density classes has shown a gradual increase of 1.6% from 1978 to 6.1% in 2008 and 17% to 2018. While the NDBI high and medium density values showed a continuous dispersion, the low-density value is perceived as a multinucleated extension. Being a neighbour to the island nation of Lesotho, MMM needs to be extremely competitive and at the same time being strategically significant. The MMM corridor has been consistent with the tenet of equitable growth and value creation. It has a strong and resilient economy and infrastructure enablers. Nevertheless, there is a need for a check and balance for the rapid land cover change in terms of urbanisation in the MMM (Figure 5.6), consequently, to mitigate an appalling environmental change.

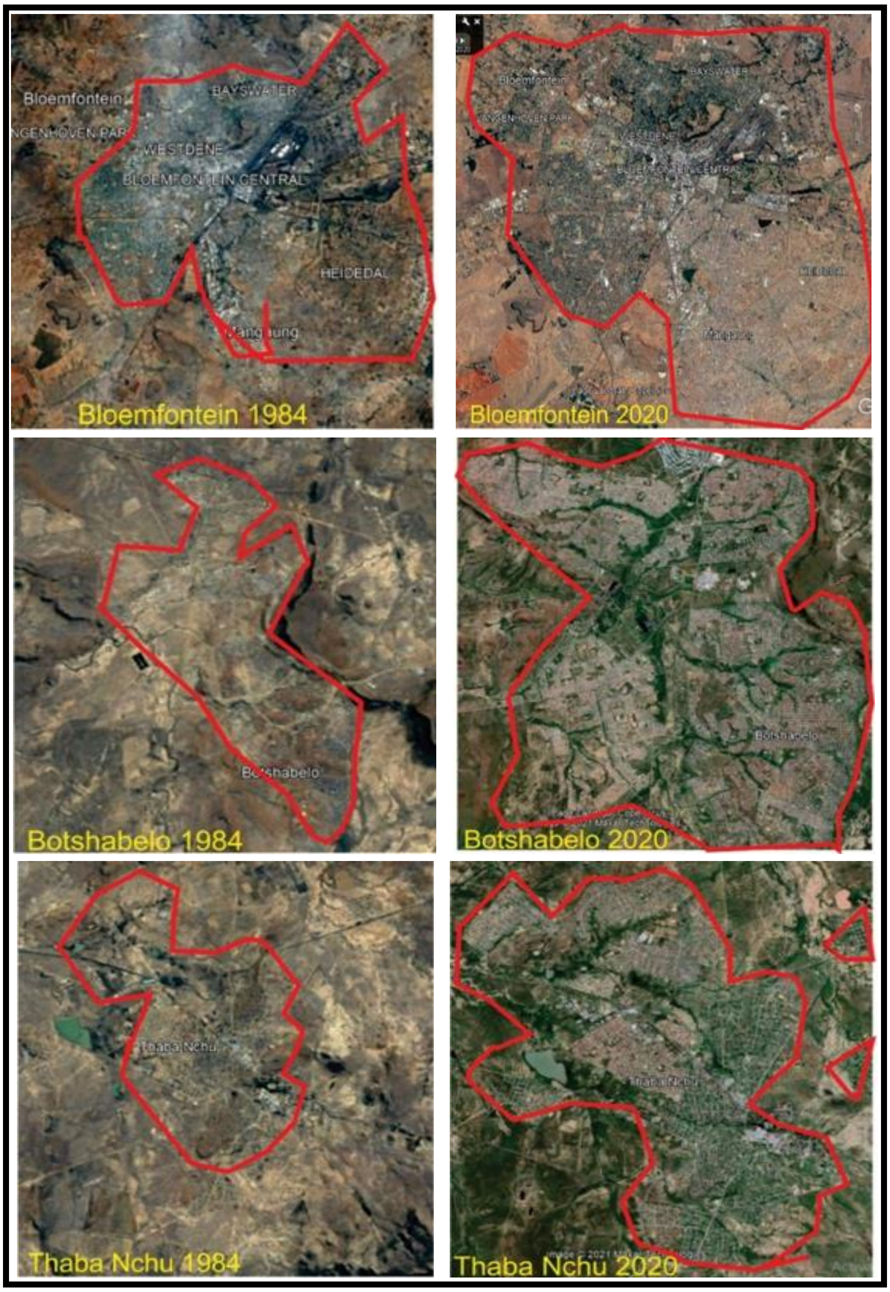


Figure 5.6: Spatial data revealing urban expansion as seen from the three main urban centres in Mangaung Metropolitan Municipality between 1984 and 2020

Source: Adapted from Google Earth (2022)

5.3 Hydrochemical assessment

Surface water across various catchments in South Africa are expose to contamination by human activities as a result of an innumerable degree of land use in formal and informal settlements (Ajala et al., 2016; Cullis et al., 2019; Ogedengbe & Akinbile, 2004; Zamxaka et al., 2004). Lack of quality drinking water in the MMM has stirred concern over environmental health impacts associated with the worsening quality of aquatic ecosystems due to incessant pollution from the urban activities (Cappiella et al., 2012; Peterson et al., 2018). The deterioration in river physicochemical properties is often slow and not noticeable as the water system adapts to the changes until an apparent alteration of the water occurs (Ajala et al., 2015). To prevent future deterioration and assure the supply of quality water for home and agricultural purposes, it is vital to monitor the condition of the MMM's river system. The Modder River plays an important role for the people of MMM in terms of potable water supply and irrigation purposes.

Hydrochemical characterisation, water quality and health risk assessment are essential for the protection of environmental and public health (Dinka et al., 2015; Dzwairo & Otieno, 2014; Peterson et al., 2018). Understanding the water quality status in the study as well as the processes controlling the hydrochemical facie is vital for water management in the MMM. The hydrochemical characterisation and assessment of water sources exposes the water quality by measuring the concentration of physicochemical parameters and comparing them to the drinking water and irrigation standards as prescribed by SANS 241 and the WHO. The facie analysis reveals the impact of chemical processes in waterbodies and investigates water chemistry variability in terms of hydrochemical evolution (Ravikumar et al., 2015; Zhang et al., 2018). Gibb's diagram (1970) is widely used to establish the relationship of water constituents and mechanisms controlling hydrochemical parameters, while the Piper illustration diagram assesses the evolution of water as well as the relationship between rock kinds and water composition (Piper, 1944; Rahman et al., 2017).

5.3.1 Physicochemical parameters

The physicochemical parameters from the study area between 1978 and 2018 are presented in Table 5.3. In 1978, the concentration of Ca ranged between 22.90 mg/l and 38.24 mg/l, with an average of 28.82 mg/l, while the amount of Cl was between 3.96 mg/l and 45.335 mg/l, with a mean value of 19.37 mg/l. The mean Dissolved Major Salts (DMS) was 229.57, while the average EC was 37.63 µS/cm. Fluoride in water of the area during this year was between 0.21 and 0.49 mg/l, with an average of 0.32 mg/l. The average amounts of K, Mg, Na, NH_4, NO_3, pH, PO_4, Si and SO_4 were 4.06 mg/l, 13.88 mg/l, 26.34 mg/l, 0.05 mg/l, 0.33 mg/l, 7.48 mg/l, 0.04 mg/l, 2.95 mg/l and 11.94 mg/l, respectively. The values of total hardness of the water ranged between 106.40 mg/l and 195.09 mg/l, with an average of 144.33 mg/l.

Table 5.3: Statistical summary of surface water parameters obtained from the study area

Parameter	Unit	1978			1988			1998			2008			2018			WHO (2006)	SANS (2015)
		Mean	S.D.	Variance	Mean	S.D.	Variance	Mean	S.D.	Variance	Mean	S.D.	Variance	Mean	S.D.	Variance		
pH		7.48	0.35	0.12	7.55	0.59	0.35	8.24	0.10	0.01	8.04	0.21	0.04	8.29	0.13	0.02	6.5–8.5	5.0–9.7
EC	µS/cm	37.63	12.06	145.41	30.42	15.23	232.05	40.75	16.89	285.35	43.34	13.44	180.75	32.80	12.66	160.20	500	170
TDS	mg/l	286.97	101.50	10 302.99	221.06	117.73	13 860.83	317.09	105.54	11 138.53	295.82	114.40	13 087.32	230.27	108.98	11 875.75	1 000	1 200
Total alkalinity	mg/l	144.33	36.72	1 348.00	105.75	53.70	2 883.64	146.74	31.47	990.50	157.61	46.28	2 141.72	161.87	49.44	2 327.71	–	–
Calcium	mg/l	28.82	6.22	38.71	23.91	9.17	84.00	29.68	6.10	37.25	32.10	7.71	59.41	21.05	6.85	46.89	75	–
Magnesium	mg/l	13.89	4.73	22.38	11.79	7.24	52.45	15.11	6.38	40.71	16.53	5.87	34.49	9.28	4.51	20.31	30	–
Sodium	mg/l	26.34	13.10	171.56	18.85	13.96	194.81	30.75	20.49	420.02	32.70	15.82	250.26	22.71	12.46	155.17	200	200
Potassium	mg/l	5.07	1.93	3.74	3.75	1.09	1.19	5.02	1.74	3.04	6.24	2.97	8.85	5.33	2.29	5.23	200	–
Chloride	mg/l	19.37	16.00	255.85	18.51	14.14	199.82	25.78	26.60	707.63	30.08	20.95	439.00	22.47	15.25	232.45	250	300
Sulphate	mg/l	11.94	7.38	54.42	12.81	12.18	148.47	28.69	23.37	546.05	25.09	10.86	117.94	16.10	9.01	81.18	250	500
Nitrate	mg/l	0.33	0.36	0.13	0.36	0.25	0.06	0.47	0.75	0.57	1.61	3.40	11.57	2.59	3.74	13.96	10	11
Phosphate	mg/l	0.05	0.05	0.00	0.12	0.25	0.06	0.22	0.45	0.20	0.77	1.52	2.31	0.39	0.60	0.36	–	–
Fluoride	mg/l	0.32	0.12	0.01	0.29	0.09	0.01	0.28	0.04	0.00	0.32	0.15	0.02	0.20	0.09	0.01	1.5	1.5
Ammonium Nitrogen	mg/l	0.06	0.05	0.00	0.09	0.07	0.00	0.07	0.06	0.00	0.35	0.27	0.07	0.25	0.57	0.33	–	–
Silicon	mg/l	3.69	3.72	13.87	4.73	1.45	2.11	3.94	1.83	3.33	4.91	2.17	4.69	5.28	1.58	2.50	–	–

Note: S.D. = Standard deviation

5.3.2 Hydrochemical facie and evolution

The hydrochemical values obtained from the water samples from the study area were plotted by using the Piper (1953) trilinear diagram and other hydrochemical plots (Figure 4.7) to recognise the hydrochemical facies that are able to provide clues to how the water quality changed through the years due to rapidly increase in the urban areas (Didar-Ul Islam et al., 2017; Sivasubramanian et al., 2013). This diagram is also used to classify the water types (Wen et al., 2005), which are generally distinct zones in which cation and anion concentrations are described within the defined composition categories.

The Piper plot of hydrochemical data from the study area is presented in Figure 5.7. A total of 88% of the samples lies in the $CaMgHCO_3$ region, while samples from Shannon collected in 1998 and 2008 made up 4% of the total samples plotted in the mixed CaMgCl. Samples collected from Rietspruit I in 1988, 1998, 2008 and 2018 thus made up 8% of the total samples in the CaCl region. In terms of cations, 94% of the samples represent the non-dominant type region, while 6% plotted in the Ca type region. However, for anions, only 4% of the samples plotted in the non-dominant type region, while 4% plotted in the SO_4 and Cl^- type regions. Furthermore, 88% of the samples were plotted in the HCO_3 type region.

This study showed that water in this area mostly belong to the $CaMgHCO_3$ type group, although mixed CaMgCl and CaCl groups also featured (Figure 5.6). The dominance of CaMg in the water suggests that they may be hard due to influences from the land surface, mostly urban factor.

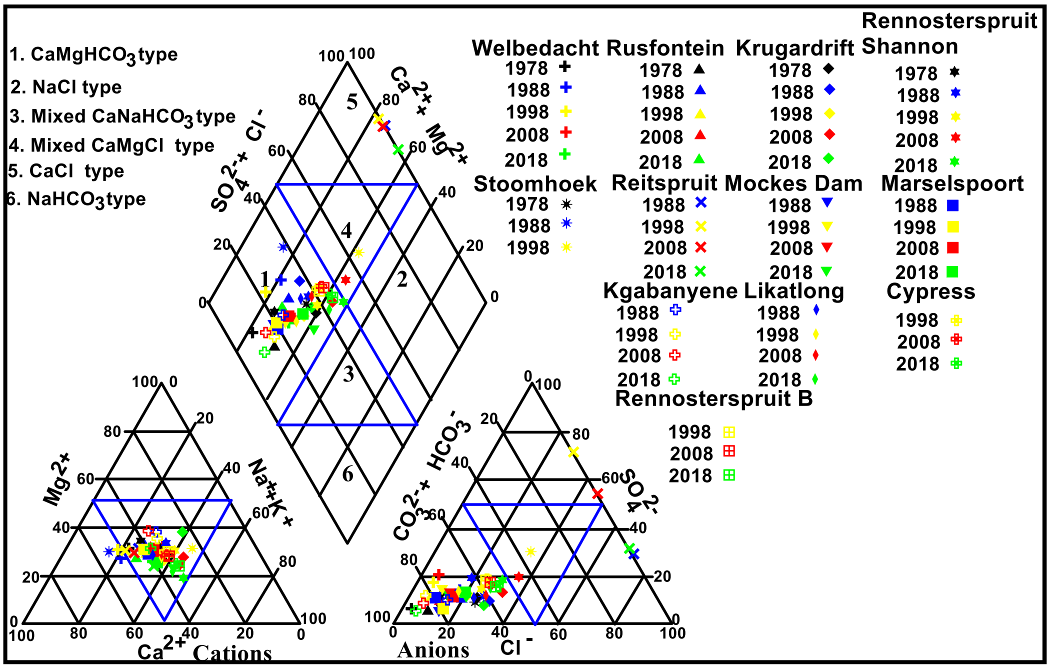


Figure 5.7: Piper plot of the study area

The Durov diagram (Durov, 1948) was generated to further describe the hydrochemical characteristics of water in the study area (Figure 5.8). This also showed that 88% of the samples from 1978 and 1988 lies in the ionic exchange, while 75% of the samples in 1998 and 2008 plotted in the reverse ionic exchange. However, most of the samples in 2018 lies in the simple dissolution or mixing region. Figure 4.7 reveals that all the water samples analysed have a TDS value of < 1 000 mg/l, with HCO_3 as the main anion. The concentrations of anions are close to each other for the 2008 and 2018 water samples, indicating a mixed type of water which suggests the dissolution of freshwater and wastewater from the urban centres.

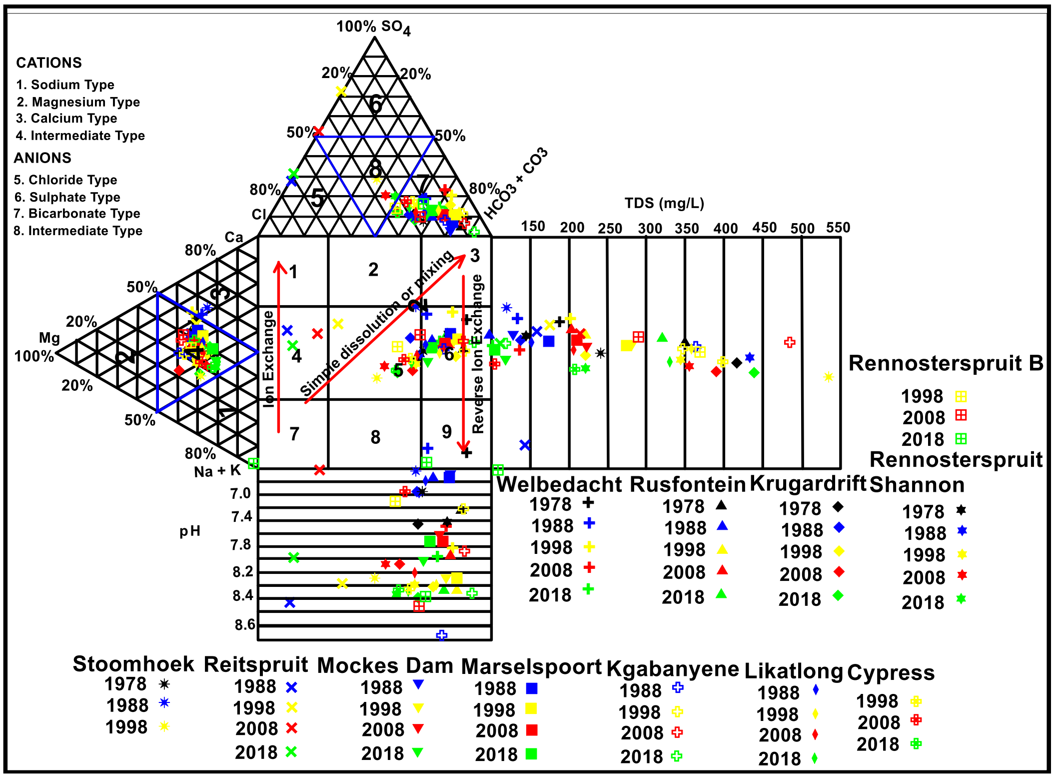


Figure 5.8: Durov diagram of the study area

The results of the Gibbs plot showed that the Na/Na+Ca values were less, while the TDS values were between 90 mg/l and 600 mg/l. This showed that freshwater abounds in the area. All samples collected from the study area over a period of 50 years falls within the rock dominance process. This signifies that geogenic processes, especially chemical weathering of rocks, may have contributed greatly to the ionic concentration of the water. The result of the Gibbs plot suggest that all the water observed in the area are influenced chemically by sources from the surrounding environment and weathering processes. Mixing of water from different geogenic sources is eminent. The hydrochemical characterisation indicates that many heavy metals have been deposited in the soil due to natural processes such as rock weathering and leaching, as well as human activities such as smelting, fossil fuel burning, pesticide use, and sewage sludge.

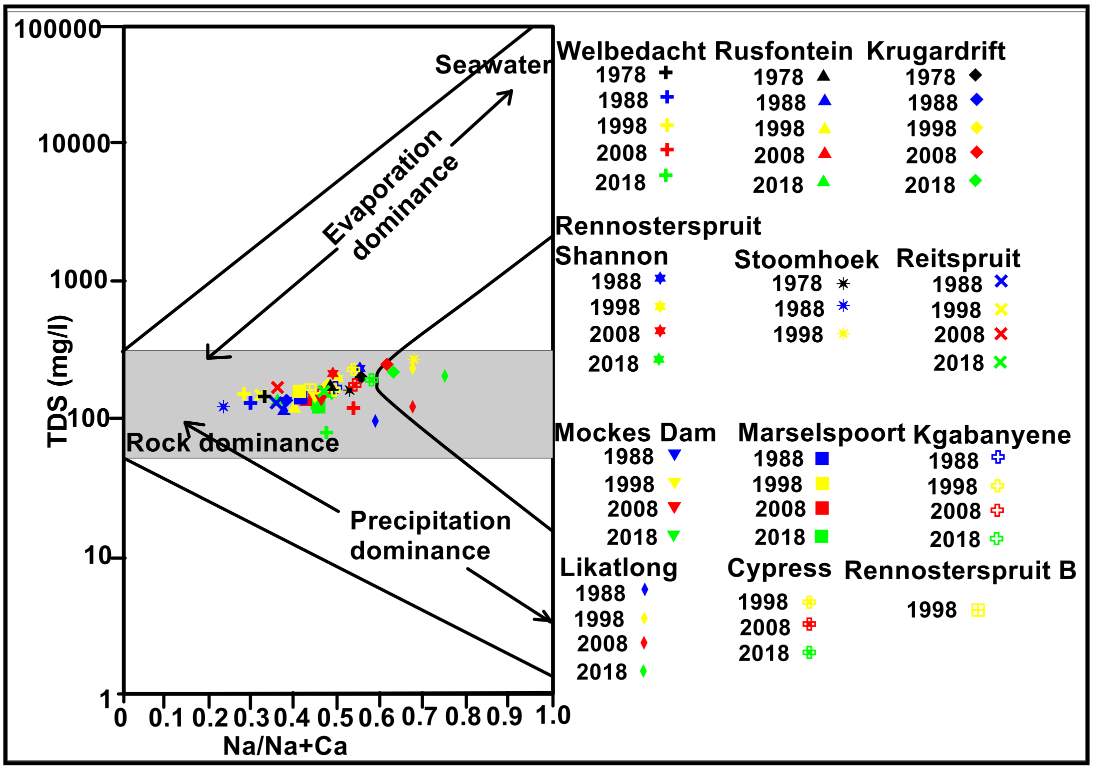


***Figure 5.9:** Gibbs plot of the study area indicating general mechanisms of water evolution*

5.3.3 Water Quality Index

The WQI observed in the study area is presented in Table 5.4. The average WQI scores ranged between 19.98 and 56.56 for 1978 to 2018, respectively, suggesting excellent and undesirable water quality for drinking and irrigation supply. The water quality observed in year 1978 ranged from 24.19, 27.47, 33.95, 43.07, 27.73, 23.38 for samples in Welbedacht, Rietspruit, Rustfontein, Krugersdrift, Stoomhoek and the Renosterspruit at Shannon, which suggest that the water quality in this year is categorised as excellent in Welbedacht and Renosterspruit, while water quality rating for the other river systems is rated as good for this period.

The WQI for the 1988 values for all the samples observed in the study area scored 20.12, 27.47, 23.21, 24.98, 20.27, 24.88, 40.16, 18.69, 43.32, 39.71, and 22.16. All the samples were of excellent quality, except for Kgabanyane and Renosterspruit, which were of lower quality with a rating as good. The WQI rating for 1988 comprised of good and poor water quality rating with the values ranging from 26.05, 27.64, 2.86, 31.67, 27.45, 46.83, 31.64, 37.80, 53.49, 40.99, and 22.16. This suggest the water observed in the study area deteriorated more in 1998 as compared to 1978, which suggest that the impact of urbanisation was reflecting on the water quality in the study area. Furthermore, water quality ratings for the year 2008 ranged between 29.76, 28.05, 29.44, 29.02, 34.52, 44.80, 46.17, 46.18, 56.56, 29.53, and 34.38, which are of good and poor index score ratings as seen in 1998. While in 2018, the quality rating of the samples observed were excellent and good, respectively, with the following index scores: 19.98, 25.69, 28.53, 22.47, 25.42, 41.01, 38.43, 27.62, 45.64, 18.44, and 49.07 (Table 5.4).

Table 5.4: Summarised results of water quality index in the study area

Locality	1978		1988		1998		2008		2018	
	Value	Index	Value	Index	Value	Index	Value	Index	Value	Index
Welbedacht	24.19	Excellent	20.12	Excellent	26.05	Good	29.76	Good	19.98	Excellent
Rietspruit	–	–	27.47	Excellent	27.64	Good	28.05	Good	25.69	Good
Mockes Dam	–	–	23.21	Excellent	32.86	Good	29.44	Good	28.53	Good
Maselspoort	–	–	24.98	Excellent	31.67	Good	29.02	Good	22.47	Excellent
Rustfontein	33.95	Good	20.27	Excellent	27.45	Good	34.52	Good	25.42	Good
Cypress	–	–	–	–	46.83	Good	44.80	Good	41.01	Good
Krugersdrift	43.07	Good	24.88	Excellent	31.64	Good	46.17	Good	38.43	Good
Kgabanyane	–	–	40.16	Good	37.80	Good	46.18	Good	27.62	Good
Stoomhoek	27.73	Good	18.69	Excellent	53.49	Poor	–	–	–	–
Renosterspruit/ Shannon	–	–	43.32	Good	40.99	Good	56.56	Poor	45.64	Good
Renosterspruit B	–	–	39.71	Good	–	–	29.53	Good	18.44	Excellent
Likatlong	–	–	22.16	Excellent	38.44	Good	34.38	Good	49.07	Good

5.4 Contaminant and health risk assessment

Estimated health risk assessment of NO_3 in water from the MMM area is shown in Table 5.5. The monitored surface water samples were from 1978, 1988, 1998, 2008 and 2018. Average daily intake, oral ingestion and dermal contact are discussed in this section. The average daily intake of NO_3 for four categories of people (adult males, adult females, children and infants) in different sampling areas are presented in Table 5.5. The results showed that in Mangaung, the average daily intake for adult males in 1988, 1998, 2008 and 2018 is 6E-2 mg/kg per day, 1E-2 mg/kg per day, 9E-3 mg/kg per day and 7E-1 mg/kg per day, respectively. The average exposure rates to NO_3 through oral ingestion and dermal contact for adult females is 6E-2 mg/kg per day, 1E-2 mg/kg per day, 1E-2 mg/kg per day and 7E-1 mg/kg per day each. For children, the total ADI for 1988, 1998, 2008 and 2018 is 3E-2 mg/kg per day, 7E-3 mg/kg per day, 7E-3 mg/kg per day and 4E-1 mg/kg per day. For infants, the average exposure rates to NO_3 through oral ingestion and dermal contact is 3E-1 mg/kg per day, 5E-2 mg/kg per day, 5E-2 mg/kg per day and 2E+1 mg/kg per day.

This study showed that average daily intake of NO_3 in water in the study area is less than 3.7 mg/kg per day, which is the recommended average daily intake by the Joint FAO/WHO

Expert Committee on Food Additives (2002). This showed that oral ingestion and dermal contact with water laden with NO_3 in the area may not cause health issues.

5.4.1 Health Quotient and Hazard Index

The average health quotient and hazard index of NO_3 for both carcinogenic and non-carcinogenic health risks on surface water in the MMM for both adults and children are presented in Table 5.5. The results showed that the mean average health quotients for non-carcinogenic health risks for NO_3 in water via ingestion for adult males during 1978, 1988, 1998 and 2018, were 0.01, 0.02, 0.05 and 0.05, respectively, while for adult females it was 0.01, 0.03, 0.05 and 0.05 each. For children, the health quotient for 1978, 1998, 2008 and 2018 were 0.01, 0.03, 0.05 and 0.05, respectively, while for infants it was 0.02, 0.15, 0.33 and 0.27 each.

However, the samples observed in Likatlong showed that mean average health quotients for non-carcinogenic health risks for NO_3 in water via ingestion for adult males during 1988, 1998, 2008 and 2018 were 0.07, 0.02, 0.02 and 0.67, respectively, while for adult females it was 0.07, 0.02, 0.02 and 0.71 each. For children, the health quotient for 1988, 1998, 2008 and 2018 were 0.07, 0.02, 0.02 and 0.72, respectively, while for infants it was 0.49, 0.10, 0.09 and 5.21 each. Likewise, for samples in Cypress, the health quotient for adult males for 1998, 2008 and 2018 were 0.19, 0.16 and 0.18, respectively, while for adult females it was 0.20, 0.17 and 0.19. For children, the health quotient for 1998, 2008 and 2018 were 0.20, 0.17 and 0.19. respectively. while for infants it was 1.45, 1.21 and 1.35 each.

This study showed that NO_3 in water of the area did not pose any health risks. However, infants in Likatlong in 2018 were prone to non-carcinogenic health issues.

Table 5.5: Health quotient and health index of nitrate in water through oral ingestion and dermal contact

Locality	Parameters	1978				1988				1998				2008				2018			
		AM	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**
Likatlong	HQ oral ingestion	–	–	–	–	0.03	0.03	0.03	0.17	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.03	0.23	0.24	0.24	1.74
	HQ dermal contact	–	–	–	–	0.05	0.05	0.05	0.33	0.01	0.01	0.01	0.07	0.01	0.01	0.01	0.06	0.45	0.48	0.48	3.47
	Health Index	–	–	–	–	0.07	0.07	0.07	0.49	0.02	0.02	0.02	0.10	0.02	0.02	0.02	0.09	0.67	0.71	0.72	**5.21**
Renosterpruit B	HQ oral ingestion	–	–	–	–	0.01	0.01	0.01	0.03	–	–	–	–	–	–	–	–	–	–	–	–
	HQ dermal contact	–	–	–	–	0.01	0.01	0.01	0.05	–	–	–	–	–	–	–	–	–	–	–	–
	Health Index	–	–	–	–	0.01	0.02	0.02	0.08	–	–	–	–	–	–	–	–	–	–	–	–
Renosterpruit Shannon	HQ oral ingestion	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.02	0.02	0.02	0.11	–	–	–	–	0.02	0.02	0.02	0.09
	HQ dermal contact	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.10	0.03	0.03	0.04	0.22	–	–	–	–	0.03	0.03	0.03	0.18
	Health Index	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.15	0.05	0.05	0.05	0.33	–	–	–	–	0.05	0.05	0.05	0.27
Stoomhoek	HQ oral ingestion	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.07	0.03	0.03	0.03	0.17	–	–	–	–	–	–	–	–
	HQ dermal contact	0.01	0.01	0.01	0.05	0.02	0.02	0.02	0.14	0.05	0.05	0.05	0.34	–	–	–	–	–	–	–	–
	Health Index	0.01	0.01	0.01	0.07	0.03	0.03	0.03	0.20	0.07	0.07	0.07	0.50	–	–	–	–	–	–	–	–
Kgabanyane	HQ oral ingestion	–	–	–	–	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02
	HQ dermal contact	–	–	–	–	0.01	0.02	0.02	0.08	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.03
	Health Index	–	–	–	–	0.02	0.02	0.02	0.12	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.04
Krugersdrift	HQ oral ingestion	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.06	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.04	0.02	0.02	0.02	0.14
	HQ dermal contact	0.02	0.02	0.02	0.1	0.02	0.02	0.02	0.12	0.01	0.02	0.02	0.08	0.01	0.01	0.01	0.07	0.04	0.04	0.04	0.27
	Health Index	0.02	0.02	0.02	0.15	0.03	0.03	0.03	0.17	0.02	0.02	0.02	0.12	0.02	0.02	0.02	0.11	0.06	0.06	0.06	0.41

Locality	Parameters	1978				1988				1998				2008				2018			
		AM	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**	**AM**	**AF**	**CH**	**IN**
Cypress	HQ oral ingestion	–	–	–	–	–	–	–	–	0.07	0.07	0.07	0.49	0.06	0.06	0.06	0.41	0.06	0.07	0.07	0.45
	HQ dermal contact	–	–	–	–	–	–	–	–	0.13	0.14	0.14	0.97	0.11	0.11	0.12	0.81	0.12	0.13	0.13	0.9
	Health Index	–	–	–	–	–	–	–	–	0.19	0.20	0.20	**1.45**	0.16	0.17	0.17	**1.21**	0.18	0.19	0.19	**1.35**
Rustfontein	HQ oral ingestion	0.03	0.03	0.03	0.18	0.01	0.01	0.01	0.06	0.01	0.01	0.01	0.03	0.05	0.05	0.05	0.35	0.01	0.01	0.01	0.03
	HQ dermal contact	0.05	0.05	0.05	0.35	0.02	0.02	0.02	0.11	0.01	0.01	0.01	0.06	0.09	0.10	0.10	0.69	0.01	0.01	0.01	0.06
	Health Index	0.07	0.08	0.08	0.53	0.03	0.03	0.03	0.17	0.01	0.02	0.02	0.08	0.14	0.15	0.15	1.04	0.02	0.02	0.02	0.08
Maselspoort	HQ oral ingestion	–	–	–	–	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.04	0.02	0.02	0.02	0.15
	HQ dermal contact	–	–	–	–	0.01	0.01	0.01	0.07	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.07	0.04	0.04	0.04	0.29
	Health Index	–	–	–	–	0.02	0.02	0.02	0.10	0.01	0.01	0.01	0.05	0.02	0.02	0.02	0.10	0.06	0.06	0.06	0.43
Mockes Dam	HQ oral ingestion	–	–	–	–	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.03	0.07	0.07	0.07	0.51
	HQ dermal contact	–	–	–	–	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.05	0.13	0.14	0.14	**1.01**
	Health Index	–	–	–	–	0.01	0.01	0.01	0.07	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.07	0.20	0.21	0.21	**1.51**
Rietspruit	HQ oral ingestion	–	–	–	–	0.01	0.01	0.02	0.08	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.14
	HQ dermal contact	–	–	–	–	0.02	0.02	0.03	0.15	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.04	0.04	0.04	0.04	0.27
	Health Index	–	–	–	–	0.03	0.03	0.04	0.22	0.01	0.01	0.01	0.07	0.01	0.01	0.01	0.06	0.06	0.06	0.06	0.41
Welbedacht	HQ oral ingestion	0.01	0.01	0.01	0.07	0.02	0.03	0.03	0.15	0.01	0.01	0.01	0.06	0.01	0.01	0.01	0.04	0.02	0.02	0.02	0.12
	HQ dermal contact	0.02	0.02	0.02	0.13	0.04	0.05	0.05	0.3	0.02	0.02	0.02	0.11	0.01	0.02	0.02	0.08	0.03	0.04	0.04	0.23
	Health Index	0.03	0.03	0.03	0.19	0.06	0.07	0.07	0.45	0.03	0.03	0.03	0.17	0.02	0.02	0.02	0.12	0.05	0.05	0.05	0.34

Note: AM=Adult Male; AF=Adult Female; CH=Children; IN=Infant

5.4.2 Exposure assessment of nitrate in Mangaung Metropolitan Municipality

The exposure assessment of NO_3 in the MMM revealed that in the high-risk group infants is at a high risk, with a health quotient in Likatlong of 4.4, and a health quotient at Mockes Dam of 1.45, both significantly higher than 1. Infants have a higher health risk than adults, as shown in Table 5.5 above. From 1978 to 2018, the qualified rate of NO_3 in surface water was only 48.59%, according to the monitoring data of drinking water quality in the MMM. The level of NO_3 in the study area, including Mockes Dam, Cypress River on the Modder River and Likatlong River, is higher than the other rivers studied, which may be related to the geological environment. It may also be related to the large amount of fertiliser used for agricultural activities.

In this study, there was no significant change of NO_3 content between 1978 and 1998, except for 2008 and 2018, which indicated that NO_3 content increased in recent years as urban growth expanded. Little information on the adverse effects of NO_3 on adult health was emphasised in this study. The majority of studies concentrate on the health risks of toxicological indices such as fluoride in drinking water. Some studies have found a link between excessive NO_3 consumption and thyroid malfunction and gastrointestinal cancer (Achadi et al., 1995; Yu et al., 2020). A study by Brender (2013) revealed that women in two states in the United States who drank drinking water with a high NO_3 content had children with birth abnormalities. The internationally accepted risk threshold is between 1×10-6a 1 and 1×10-4a 1, while risk levels of more than 1×10-4a 1 are regarded as unacceptable. Risk levels of less than 1×10-6a 1 are regarded as acceptable, whereas risk levels greater than 1×10-5a 1 are considered as moderate. Only one toxicological index of NO_3 was examined in this study, and the Rn value of children reached a high level ($1.64*10^7$).

The health quotient of both adults and infants in this investigation was greater than 1. Although adult females are more sensitive to NO_3 pollution than adult males, the difference is not statistically significant. In this study, children and infants have the highest exposure risk. Even when the dermal contact pathway is excluded, the health quotient value of juveniles was much higher than that of adults. This suggests that juveniles are more vulnerable to the health concerns associated with NO_3 in drinking water. Because of juveniles' unique physiological and behavioural traits, as well as their bodies' growth stage, their gastrointestinal absorption of certain substances increases, making them more exposed to external toxins (Chen et al., 2016).

5.5 Chapter summary

Remote sensing and GIS analysis was employed to investigate urban development in the MMM. LULC change was carried out to investigate land cover classification and the extent at which urban classification has changed through time. The supervised imaging classification was carried out using the maximum probability to identify different features and a false colour composition of Bands 2, 3 and 4 for Landsat TM and Landsat ETM+, while Bands 3, 4 and 5 were combined for Landsat 8.

The different LULC classes in th MMM were categorised into five and assessment for change detection. The LULC classification observed in this study included the urban area which included all infrastructure, road networks and settlements, likewise waterbodies including dams, rivers, streams and lakes. Vegetation such as natural vegetation, forestry, agricultural lands and barren surface areas, including unused lands, open space, and bare soil, was observed. The LULC supervised classification showed significant changes in the study observed in the MMM over the period 1978 to 2018.

Furthermore, hydrochemical characterisation, water quality and health risk assessments were carried out in the MMM. Water samples were collected across the rivers and dams in the study area. The hydrochemistry analysis from the Gibbs diagram indicated that the major processes controlling the water quality was influenced by precipitation and rock weathering from the land and urban areas.

According to the water types examined using Piper diagrams, the dominant hydrochemical facies in Maselspoort and Mockes Dam belong to the HCO_3-CO_3 water types, which is typically HCO_3, while water in the Rustfontein Dam was characterised by HCO_3-CO_3 and $Ca(Mg)(HCO_3)$ water types. The results of the water quality index showed a trend from excellent to fair quality, with most of the decrease in quality occurring in 2018.

Finally, the two NO_3 exposure pathways through drinking water and dermal contact were considered in the health risk evaluation. The study found a significant difference between the two exposure paths. The health quotient value induced by drinking water was significantly greater than that caused by the dermal contact pathway. It can be shown that drinking water was still the most common source of NO_3 exposure in this area, including both direct drinking water and water consumed through food.

Chapter 6

DEVELOPMENT OF AN URBAN HEALTH SUSTAINABILITY INDEX

6.1 Introduction

Environmental assessment is a systematic and integrative process for considering possible impacts of human activities on the environment for a sustainable environment and human health (Oertwig et al., 2015; Schmiedeknecht, 2013; Wood, 2003). This study has revealed the rapid urban development in the MMM, as well as other major cities in South Africa. Consequently, the water quality analysis revealed deterioration of water sources in the study area due to raising amount of contaminants from urban and agricultural activities. In this study, different methods of sustainability assessment has been discussed in Chapter 2, using varying environmental factors. This chapter tends to discuss the development of UHS to assess the impact of urban development on water systems, climate variability and human health for sustainable environmental health of MMM. The purpose of an UHS index in this study was to determine the potential environmental, social, and health effects of urban development. The model was intended to simplify the assessment of a sustainable urban environment and informed policymakers to avoid, reduce or mitigate potential adverse impacts of rapid urban development.

The study adopted principles of environmental sustainability assessment (Esty et al., 2005) in the design of a UHS index. The ESI measures the overall progress of nations towards environmental sustainability and the UN sustainable development goals (Schmiedeknecht, 2013). As a composite index, the UHS index tracks a set of environmental and social indicators that characterise and influence the environment on an urban scale.

The model index will be used for future projection on urban development trends and its sustainability for the environment and water security. In developing a sustainability model, the consideration of specific factors requires parameters associated with the phenomenon (Alowo, 2021; Coccia, 2020; Oertwig et al., 2015; Oke, 2015). Therefore, UHS will factor in the climate, water quality, ecological and social environmental parameters. The outline of the UHS is presented in Figures 6.3 and is further discussed in this chapter.

6.2 Conceptual framework of urban health sustainability

The demand for residential space and service delivery has been increasing as well as the rapid growth of the population in most of the cities in South Africa. It is observed that synergistic interaction between urbanisation and climate change often causes serious environmental degradation globally (Coccia, 2020; Chrair et al., 2020). This chapter aims at developing a simplified UHS index to analyse the current and future environmental health statuses in a rapidly urbanising area to align with the 2030 sustainable development goals as proposed by the UN. Models of environmental sustainability have been developed across the globe; however, this model focuses on sustainable urban health in the looming face of rapid urbanisation and climate change. This research has found a distinct evidence and relationship between the increasing pollution, CO_2 emissions, climate variability and urbanisation.

This model will observe the relationship between urban sprawl, land use and land cover change, climate variables, vegetation and water in terms of its sustainability. Furthermore, this research will simulate future land cover classification, focussing on urban growth development and the availability of water sources. This chapter develops environmental health sustainability that allows for tracing the interaction between urban activities and environmental factors and the interaction among environmental factors.

Undoubtedly, the scope of environmental assessment may be very broad, covering a multiplicity of sectors, populations, geographical locations and urban activities. There were several attempts to develop models to address environmental issues and sustainability (Coccia, 2020). This section focuses on the interactions and the necessities of simulation for urban impact analysis from the viewpoint of harmonisation of urban development and environmental conservation factors (Figure 6.1).

Figure 6.1: Urban activities and related environmental factors

Source: Coccia (2020)

The major concern in the rapid urbanising and environmental degradation is how we can lower or mitigate the peak of environmental degradation to a more sustainable environment for sustainable environmental health. This can be idealised in the scenario in Figure 6.2.

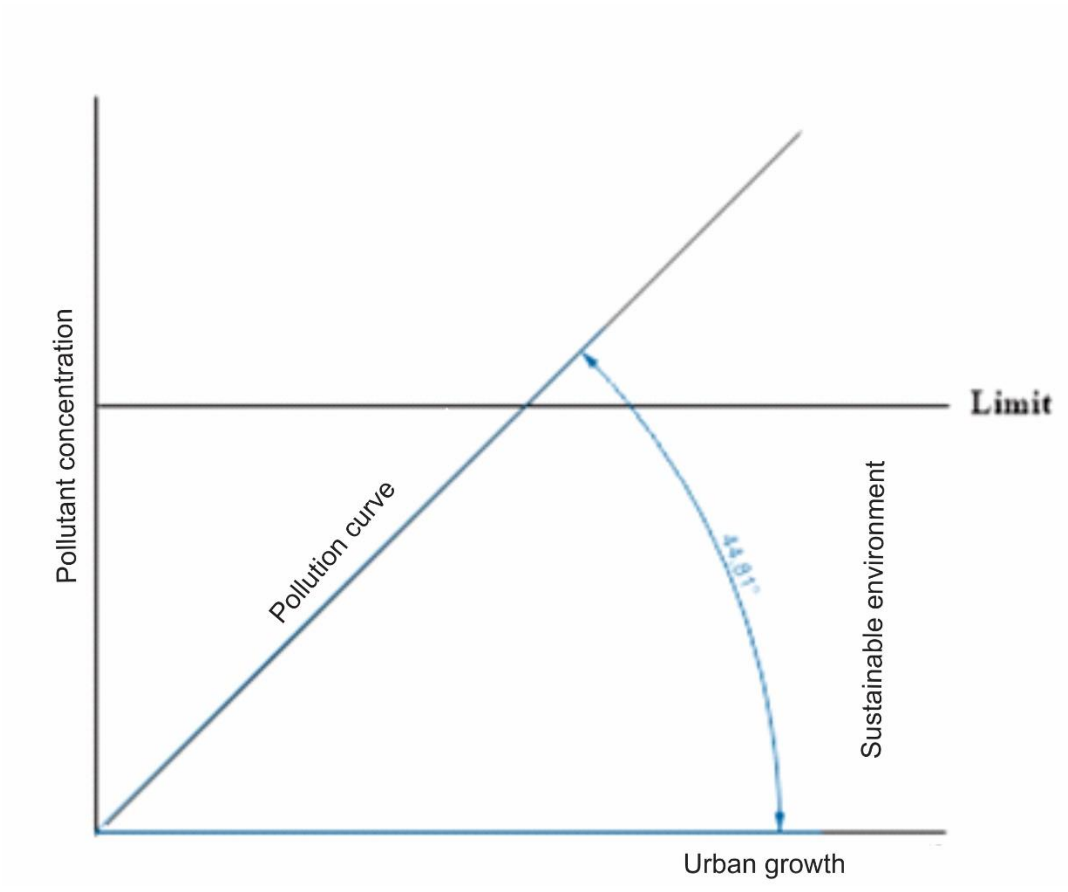


Figure 6.2: Sustainable environmental curve and urban growth

Source: Chrair et al. (2020)

6.3 Urban health sustainability weighting methods

The aim of this research framework was for sustainable environmental health in the MMM through development of a simplified UHS index. There are several sustainability models that address different areas of the environment. Oke (2015) presented a major decision in the development of the vulnerability assessment that can be adapted in sustainability assessment of hydrological systems in a less data locality. Alowo (2021) built on the vulnerability assessment to develop a groundwater sustainability model of C52 catchments using different hydrogeological and climatic environmental factors. In developing a sustainability model, the consideration of factors requires parameters associated with the phenomenon (Alowo, 2021; Coccia, 2020; Oertwig et al., 2015; Oke, 2015). In the case of aquifer vulnerability, assessment of fractured geological terrains requires methods which factor in the nature of fractures (Goldscheider et al., 2019; Oke, 2015), while an urban growth and environmental sustainability method will factor in the climate variability and land surface parameters (Chrair et al., 2020; Deilami & Kamruzzaman, 2017; Ma et al., 2016).

The development of a simplified UHS which meets all given requirements from urban classification, climate data variability, vegetation, water system and socio-economy in sustainability perspectives requires an information base on which several evaluations can be performed in a given urban setting. Since an urban environment consists of several different factors which are related to each other on several levels, it is necessary to consider all influences and possible effects within the model development process.

The UHS index has been designed to use important climate parameters, vegetation indices, water quality data in conjunction with the urban development data to assess environmental sustainability of an urban area such as the MMM. This index model considers the impact of rapid urban development relative to the available resources in the municipality and cater for other processes that affect the land use and water sources for a sustainable environmental health.

The following steps in Figure 6.3 were employed to create the UHS maps:

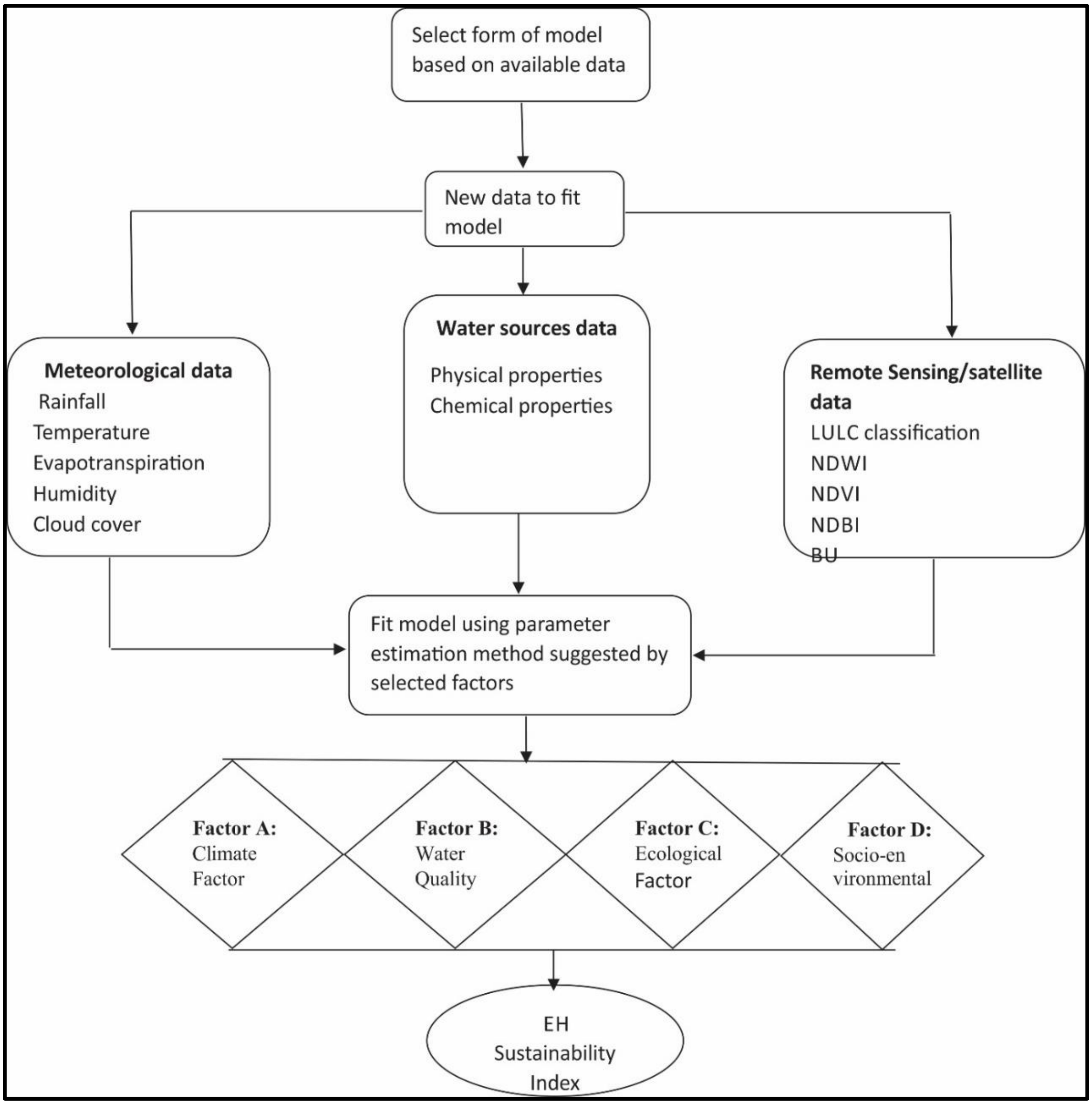


Figure 6.3: Types of data and parameters collected for the model application

6.3.1 Climate factor

Climate conditions is an important parameter of any methods of environmental sustainability (ESG, 2010). The standard was determined based on global world meteorological reports and databases of the World Meteorological Organization (Xiong et al., 2019). The highest and lowest global values recorded were used for scoring in this research. Precipitation is a critical parameter in the urban hydrological processes and response to climate change. Globally, it is given a maximum score of 5 for areas of rainfall above 3 000 mm per year and a low score of 1 for areas with rainfall of less than 400 mm per year. Hence, 3 000 mm and 400 mm were marginal values adopted in this method (Alowo, 2021; Cobon et al., 2017; Oke, 2015). A similar approach was adopted to assign the maximum and minimum rating to evapotranspiration, humidity, temperature, cloud cover and climate zones. Climate factor is an important parameter to be considered in the modelling of an UHS due the direct cause by human activities on climate change. Human emissions of greenhouse gases are the primary driver of climate change across the globe today. There has been a rise in ocean levels, a decrease in snowfall, and a shift in the patterns of rainfall, temperature and climate extremes as a result of warming of the atmosphere.

Climate factors are terrestrial variables that influence the weather and its conditions. Climate components and climate factors such as rainfall, sunshine and humidity contribute to the variability of the climate (Booth, 1991; Obiero et al., 2019; Saintilan et al., 2019). Table 6.1 shows the standards and scores which were assigned to the parameters considered for the climate factor. Furthermore, the equation that represents the evaluation of the climate factor parameters for the UHS model is given as:

$$C_f = \sum_{k=0}^{n} k(P + E + H + T + C_c + C_z)$$

Equation 29

Where:

C_f = the total score of all the parameters;

K = the sum of the score of all the parameters considered;

P = the amount of rainfall;

E = the evapotranspiration;

H = the humidity;

T = the temperature;

C_c = the cloud cover; and

C_z = the climatic zones.

Table 6.1: Standards and scores for climate factor

Rating	Score	Description of rank
	Precipitation (mm)	
5	>1 600	Very high
4	1 200−1 600	High
3	800−1 200	Moderate
2	400−800	Low
1	<400	Very low
	Evapotranspiration (mm)	
5	>200	Very high
4	200−150	High
3	150−100	Moderate
2	100−50	Low

Rating	Score	Description of rank
1	<50	Very low
Temperature		
1	0−5	Very low
2	5−10	Low
3	10−25	Moderate
4	25−50	High
5	>50	Very high
Cloud cover		
1	0−5	Very low
2	5−10	Low
3	10−25	Moderate
4	25−50	High
5	>50	Very high
Humidity		
5	>85	Supersaturated
4	50–85	Saturated
3	30–50	Average
2	20–30	Low
1	0–20	Devoid of water vapor
Climatic zones		
1	Desert	Excess of evaporation
2	Arid to semi-arid	Lack of moisture
3	Temperate	Moderate rainfall
4	Monsoon	Distinct wet and dry
5	Tropics	Warm all year

6.3.2 Water quality factor

Water quality is crucial to biodiversity and life on our planet (UNEP, 2015). Therefore, understanding the principal water indicators and their parameters is a key factor in environmental health sustainability (Li et al., 2019; Morris, 2019). Water quality is one of the most important health indicators in an ecosystem. Good quality water sustains human life, wildlife and marine life and is a key element of maintaining biodiversity. Monitoring water quality is thus critical for identifying potential environmental health challenges and developing effective preventative strategies. Hence, water quality has been considered as a factor in developing the UHS index. The water quality of the MMM has been calculated by using Equation 19, as discussed in Chapter 4. The standard and scores for water quality factor can be seen in Table 6.2. The weighting and rating of the water quality factor in the UHS index followed the acceptable water quality index rating by Banda (2015) and further adopted by Senbore and Oke (2021).

Table 6.2: Index score classification for the Water Quality Index

Rating	Score	Description of rank and classification	Water quality status
1	<25	This suggests that water quality is protected with a virtual absence of threat	Excellent
2	25–50	This suggests that water quality is regularly protected with only a minor degree of threat	Good
3	50–75	This refers to water quality that is protected but often threatened	Poor
4	75–100	This suggests that water quality is always threatened	Undesirable

6.3.3 Ecological factor

Vegetation is important in our natural ecosystem and sustains the biosphere in a variety of ways; it serves to regulate the flow of multiple biogeochemical cycles, particularly those of water, carbon, and nitrogen; and it contributes to local and global energy balances (Kerns & Peterson, 2014). Vegetation affects the energy balance at the earth's surface and inside the atmospheric boundary layer, frequently reducing local temperature extremes. Vegetation both emits oxygen and absorbs carbon. The vegetation factor (V_f) was considered for the development of an environmental sustainability model because it is an important parameter to observe in the study of urbanisation, climate change and environmental health balance (Table 6.3). Vegetation factors consider vegetation differences, moisture content and geographical zones as the parameter for the V_f.

In summary, Equation 30 represents the evaluation of V_f:

$$\mathrm{E}_f = \sum_{k=0}^{n} k\,(V + M + Aq + G)$$ *Equation 30*

Where:

E_f = the total score of all the parameters considered under V_f;

k = the score of all the parameters considered under V_f;

V = the vegetation difference of the MMM;

M = the moisture difference of the MMM;

Aq = the air quality of the environmental ecology; and

G = the geo zones for the area of the study.

Table 6.3: Standards and scores for the ecological factor

Rating	Score	Description
Vegetation difference		
5	0.7–0.9	Dense vegetation
4	0.4–0.7	Moderate vegetation
3	0.2–0.4	Sparse vegetation
2	0.1–0.2	Bare soil
1	−1–0.1	No vegetation
Moisture difference		
4	0.2–0.6	Surface water
3	0.0– 0.2	Flooding
2	−0.3–0.0	Moderate drought
1	−1.0–(−0.3)	Intense drought
Air quality		
1	0–50	Excellent
2	51–100	Good
3	101–150	Moderate
4	151–200	Unhealthy
5	201–300	Very unhealthy
Vegetation zone		
5	Tropical forest	–
4	Temperate forest	–
3	Savanah grassland	–
2	Semi-dessert shrub	–
1	Dessert shrub	–

6.3.4 Social environmental factor

The social environmental factor encompasses all those human-related daily activities. These daily activities are personal, societal, institutional, cultural, and physical. These activities sum up human interactions within the urban environment. Furthermore, human behaviours, decisions, and policies influence the ecosystems (e.g., water, vegetation, land use and built-up areas, air, population, and their sustainability) that, in turn, influence human beings' quality of life. The scoring and rating for the population in the MMM, water uses and built-up area, has the same inclination as that of the ecological factor. These values were obtained from global reports and databases (Messerschmid et al., 2018). However, in terms of an analysis of the MMM, the values assigned were derived from the DWS database (Olayele & Goel, 2022) and spatiotemporal analysis. Based on these values, data scores were assigned as shown in Table 6.4, with the lowest scores corresponding to unhealthy social environmental practises, while the highest score of 5 denotes a healthy social environmental practice.

The rating and weighting limit conditions for all factors considered in developing the UHS were based on the global highest values and global lowest values that have ever been recorded. This was adopted so that the UHS would be applicable to any other municipality in South Africa or any part of the world. All the parameters under the social environmental factor in Table 6.4 were considered independently, although there was common linkages and relationships between them and the built-up area. In addition, as an example, a population in the catchment of greater than 2 000 000 was assigned a score of 1 because it was not a desired situation (Alowo, 2021), while a population of less than 500 000 received a score of 5 because it is a low value. The score of 1 to 5 were ranged equally according to the differences between these two sets of boundaries as shown in Table 6.4.

Furthermore, some activities such as irrigation and power generation, use more water than others such as domestic use. Water uses for large-scale activities such as mining and power generation scored higher compared to domestic use, which is a global management practise of ensuring water sustainability. Equation 31 represents the evaluation of the social environmental factor.

$$SE_f = \sum_{k=0}^{n} k\ (P + W + BU + LU)$$ *Equation 31*

Where:

SE_f = the total score of all the parameters considered for the social environmental factor;

k = the score of all the parameters considered for the social environmental factor;

P = the population present in the municipality;

W = the water uses;

BU = the build-up area; and

Lu = the land use characterisation of the area.

Table 6.4: Standards and scores for the social environmental factor

Rating	Score	Description
Population in the catchment		
1	>2 000 000	Very high
2	1 500 000−2 000 000	High
3	1 000 000−1 500 000	Moderate
4	500 000−1 000 000	Low
5	<500 000	Very low

Rating	Score	Description
Water uses (ℓ/d)		
5	<2	Domestic
4	2−20	Afforestation
3	20−100	Mining and bulk industrial
2	100−300	Irrigation
1	>300	Power generation
Built-up		
1	<2	Very low
2	2−20	Low
3	20−100	Intermediate
4	100−300	High
5	>300	Very high
Land use		
5	Urban	
4	Vegetation	
3	Farmland	
2	Water	
1	Barren surface	

6.4 Urban Health Sustainability Index method

There is solid evidence of significant environmental linkages between urban development and human health sustainability (Haines et al., 2012). These links were highlighted in 1987 in the report of the UN World Commission on Environment and Development (CSDH, 2008; WHO, 2014). Adopting a greenery environment and quality water sources may aid in the promotion of both human health and urban development. Furthermore, depleting natural resources, population expansion, and the consequences of climate change are all likely to stymie global health improvement (Jamison 2013; WHO, 2014).

This method is based on using various factors of the environment to understand a set of selected parameters, such as climate variabilities, vegetation, water quality and the social environmental indicator (Kurokawa, 2001). The developed sustainability index method is applicable to the available data sets in any given locality.

Finally, the UHS index was computed by combining the factors of ecological, climate, water quality and the social environmental factor with an acceptable rating for each of the factors. This is proposed in the following formula:

$$UHS = \sum Cf + WQ + EF + SE$$

Equation 32

Where:

Cf = climatic factor score;

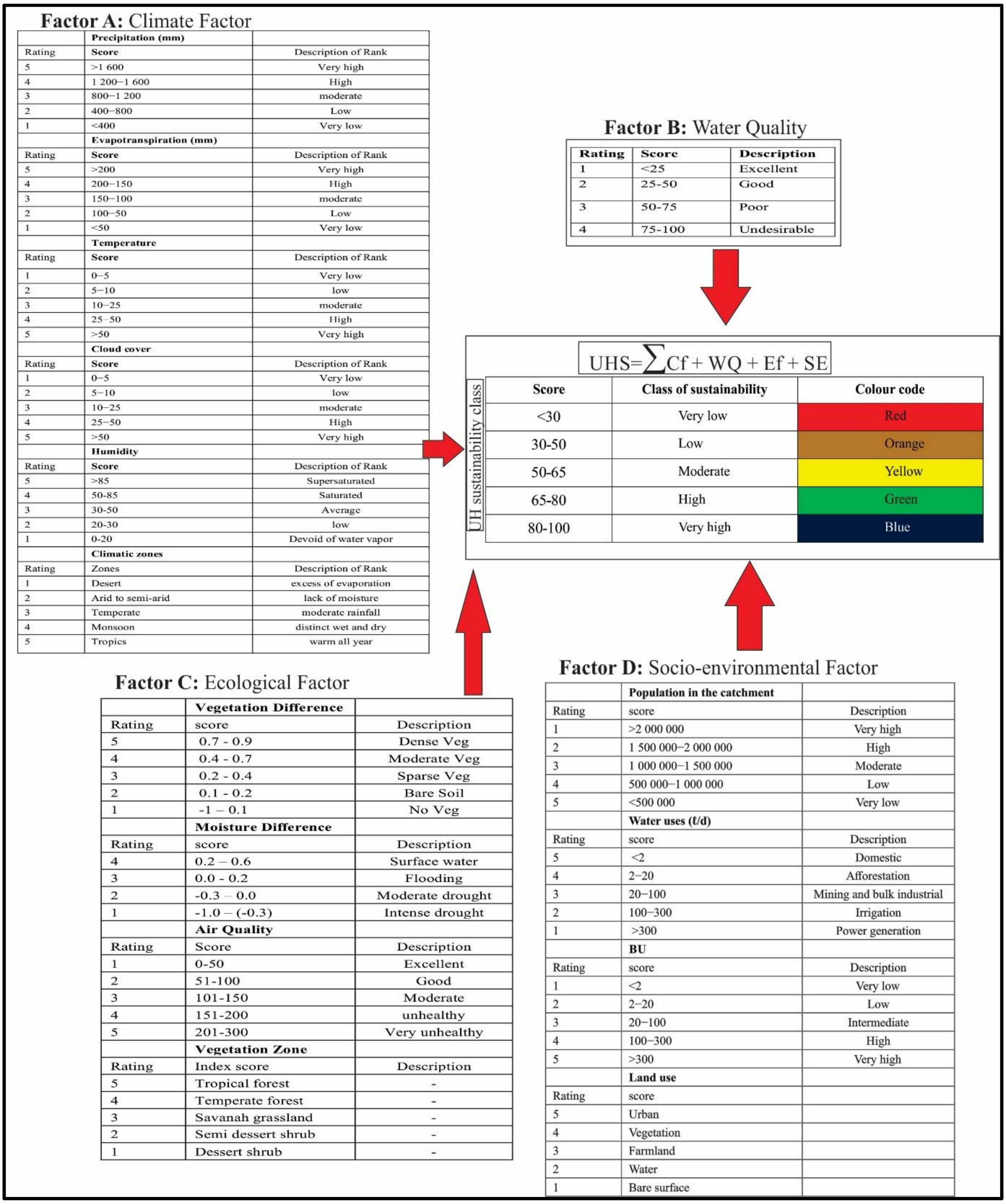
WQ = water quality factor score;

Ef = ecological factor score; and

SE = social environmental factor score.

The UHS index method, as shown in Figure 6.4, is based on the fact that the parameters are known and measured/collected data; therefore, UHS is based on available information. Furthermore, various rates are assigned based on global standards (Abbott & Marchant, 2010; Oke, 2015; UNCED, 1992). The UHS index factors were summed up (Equation 32, Figure 6.4). The factors are considered imperative to environmental sustainability in the context of climate change. It is worthy to note that environmental sustainability is ambiguous and therefore this model has focused on vegetation loss and water quality in a rapidly growing urban environment.

The UHS index was weighted and rated using a percentile system. The percentile system establishes a range from 100, which indicates a very sustainable system, to 19, which indicates the least sustainable system. In this study, the UHS status, with a score of 1, was allocated "severe impact", and a score of 5 was assigned "least impact". The final UHS index score of 19–35 indicates very low sustainability, 35–51 indicates low sustainability, 51–67 indicates moderate sustainability, 67–83 indicates excellent sustainability, and 83–100 indicates extremely high sustainability. The UHS index is divided into five categories (Figure 6.4).



Factor A: Climate Factor

	Precipitation (mm)	
Rating	**Score**	Description of Rank
5	>1 600	Very high
4	1 200–1 600	High
3	800–1 200	moderate
2	400–800	Low
1	<400	Very low
	Evapotranspiration (mm)	
Rating	**Score**	Description of Rank
5	>200	Very high
4	200–150	High
3	150–100	moderate
2	100–50	Low
1	<50	Very low
	Temperature	
Rating	**Score**	Description of Rank
1	0–5	Very low
2	5–10	low
3	10–25	moderate
4	25–50	High
5	>50	Very high
	Cloud cover	
Rating	**Score**	Description of Rank
1	0–5	Very low
2	5–10	low
3	10–25	moderate
4	25–50	High
5	>50	Very high
	Humidity	
Rating	**Score**	Description of Rank
5	>85	Supersaturated
4	50-85	Saturated
3	30-50	Average
2	20-30	low
1	0-20	Devoid of water vapor
	Climatic zones	
Rating	Zones	Description of Rank
1	Desert	excess of evaporation
2	Arid to semi-arid	lack of moisture
3	Temperate	moderate rainfall
4	Monsoon	distinct wet and dry
5	Tropics	warm all year

Factor B: Water Quality

Rating	**Score**	**Description**
1	<25	Excellent
2	25-50	Good
3	50-75	Poor
4	75-100	Undesirable

$$UHS = \sum Cf + WQ + Ef + SE$$

UH sustainability class

Score	**Class of sustainability**	**Colour code**
<30	Very low	Red
30-50	Low	Orange
50-65	Moderate	Yellow
65-80	High	Green
80-100	Very high	Blue

Factor C: Ecological Factor

	Vegetation Difference	
Rating	score	Description
5	0.7 - 0.9	Dense Veg
4	0.4 - 0.7	Moderate Veg
3	0.2 - 0.4	Sparse Veg
2	0.1 - 0.2	Bare Soil
1	-1 – 0.1	No Veg
	Moisture Difference	
Rating	score	Description
4	0.2 – 0.6	Surface water
3	0.0 - 0.2	Flooding
2	-0.3 – 0.0	Moderate drought
1	-1.0 – (-0.3)	Intense drought
	Air Quality	
Rating	Score	Description
1	0-50	Excellent
2	51-100	Good
3	101-150	Moderate
4	151-200	unhealthy
5	201-300	Very unhealthy
	Vegetation Zone	
Rating	Index score	Description
5	Tropical forest	-
4	Temperate forest	-
3	Savanah grassland	-
2	Semi dessert shrub	-
1	Dessert shrub	-

Factor D: Socio-environmental Factor

	Population in the catchment	
Rating	score	Description
1	>2 000 000	Very high
2	1 500 000–2 000 000	High
3	1 000 000–1 500 000	Moderate
4	500 000–1 000 000	Low
5	<500 000	Very low
	Water uses (ℓ/d)	
Rating	score	Description
5	<2	Domestic
4	2–20	Afforestation
3	20–100	Mining and bulk industrial
2	100–300	Irrigation
1	>300	Power generation
	BU	
Rating	score	Description
1	<2	Very low
2	2–20	Low
3	20–100	Intermediate
4	100–300	High
5	>300	Very high
	Land use	
Rating	score	
5	Urban	
4	Vegetation	
3	Farmland	
2	Water	
1	Bare surface	

Figure 6.4: Criteria used in the Urban Health Sustainability Index

6.5 Limitations and weaknesses of the urban health sustainability method

The recently adopted term *environmental sustainability* was used to predict the level of environmental pollution in the phase of urbanisation and climate change. Urbanisation has had various large impacts on the ecosystem. Therefore, the UHS method, just like other sustainability methods, has its limitations. The UHS limitations are as follows:

- Scaling and weighting are based on the available information and consideration of factors; however, this can be revised for improvement with better and robust biodiversity data on human health sustainability globally.
- Some environmental factors have been nullified because they could not be measured directly.
- The UHS is formulated by the specific indicators chosen and the results obtained may differ if different variables were considered.
- The UHS is subject to problems with differences in the quality of data and the interpretation by users.
- The UHS index could be improved with better and robust data collection.
- The UHS does not account for specific pollutants in water quality.

6.6 Conclusion

The UHS index methodology was explained in this chapter. The weighting and rating of criteria, as well as the precise technique and data collection, were all discussed in detail. Both subjective and physically validated methods were utilised in the UHS index development. In order to assign a value or score, the researcher used the global highest and lowest values recorded. This was done to ensure that the index could be used in any part of the world, regardless of region. For water quality, the DWS reports and SANS 241 standard values were used to verify and rate the data. The theory, links, and relationships between all of the parameters and factors in the study were taken into consideration while making the assessments. A conceptual methodology tree is presented in Figure 6.5.

Urban and built-up expansion lead to environmental degradation and pollution, which in turn, accelerates climate change. There are different ways of looking at environmental and urban management issues, and these classes are based on those methodologies. Sustainability levels can range from extremely high to extremely low when using these techniques. It is simple to compile and use the generated sustainability model/index. It was made for places like South Africa and other rapidly urbanising regions of the world.

The UHS index can be applied to evaluate environmental health sustainability of any urban region across the globe, depending on the available data. Consequently, the next chapter presents the application of the developed UHS index in the MMM to analyse the current environmental health status that can also be adopted for use in other metropolitan municipalities and provinces in South Africa.

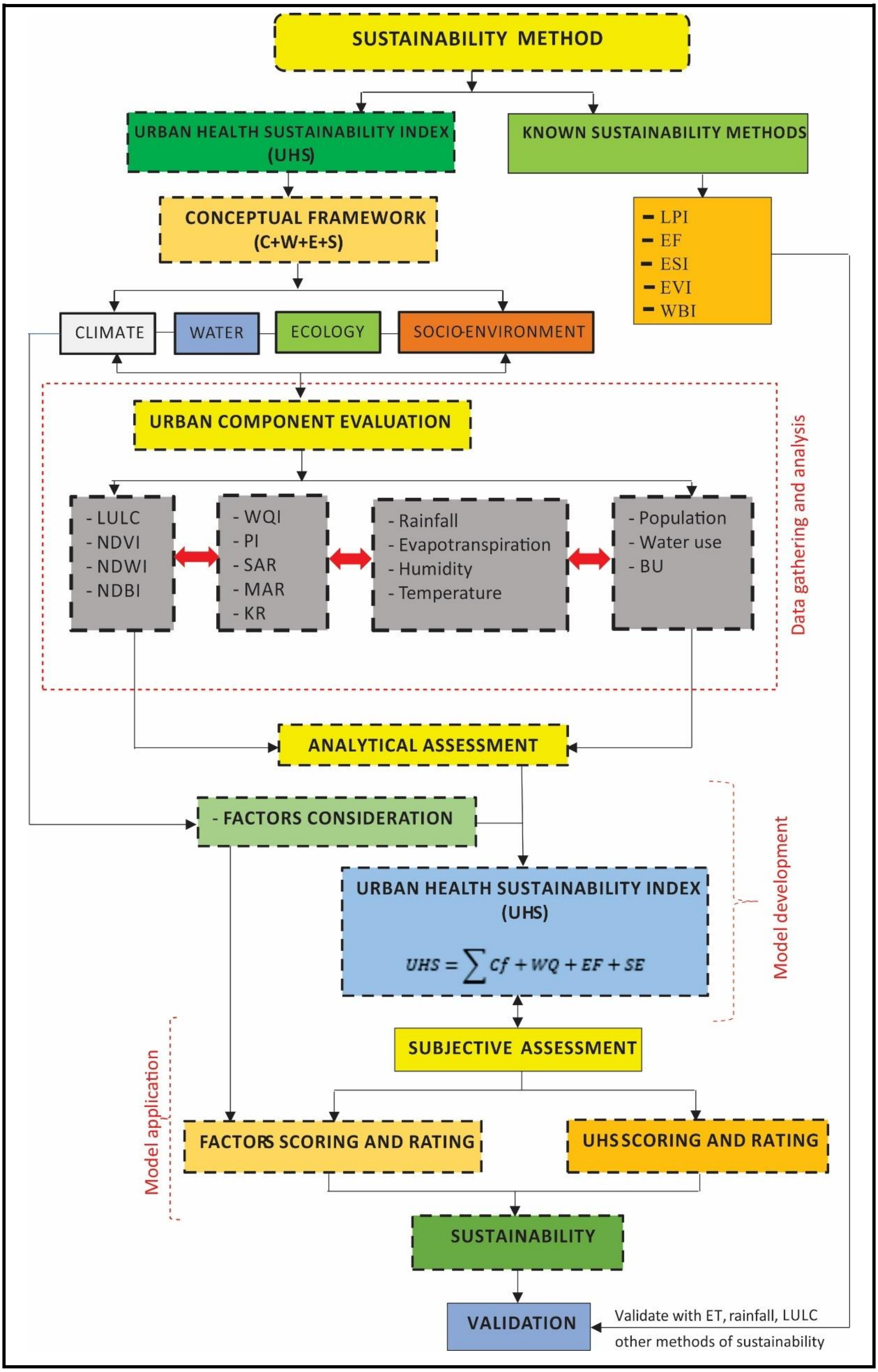


Figure 6.5: Summary of methodology and description of activities of the study

Chapter 7

APPLICATION OF THE URBAN HEALTH SUSTAINABILITY INDEX IN THE MANGAUNG METROPOLITAN MUNICIPALITY

7.1 Introduction

Application of the sustainability index is important to test and validate the developed index for future use. Thus, this chapter tests and applies the developed UHS index on the MMM, with emphasis on urban growth, vegetation and water quality. This chapter further details the processes on available data and provide maps for all the selected factors recommended for the model. Finally, a UHS map is designed from the analysis and processes from all the corresponding factors.

The component of the sustainability assessment of an area provides a decision-making approach for environmental sustainability into the daily work of the municipality (National Research Council, 2011). This chapter is devoted to describing the elements of the UHS assessment and component and the analytic tools for use in applying it.

Researchers have proposed the following steps to be followed in model development (Beven 2001; Oke & Alowo, 2021):

- Identify objectives for the model.
- Draw diagrams to formulate a conceptual framework for the model.
- Identify the inputs and conditions, and specify the parameter values required by the model.
- Validate concepts of the model.
- Execute a preliminary sensitivity analysis using the model.
- Collect data to validate the model.

The UHS index was subjected to the steps outlined above, which used both subjective and physically-based techniques. The parameters of the sustainability model have been designed for application to evaluate the environmental health sustainability of the MMM, which can also be applied in another municipalities globally.

7.2 Data collection and preparation of sustainability maps

Climate data, water quality parameters, ecological data and spatial data were used in calculating the UHS model. The water quality of the MMM, LULC classification, vegetation and moisture index and built-up area were used for the UHS model, as well as meteorological data such as rainfall, humidity, temperature that were discussed in Chapter 3.

The water quality dataset were acquired from the DWS. Satellite data (USGS), climate variability data (SAWS, 2020) and a literature review on the social environmental dataset were also used (see Appendix C). The following environmental assessment parameters were collected:

- Physical processes such as climatic factors, including climatic zone precipitation, humidity and evapotranspiration.
- Hydrochemical data across various DWS monitoring stations in the MMM.
- River catchment delineation data base, water management systems using GIS.
- Social environmental characteristics and land use such as population in the catchment, built-up and water uses.

The GIS software (ArcGIS 10.2 and QGIS 2.61) were used for the mapping and production of the UHS maps and predictive analysis. ArcGIS and QGIS are flexible GIS software with environmental mapping facilities and other similar applications.

7.3 Parameters and scoring of the Mangaung Metropolitan Municipality

The modelling of the UHS and land use of the MMM was discussed in the previous chapters. Applying the model will allow to check the effectiveness and measure the urban environment as the population increases. Climate parameters play an important role in environmental sustainability assessment (EPA, 2019). Climate factor parameters was given the maximum score of 5, representing a high and low score of 1 for areas representing a low value based on global standards. A similar approach was taken to assign the maximum and minimum scores to the ecological factor and social environmental factor, while the water quality factor was considered using a standard procedure following WHO and SANS 241 standards.

The values for the climatic factor were received from the SAWS stations. Considering global standard in areas where annual rainfall was very low (< 400 mm/year), the lowest value of 1 was assigned as discussed in the previous chapter. Climate factor parameters were essential parameters to be considered in sustainability assessment of the MMM. Climate factors such as rainfall, evapotranspiration and humidity explain variation in environmental conditions in an urbanised area; hence, they have been considered in this study to determine the variation towards environmental health sustainability.

Climate factor variability is the resultant factor of human activities as discussed in Chapter 3. Table 7.1 illustrates the assigned values/scores for each component of the climate factor. Investigation of climate parameters in Chapter 3 showed an assignment of values from lowest to highest for the municipality. As discussed in the previous chapter, human activities and urban sprawl in an area can significantly influence other climatic parameters such as rainfall and evapotranspiration. Furthermore, a low score of 1 corresponds to an area with a low precipitation. A low climate factor of 0 to 8 corresponds to places with climatic conditions that are susceptible to urban impact.

The climate factor map is presented in Figure 7.2 shows areas of a moderate to high class of sustainability. The moderate classes suggest areas with adequate climatic conditions, while the high classes suggest areas that have been environmentally degraded.

Table 7.1: Climate factor values/scores

Score	Class of sustainability	Colour code
0–8	Very low	Red
8–20	Low	Orange
20–25	Moderate	Yellow
25–35	High	Green
35–40	Very high	Blue

Source: Author's own (2022)

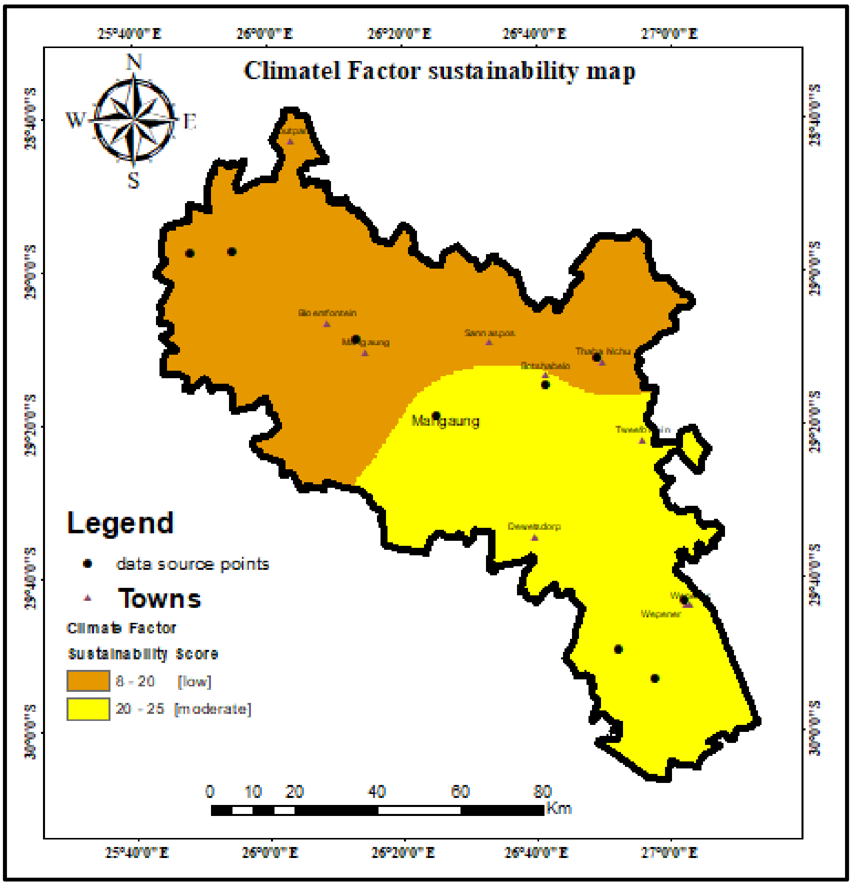


Figure 7.1: Factor A: Climatic factor assessment map

The sum of urban activities as the population increases determine the current water quality in the catchment. Historical water quality revealed that the quality of water in the catchment reduced from being excellent to good even though it was acceptable for drinking and irrigation purposes in selected parts of the municipality. The maximum score of 4 was assigned to water quality greater than 75, the lowest score of 1 to water with less than 25. Based on global reports and data bases used in this study, values and scores were assigned as shown in Table 7.2, with the lowest scores corresponding to excellent water quality status and a highest score of 4 to poor water quality status.

Data gathered from the DWS monitoring station used in the MMM for the analysis and application of the model. The values or scores were assigned by the author based on global high and low values as stated in the previous chapter. This was done so that the index can be applicable to any catchment or any part of the world. For all factors, the values were checked against DWS reports. The same treatment was given to all the parameters' properties observed in the water quality factor, given the theory, linkages and relationships between them.

Figure 7.3 represents the spatial distribution and scoring of the water quality factor. The sustainability class of the water quality marked mostly orange, yellow, and green, suggested areas that were the opposite of the desired scenario: yellow is moderate, while green represents a desirable situation. These places are not surrounded by urban areas with not much human activities close to the rivers.

Table 7.2: Water quality factor assigned values/scores

Score	Class of sustainability	Colour code
50–60	Very low	Red
43–50	Low	Orange
31–43	Moderate	Yellow
19–31	High	Green
0–19	Very high	Blue

Source: Author's own (2022)

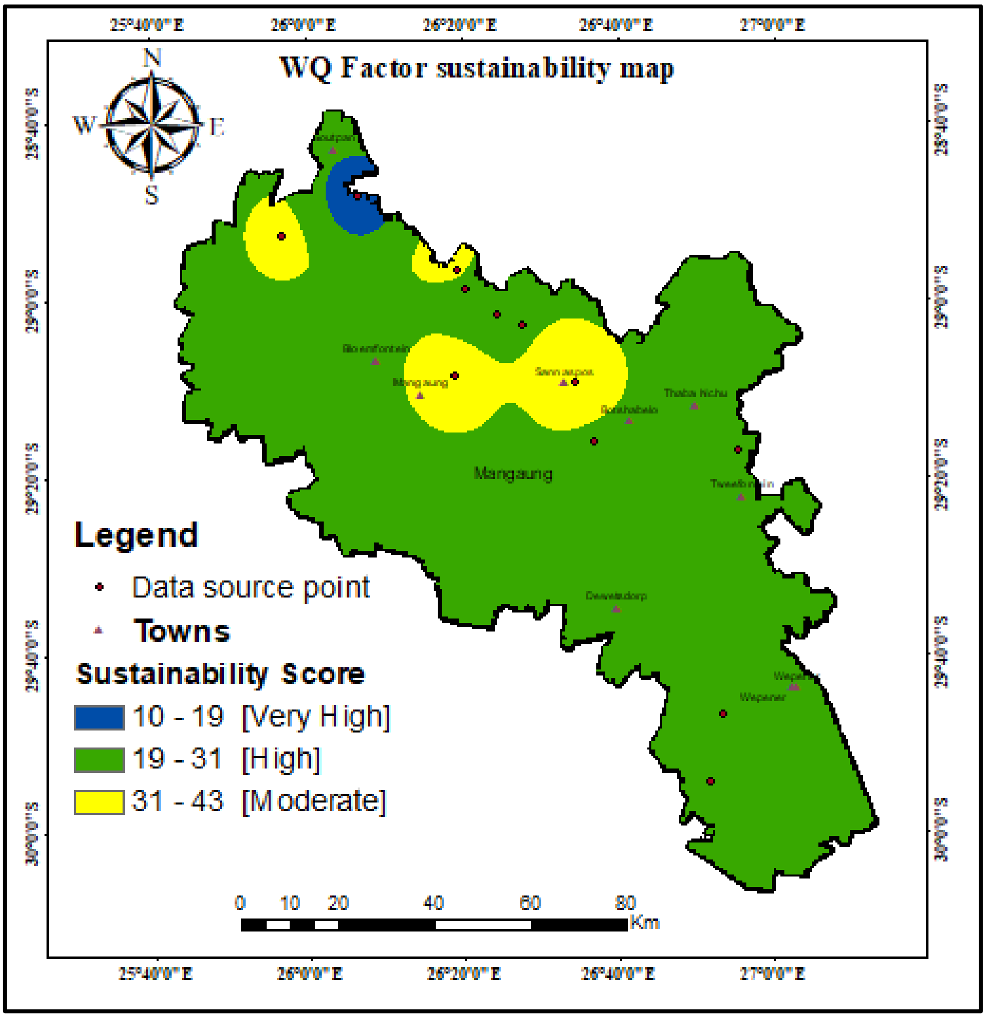


Figure 7.2: Factor B: Water quality map

The ecological factor in the MMM was assigned a maximum score of 5, to vegetation greater than 0.7 which is a definition of densely vegetation. A score of 1 was assigned to a vegetation index of less than 0.1. This is the lowest score and it indicated bare soil or no vegetation, which was not sustainable nor greenery for the environment. The score for the moisture content and air quality in the catchment showed the same trend as the ecological assessment.

In terms of the air quality analysis of the MMM, the values assigned and scored were derived from the SAWS database. Based on this data, scores were assigned as shown in Table 7.3, with the lowest scores corresponding to best practises, while the highest score of greater than 150, denoted an unhealthy practice. The values/scores were assigned by the author after comparing the municipality's value to the global high and low amounts ever recorded, as detailed in Chapter 2. Figure 7.4 shows the scoring and map of the ecological factor in the MMM.

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Table 7.3: Ecological factor assigned values/scores

Score	Class of sustainability	Colour code
0–4	Very low	Red
4–8	Low	Orange
8–12	Moderate	Yellow
12–16	High	Green
16–20	Very high	Blue

Source: Author's own (2022)

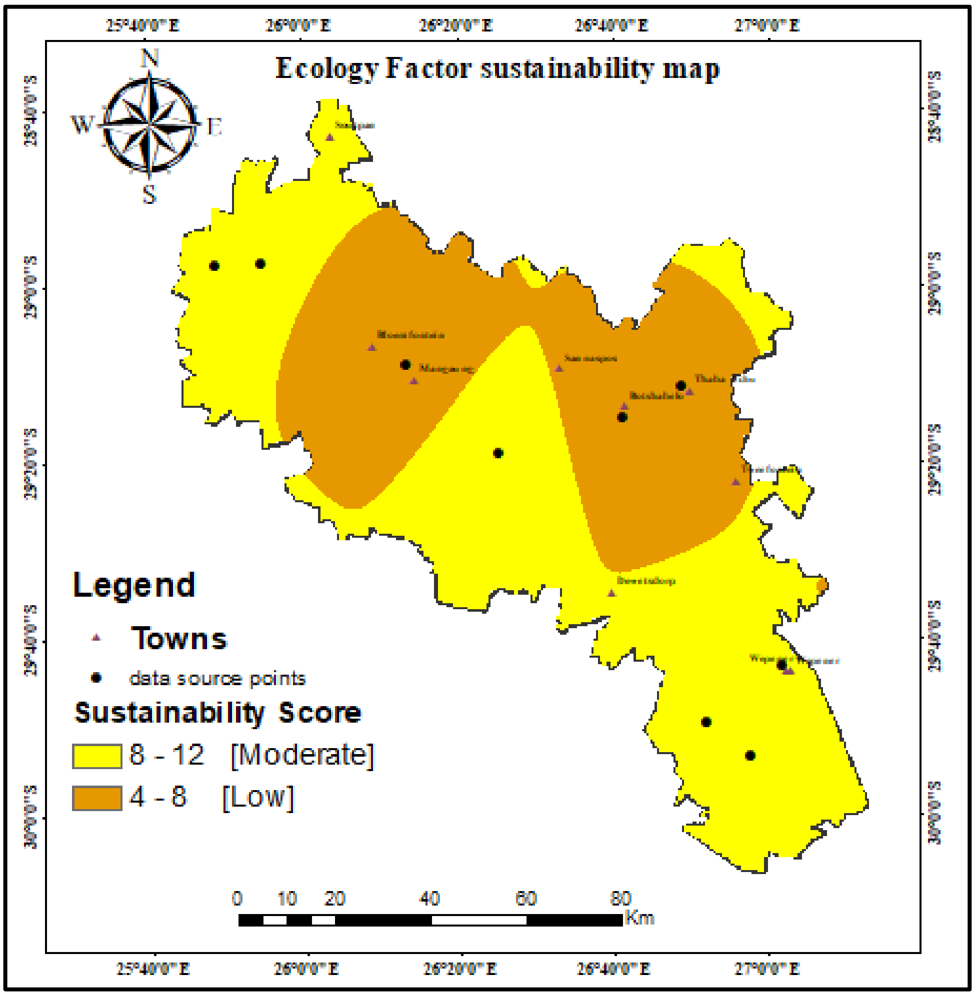

Figure 7.3: Ecological factor sustainability map of the Mangaung Metropolitan Municipality

Factors in the social environment are important to environmental health sustainability of the MMM. These include population per area, built-up as per population growth and infrastructure balance, amount of water use per day and land use in the municipality. Urban land cover has shown an increase, with a high demand for water as the population increases. However, waterbodies have been experiencing reduction and incessant contamination by an urban activity. Thus, it literally represents unsustainable environmental health, especially for future classification.

Figure 7.5 represents the scoring of the social environmental factor observed in the MMM. The sustainability class of the social environment was also marked mostly orange and suggested areas with major human activities that were usually densely populated, with high water use and demand and high agricultural activities.

Table 7.4: Social environmental factor assigned values/scores

Score	Class of sustainability	Colour code
0–5	Very low	Red
5–15	Low	Orange
15–20	Moderate	Yellow
20–25	High	Green
25–30	Very high	Blue

Source: Author's own (2022)

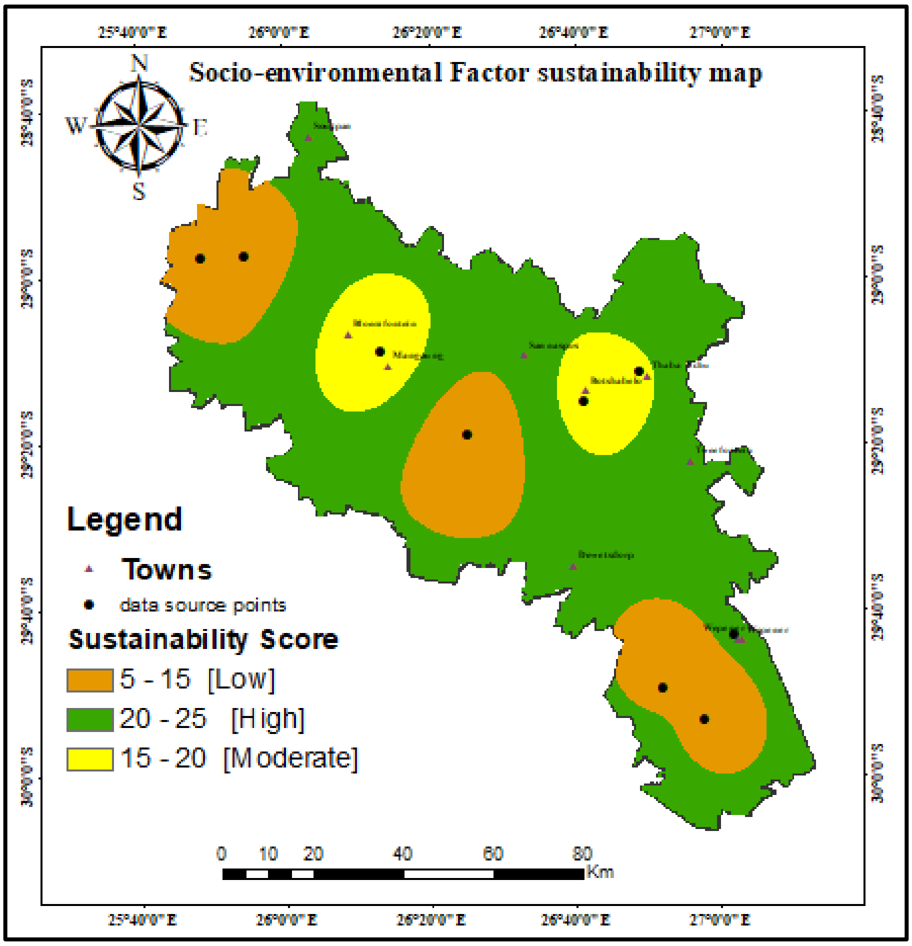

Figure 7.4: Social environmental factor sustainability map of the Mangaung Metropolitan Municipality

7.4 Urban health sustainability map of the Mangaung Metropolitan Municipality

The final UHS map as shown in Figure 7.6, was derived from the sustainability index calculations of all the factors considered above in Chapter 6. The final UHS index was computed, based on the principles behind sustainability assessment as reported in Chapter 2. The sustainability assessment methods developed for this research combine the factors of climatic environments, water quality of the surrounding surface water, ecological factors, and social environmental conditions of the study area. Furthermore, factors considered in this model were given equal weighting and were summed up to arrive at the final sustainability in Equation 28, with specified weighting and scoring figures.

The final sustainability factors were summed up using Equation 28 because they all impacted the environmental sustainability of any given area. The social environmental factor is an important parameter which accelerates changes in environmental health sustainability if not properly managed. The sustainability index has been categorised into five classes (Table 7.5). The classes and sustainability condition of the MMM are presented in Figure 7.6. The final UHS index class score of 19−35 meant a class of very low sustainability, 35−51 a class of low sustainability, 51−67 a class of moderate sustainability, 67−83 mean a class of high sustainability and 83−100 very high sustainability.

The high and very high sustainability classes correspond to areas with a favourable environmental health condition as urban areas continue to increase. The moderate to low classes represent areas that are opposite to the favourable environmental health condition, suggesting uncontrolled urban clusters, unfavourable weather and climatic conditions, as well as air quality and water quality deterioration. Specifically, for the MMM (Figure 7.6), the urban areas of Bloemfontein and Mangaung have low urban environmental health sustainability, while Thaba 'Nchu, Botshabelo and Soutpan are moderately sustainable. The rest of the MMM, such as Dewetsdorp, Wepener and Van Stadensrus, have high urban environmental health sustainability.

Table 7.5: Urban health sustainability class and index score

Score	Class of sustainability	Colour code
<30	Very low	Red
30–50	Low	Orange
50–65	Moderate	Yellow
65–80	High	Green
80–100	Very high	Blue

Source: Author's own (2022)

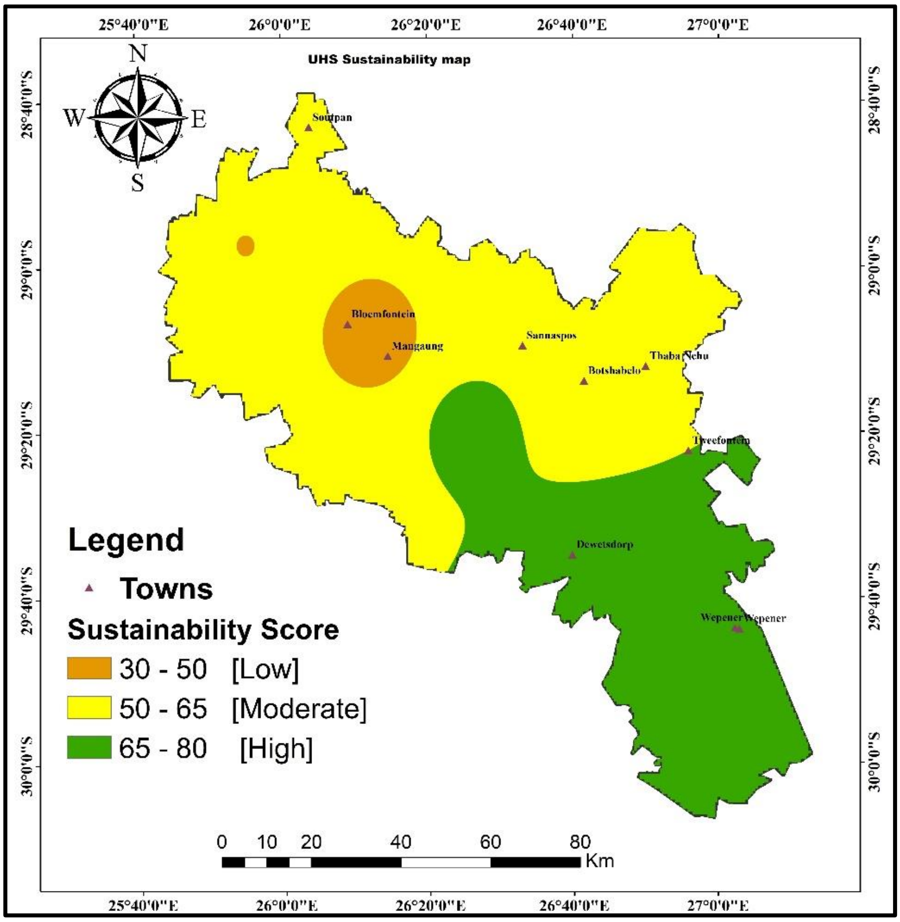

Figure 7.5: Final urban health sustainability map of the Mangaung Metropolitan Municipality

7.5 Environmental pollution assessment of the Mangaung Metropolitan Municipality using existing methods

The environmental assessment of the MMM is evaluated in this section, with other established environmental and pollution assessment methods such as EVI and CEPI methods as highlighted in Chapter 2. Sustainability maps and results from these methods will be compared to the UHS methods and observed areas of similarity and differences discussed in Chapter 8. The selected environmental assessment methods were chosen because they assess the urban environment differently as compared to the UHS method and based on the available data. The selected environmental assessment methods were established on separate environmental properties and parameters, but they all work toward assessing the sustainability of an environment to contaminations and pollution in an ecosystem.

7.5.1 Application of the Environmental Vulnerability Index method

The environmental vulnerability index is a function of exposure, sensitivity, and adaptive capacity. The environment is affected by various natural and human indicators. This method selects appropriate indicators for environmental vulnerability evaluation (Table 7.6). Indicators were selected based on available data and considering the geographical location, climate condition, soil type, and anthropogenic situation. It should be noted that this selection was not exhaustive and that only those salient indicators for which information is of great significance to urban contamination, were considered.

Table 7.6: Indicators used in assessing environmental vulnerability in Mangaung Metropolitan Municipality

Indicators	Indicator description	Data source
Soil type	Soil texture	
NDVI change	Vegetation cover over the surface	Landsat Satellite data
Maximum temperature	Monthly maximum temperature	South African Weather Service
Water level		Department of Water and Sanitation
Population density	Population number per unit area	Community survey by Statistics South Africa
Salinity	Average saline level in water	Water quality parameters
Cumulative dry day	Number of dry days in the year	Calculated from the South African Weather Service data
Cumulative wet day	Number of wet days in the year	Calculated from the South African Weather Service data
Change of population density	Change in population area in the specific period	Percentage of population change

Transformation of the original variables into new and uncorrelated variables (axis), namely principal components which are linearly combined with original variables, is the design principle of the Principal Component Analysis (PCA). PCA can be expressed as:

$$Y_i = a_{i1}x_1 + a_{i2}x_2 + a_{i3}x_3 + \cdots \dots \dots \dots \dots . + a_{im}x_m$$ *Equation 33*

Where:

Y = the component score;

a = the component loading;

x = the measured value of a variable;

i = the component number; and

m = the total number of variables.

7.5.1.1 EVI data collection

The vegetation degradation is derived by comparing the Landsat satellite data for 1978 to 2018. The climate and water level data were collected from SAWS and DWS archive. Soil type coverage of the study area were obtained from the FAO/UNESCO global soil classification, using GIS techniques. Human activities such as population density per year were collected from the South African of Bureau of Statistics.

7.5.1.2 Vulnerability assessment following the IPCC and PCA methods

Environmental vulnerability can be calculated from indicators and in the linear form of exposer, sensitivity, and adaptive capacity according to the IPCC Third Assessment Report (2007). The formula according to this report is shown as:

$$Vulnerability = Exposure \times Sensitivity - Adaptive\ capacity \qquad \text{Equation 34}$$

Each factor was assigned a weight using the PCA as described in Equation 33. The environmental vulnerability assessment map was created based on the weight of the indicators with the support of the algebraic computation as given in Equation 36. The higher environmental vulnerability value represents the more vulnerability of the environment. The integration of all indicators represents the environmental vulnerability of the study area. The integration process was done by using Equation 35.

$$Environmental\ vulnerability = B1 \times B2 \times \ldots\ldots\ldots\ldots\ldots\ldots\ldots \times Bn \qquad \text{Equation 35}$$

Where B is the major groups of indicators:

$$B = \sum_{i=1}^{n} V_i\ X\ W_i \qquad \text{Equation 36}$$

Given that the indicators represent many parameters that contribute to the research area's susceptibility and vulnerability, the influence of the parameters was not given an equal consideration. All percentage-based parameters were translated to fractions between 0 and 1. To make the collection of parameters similar, the remaining indicators were scaled between 0 and 1, as is commonly done to resolve incompatibilities when combining multiple measuring units (Nguyen et al., 2016; Tate, 2013).

Table 7.7: Weight of indicators

Classification	Indicators	Weight
Exposure (landform)	Soil type	0.120301
	Water level	0.096398
	Salinity	0.097947
Sensitivity (meteorology)	Maximum temperature	0.052774
	Cumulative dry day	0.131289
	Cumulative wet day	0.070529
Adaptability	NDVI change	0.091370
	Population density	0.119253
	Change of population density	0.112745

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7.5.1.3 Environmental vulnerability map

The environmental vulnerability map for the individual indicator was divided into five vulnerability groups consisting of very low, low, medium, high, and very high vulnerabilities with an interval of 0–10, 11–15, 16–25, 26–35, 36–45, respectively (Basso et al., 2000; see Table 7.8 and Figure 7.7).

Table 7.8: The environmental vulnerability class and index scores

Score	Class of sustainability	Colour code
>10	Very low	Red
11–15	Low	Orange
16–25	Moderate	Yellow
26–35	High	Green
36–45	Very high	Blue

Source: Basso et al. (2000)

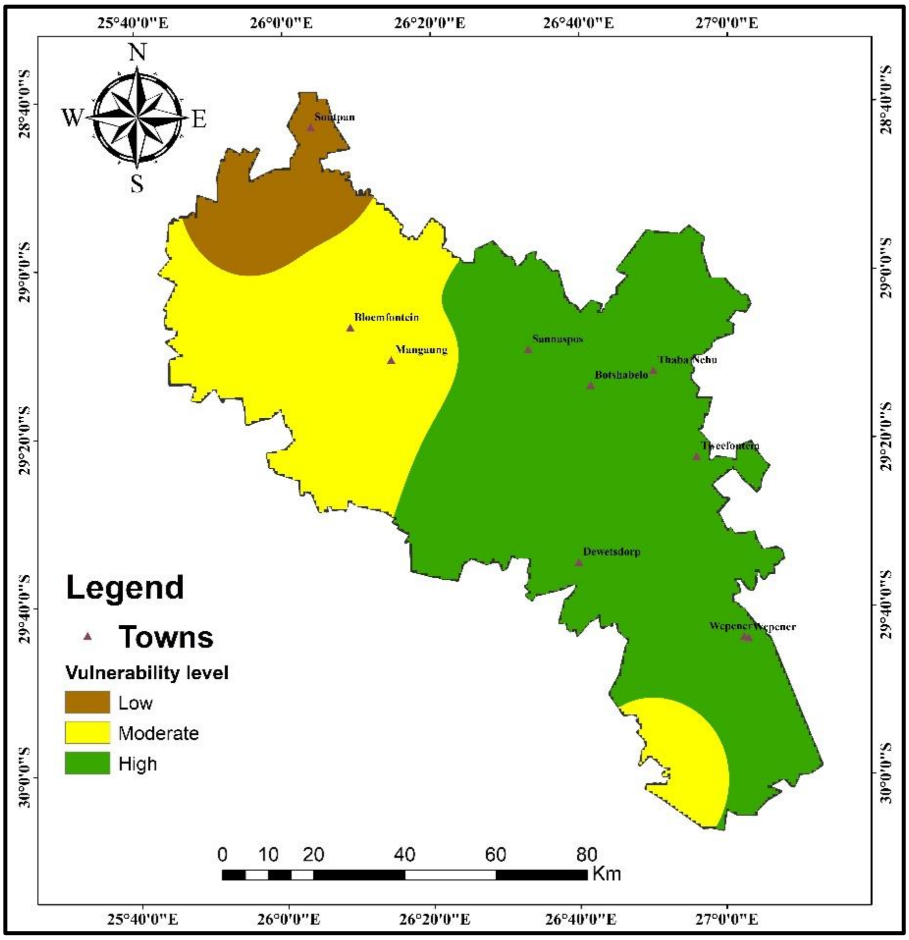

Figure 7.6: Environmental Vulnerability Index map of the Mangaung Metropolitan Municipality

From the spatial analysis, it was clear that the vulnerability groups in the MMM represented low (25%), medium (30%) and high (45%) levels. The result in Figure 7.7 shows that the areas with high levels of vulnerability are situated on the urbanised area, which lie in the central and south-western region, whereas the areas with a low level of vulnerability are in the northern region. As a result, a relatively high population density and large agricultural activities in the central and south-eastern region triggered the high vulnerability of the area. The low environmental vulnerability in other regions can be associated with low population density and human activities. Finally, it can be deduced that urbanisation and economic development have made the central region more environmentally vulnerable to pollution, which affects human health sustainability and aquatic life.

7.5.2 Application of the Comprehensive Environmental Pollution Index method

CEPI provides complete information on the extent and types of pollution caused by human and urban activities, which can be used to identify appropriate pollution mitigation measures (Rajamanickam & Nagan, 2018). The CEPI method is a **source–pathway–receptor approach** (Figure 7.8), which considers the entire geographic area affected by a polluted environment. Monitoring authorities should monitor environmental pollution and keep correct records, as this index is a quantitative way to evaluate some qualitative effects caused by human activities in an urbanised region.

The accumulated CEPI score in this study can be calculated as follows:

$$CEPI = i_m + \left\{(100 - i_m) * \left(\frac{i_2}{100}\right) * \left(\frac{i_3}{100}\right)\right\} \quad \textit{Equation 37}$$

Where:

i_m = max sub-index; and

i_2 and i_3 = sub-indices of other environmental parameters.

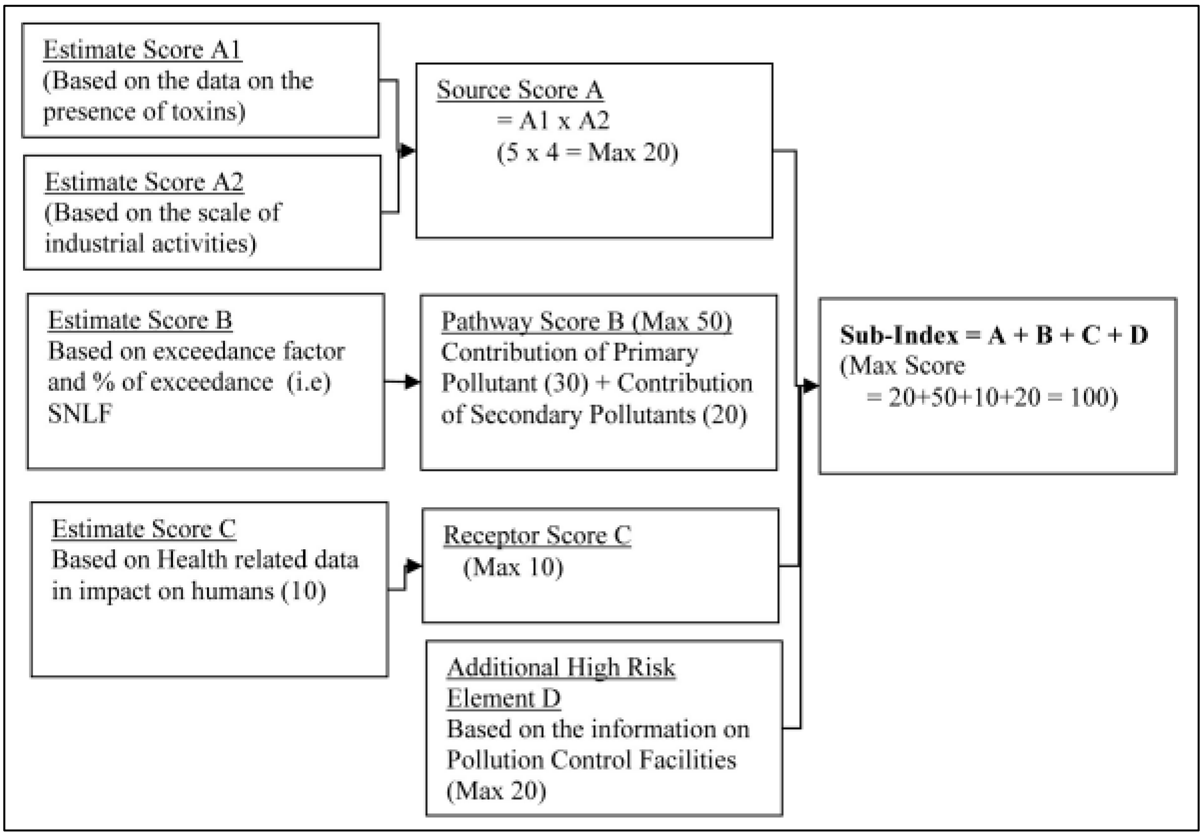

Figure 7.7: CEPI score calculation procedure

Source: Rajamanickam and Nagan (2018)

In this study, spatial variation of the CEPI in the MMM was generated using GIS techniques. The steps involved in creating the GIS images of spatial variation of CEPI in the MMM are highlighted below:

1. Creating the base map of the MMM by geo-referencing in GIS.
2. Adding the base map on a blank sheet.
3. Adding X–Y coordinates as respective latitudes and longitudes of the study area over its base map.
4. Exporting data of ambient air pollutants, surface water pollutants and groundwater pollutants one at a time over the base map.
5. Using an inverse distance weighting tool to calculate the assigned value to unknown points with a weighted average of the values available at the known points.

The CEPI analysis categorised the MMM into high polluted area, moderate polluted area and low polluted area (Figure 7.9 and Table 7.9). The areas with aggregated CEPI scores of 45–60 are considered as high polluted areas, whereas the areas with a CEPI of 25–45 are considered as moderate polluted areas. These areas should be kept under environmental monitoring and pollution control measures, whereas areas with an aggregate CEPI of below 25 are considered low polluted areas and do not contribute to environmental threat (Table 7.10).

Table 7.9: Calculation of average CEPI of the Mangaung Metropolitan Municipality

Latitude	Longitude	Air CEPI	Water CEPI	Land CEPI	Maximum sub-index (i_{max})	X (100-i_{max})	Y (X*i_2&i_3)	Z (Y/10^{-4})	Avg CEPI (Z+i_{max})	Indicator
−29.1502	26.2215	48,23	50,3	53,7	53,7	46,3	112 322,3647	11,232	64,93	High
−28.9565	25.9139	43,2	50,6	46,8	50,6	49,4	107 984,448	10,798	61,40	High
−28.958	25.8136	44,5	35,8	40,9	44,5	55,5	81 264,21	8,126	52,63	High
−29.1908	26.8158	56,7	54,8	53,9	56,7	43,3	127 896,076	12,790	69,49	High
−29.2519	26.6891	47,3	51,3	50,5	51,3	48,7	116 327,255	11,633	62,93	High
−29.3187	26.4206	50,1	55,8	56,8	56,8	43,2	120 769,056	12,077	68,88	High
−29.7208	27.0338	38,9	28,9	30,8	38,9	61,1	54 386,332	5,439	44,34	Moderate
−29.8263	26.8704	31,6	35,9	30,7	35,9	64,1	70 646,533	7,065	42,96	Moderate
−29.8912	26.9637	37,2	33,8	31,3	37,2	62,8	66 438,632	6,644	43,84	Moderate
−29.7812	26.8891	28,0	26,3	22,8	28	72	4 3174,08	4,317	32,32	Low
−29.9088	26.8605	31,1	29,5	30,2	31,1	68,9	61 383,01	6,138	37,24	Low

Table 7.10: Standard CEPI score and rating

Score	Class of sustainability	Colour code
<25	Low	Orange
25–45	Moderate	Yellow
45–65	High	Green
>65	Very high	Blue

Source: Vidayarthi et al. (2015)

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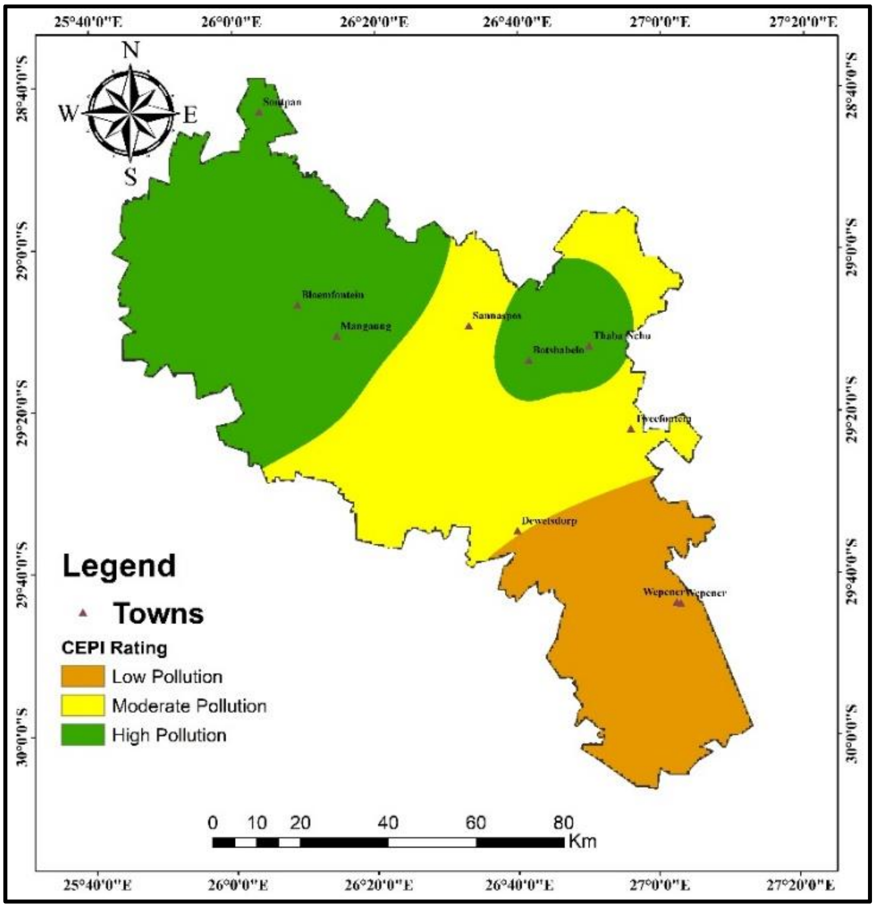

Figure 7.8: CEPI map of the Mangaung Metropolitan Municipality

7.6 Conclusion

This chapter gave an account of the application of the UHS index concept of environmental and ecological assessment for sustainable environmental health of the MMM. This chapter detailed the production of maps for all the factors under study in this thesis. The climatic condition factor, water quality condition factor, ecological factor as related to vegetation and built-up, social environmental conditions and the environmental health sustainability maps of these factors were developed using the available data. The underlying conditions responsible for the sustainability score of each factor were discussed under the maps of each factor, rather than a general description for ease of comprehension.

Data sources were identified and presented in the chapter for evaluation. It should also be noted that the tables presented in this chapter were derived and recalculated from the raw data. The raw data is presented in Appendix B. Furthermore, the UHS index is simple and understandable to apply in any environment around the world.

The chapter further applied EVI and CEPI methods to assess the environmental vulnerability and pollution index in the MMM. The vulnerability index showed a low to high vulnerability index. The high vulnerability status indicated that the area was vulnerable to environmental pollution, with a high impact on human health, while the low vulnerability score indicated areas with limited pollution and could be termed as sustainable for human health. Consequently, the CEPI revealed a similar environmental pollution score of a low to high pollution index. The low CEPI suggest areas with less pollution, while the high CEPI score suggest areas that are prone to pollution and require environmental monitoring for sustainable environmental health.

Conclusively, the UHS class in the MMM ranged from a low sustainability to high sustainability score. The low sustainability class is typical of areas with a high discharge of pollutants from agricultural and human activities, while the high sustainability class is typical of areas with a low sustainability class, generating polluting media to the atmosphere and water sources. A validation exercise will be carried out in Chapter 8 using rainfall and evapotranspiration, water quality, and LULC in the MMM. The validation of UHS will be carried out in order to compare and verify the correctness of the UHS map.

Chapter 8

VALIDATION OF THE URBAN HEALTH SUSTAINABILITY INDEX

8.1 Introduction

Validation of the newly develop model in scientific context refers to the process of establishing, through documented experimentation, that a scientific method is fit for its intended purpose (Alowo, 2021; Oke, 2015). Validation allows for comparison of calculated indices and other measured parameters (Alowo, 2021; Xanke et al., 2017). The validation of the UHS index map of the MMM is discussed in this chapter. This is important to evaluate the ability of the UHS method for an environmental sustainability assessment in a global climate change condition. An explanation of the sustainability scores is given according to the state of the municipality as observed. Furthermore, correlation of graphs and maps highlight its potency and some of the strengths and weaknesses of the urban health sustainability index map.

Daly et al. (2002), Oke (2015), Oke et al. (2018) and Saidi et al. (2011) gave account of most common validation processes carried out in physical and life science analyses, which include analogical studies, water balance, and calibrated numerical simulations. Therefore, the UHS index of the MMM will be tested using other available data. The validation for this research was therefore carried out by using traditional relationship curves and maps. The graphs in this chapter further assess sensitivities when a given parameter is varied. In other words, this chapter tests and correlates the results from the model with observed environmental and hydrochemical parameters. Therefore, the following specific validations are presented in this chapter:

- The relationship between NO_3 and PO_4 with the built-up area.
- Comparison of the relationship between evapotranspiration and rainfall in the municipality in relation to sustainability of the area.
- The plot of the relationship between built-up areas and vegetation in the municipality.
- Comparison of the modelled sustainability map with the land cover map and water quality map.

8.2 Environmental indicators in the Mangaung Metropolitan Municipality

Selected environmental indicators in the MMM, presented in Figure 8.1, show the relationship between water quality, temperature and built-up areas from 1978 to 2018. In this study, water quality is an important environmental indicator to consider for sustainable environmental health studies. This section focuses on selected parameters (NO_3 and PO_4), which influenced the deterioration in water quality over the years.

Human and plants utilise NO_3 at its minimal rate. When NO_3 levels rise faster than what the plants can use in freshwater, the plants can become overgrown with algae and NO_3 can also affect how human blood carries oxygen. In human health, consumption of NO_3 can turn haemoglobin into methaemoglobin. High amounts of NO_3 intake can cause skin to turn bluish or grey, as well as more serious health effects such as weakness, increased heart rate, weariness, and disorientation. The EPA maximum contaminant level for NO_3–N in municipal water supply is 10 mg/l and is based on acute health effects. In this study, the concentration of NO_3 was recorded to be in the maximum range of 0.80–11.03 mg/l, with a mean value of 0.29 ± 0.06 and 1.46 ± 0.98, respectively. This study has shown that the overall level of NO_3 was very low between 1978 to 1998. However, the highest concentrations of NO_3 above the permissible limit of 11.03 and 10.48 mg/l were recorded in 2008 and 2018, respectively.

The lower levels of NO_3 recorded in this study indicates that sources of pollution from urbanisation and agriculture was not significant prior to 2008. Furthermore, there has been record of significant sources of pollution from urban development and agricultural activities from 2008, which raised the NO_3 level above the permissible limit of 10 mg/l. As with NO_3, the low level of phosphate recorded in the water samples around the MMM indicates that the water was not yet exposed to eutrophication during the period 1978 to 2008; however, the highest record of phosphate was in 2008 and 2018 (Table 5.9).

Similarly, the built-up areas observed using remote sensing has shown an exponential increase in built-up areas (Figure 8.1). This is due to rapid urbanisation, population growth and industrialisation in the MMM. Consequently, the temperature shows variations from 1978 to 2018. However, the highest temperature recorded was in 1988 and 2018, respectively.

This comparison has validated that rapid urbanisation in the MMM increased the concentration level of NO_3 and PO_4 in water quality, which contributed to deterioration of the WQI in this study. Likewise, rapid urbanisation and population growth changed land use land cover patterns in the MMM.

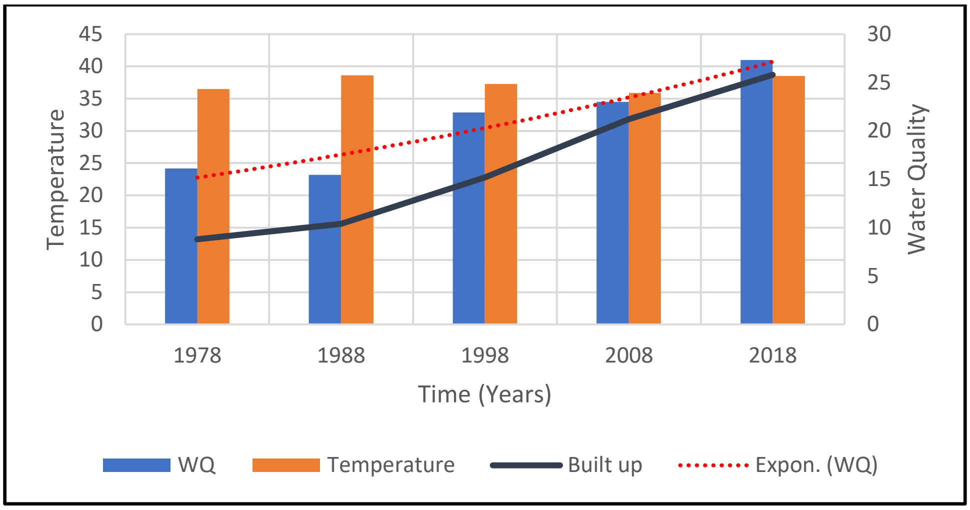

***Figure 8.1:** Comparison between water quality, temperature and built-up in Mangaung Metropolitan Municipality*

8.3 Relationship between evapotranspiration and rainfall in the Mangaung Metropolitan Municipality

Precipitation and evapotranspiration were important climate variables considered in the study area. It is described in terms of the rain received in the MMM, which represents the amount of water received in the Caledon–Modder River catchment. This determination is a measure of the mean rainfall dependent on climatic conditions, as measured by the SAWS rain gauges or stations. From the plot in Figure 8.2, evapotranspiration is on average 1 070 mm higher than the rainfall.

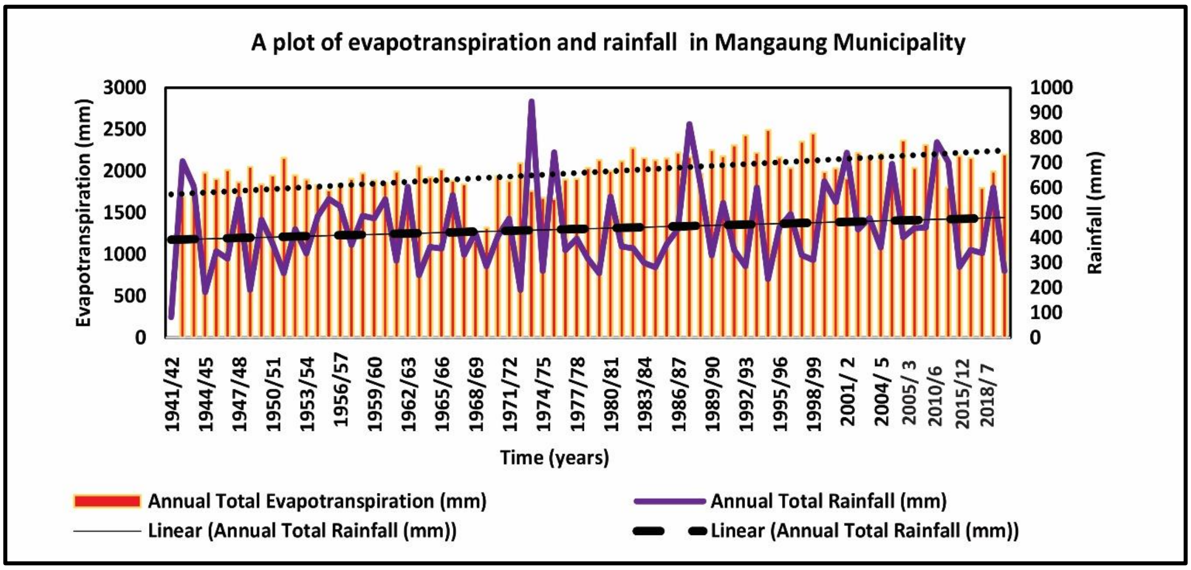

***Figure 8.2:** Relationship between evapotranspiration and rainfall across the study area*

Source: Oke and Alowo (2021)

The annual rainfall was significantly lower than evapotranspiration, which is an indication of water loss in the municipality and the catchment (Oke & Alowo, 2021), thereby suggesting an imbalance in the hydrological cycle of the MMM. The imbalance in the hydrological cycle represented the impact of urbanisation on climate variability in the study area. The Caledon–Modder River catchment received its highest rainfall in 1974/1975, with an estimated amount of 945 mm. Based on the rainfall in this period, water resource availability was higher than in recent years with an increase in the urban population. The climate factor sustainability map shows areas with a low and moderate sustainability score (Figure 6.7). The low rainfall indicated low sustainability scores in the southern part of the study area. Therefore, the climate factor sustainability was driven by the amount of precipitation in the study area.

8.4 Impact of built-up on vegetation in the Mangaung Metropolitan Municipality

Several built-up indices from satellite data have been proposed in order to investigate the urban sprawl globally (Valdiviezo-N et al., 2018). This research adopted the use of Landsat satellite data to investigate LULC in the MMM. This study focused on mapping built-up regions in the MMM. Therefore, all mapped LULC areas were divided into built-up areas and all others. Built-up regions made up almost 26% of the total study area. As previously mentioned, no more effort was taken to distinguish the precise uses of these regions in terms of residential, commercial, highways, and infrastructure.

The result of LULC classification showed an exponential increase in built-up areas from 1978 to 2018. The relationship between the built-up areas and vegetation in the MMM is shown in Figure 8.3. The built-up areas showed an exponential increase, while the vegetation cover presented a decline. The decrease in vegetation cover is due to urban sprawl and the rise in population, which therefore led to expansion of the agricultural area. The study has revealed the impact of urbanisation on vegetation and water that does not contribute to greenery and sustainable environmental health.

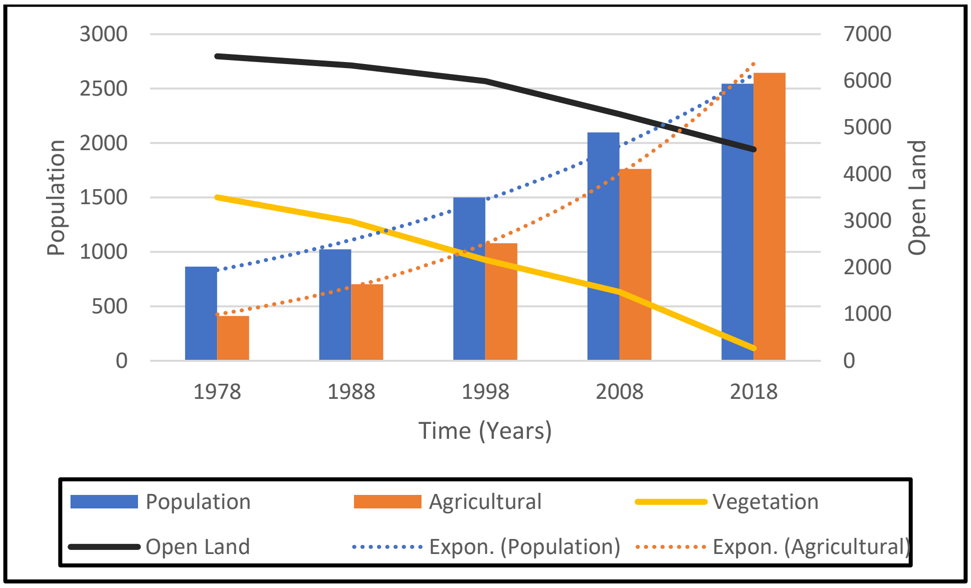

Figure 8.3: Relationship between built-up areas and vegetation loss across the study area

8.5 Comparison of the modelled sustainability map with the land cover map and water quality map

This section discusses the validation of the UHS results of the study, using the maps that were previously derived in Chapters 6, as well as the LULC classification to identify built-up areas, vegetation cover and waterbodies. This section also compares it with the UH sustainability index map generated in Chapter 6 and the current water quality map. The UH sustainability map, land cover map and water quality map for this study is presented in Figure 8.4. The three maps were placed together to assist with comparison and to identify their commonalities.

There is a generally acceptable (high score) water quality in the Caledon–Modder catchment as observed in Chapter 5. However, pockets of low score water quality was observed close to the urban area and agricultural farmland. This is due to the high rate of contaminants from the agricultural farms and urban areas. The highest water quality was found in the northern part of the study area (sparsely populated), while the central region of Bloemfontein and Botshabelo showed moderate water quality. The moderate water quality area suggests the low to moderate environmental health sustainability of that part of the municipality as seen in the UHS map (Figure 8.4).

Similarly, LULC shows urban clusters in the central region of the study area which validated the moderate water quality. This suggests the impact of urbanisation on water quality in the study area as compared with other regions with sparse urban clusters and high/excellent water quality.

Finally, the sustainability index map also shows low sustainability score in the central region of the study area (Figure 8.4). This corroborates the low water quality observed in the study area, likewise a densely populated and built-up index observed from the LULC classification. This study has revealed that there was an impact of urbanisation on the current environmental health in the MMM. The impact of urbanisation has contributed to low water sources quality in most densely populated areas, vegetation loss and low environmental health sustainability.

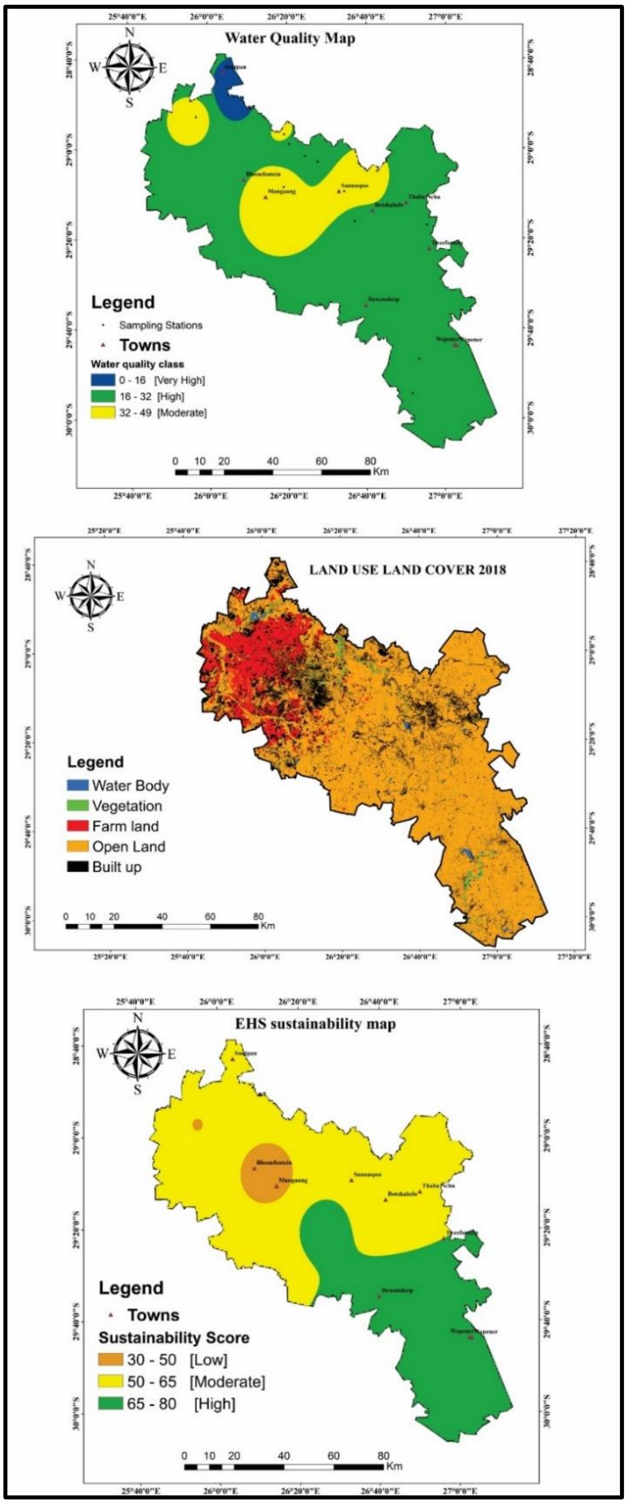

Figure 8.4: Comparison maps validating the urban health sustainability of the Mangaung Metropolitan Municipality

8.6 Comparison between the UHS, EVI and CEPI methods

The sustainability map developed from the UHS method shows areas from low to moderate and high sustainability scores as presented in Chapter 7. In validating to results of the UHS method, further assessments was conducted with other environmental pollution and vulnerability methods as presented in Chapter 2. The methods considered for the validation purposes are the EVI and CEPI methods. The EVI and CEPI methods were established on separate environmental properties and parameters; however, they all work toward assessing the sustainability of an environment to contaminations and pollution of an ecosystem.

The results from these methods will influence the outcome of the UHS maps and its validity. Figure 8.5 shows the similarity between the UHS and CEPI methods. The sustainability index observed with UHS revealed high sustainability, where CEPI shows low pollution; consequently, a higher pollution index observed using the CEPI method suggested low sustainability in the study area. The relationship between the CEPI and the UHS method in Figure 8.5 suggests reasonable agreement. This comparison was done to ascertain the degree of accuracy and inconsistency between the established environmental pollution assessment methods and the UHS method.

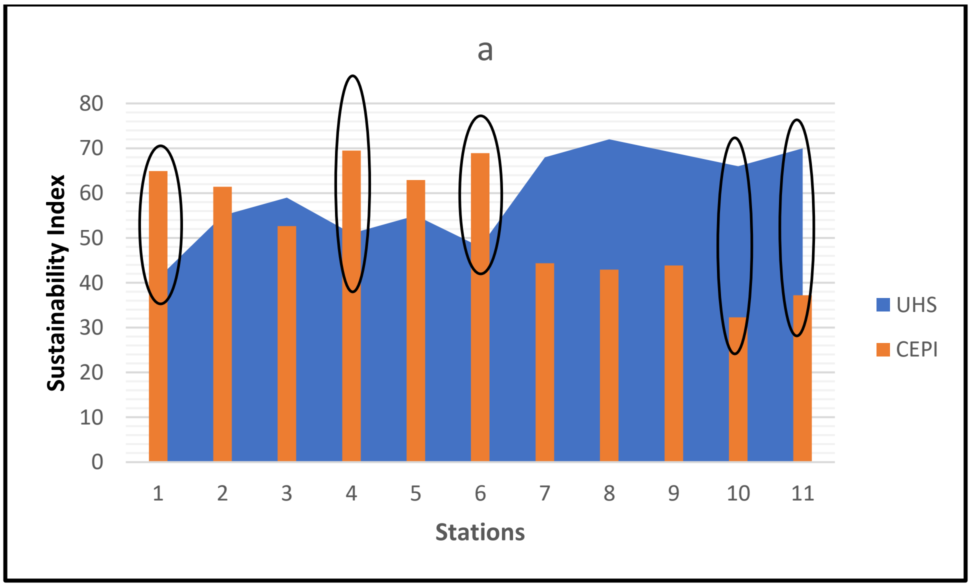

Figure 8.5: Comparison between UHS and CEPI methods

Furthermore, the comparison between the UHS and EVI methods presented in Figure 8.6 revealed similarities as well as discrepancies in the results. The highest discrepancy between the UHS, CEPI and EVI was noted between the UHS and the EVI method. The EVI revealed high to low vulnerability to environmental pollution in some areas, and the sustainability of those areas were not in agreement. Whereas, in some areas where the environmental pollution was low, the sustainability was high as shown in Stations 2, 3, 7, 8 and 11 (Figure 8.6).

The lowest discrepancy and consistency were observed between the UHS and the CEPI methods (Figure 8.5). This suggests higher accuracy between the UHS and CEPI methods as compared to the EVI methods. This implies the applicability of the UHS method to the suitability of environmental sustainability assessment, given that the CEPI method had been adopted by other researchers (Vidayarthi et al., 2015).

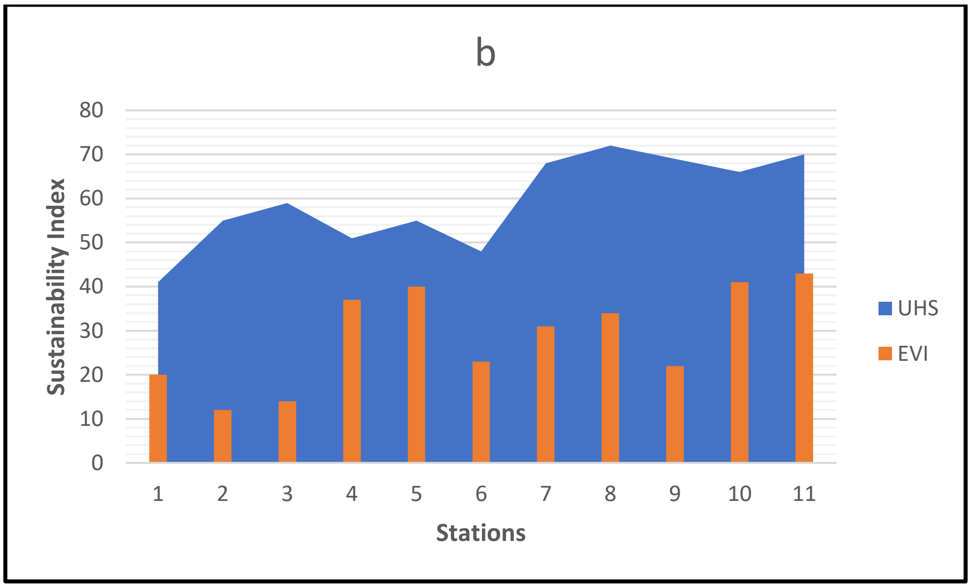

Figure 8.6: Comparison between UHS and EVI methods

8.6.1 Comparison of the sustainability methods and maps

Comparison between the three sustainability methods and maps gave an account of the validity and variation between the UHS and other existing methods. The three environmental assessment methods showed some similarities as well as differences in the results obtained. This section compares the parameters considered in the UHS methods, with other sustainability methods considered in Chapter 7. Table 8.1 presents the similarity and differences in the parameter considered in the three methods.

The UHS and EVI methods considered more parameters, while the CEPI method had the least considered parameters. Only the UHS and EVI considered the land use and vegetation which are major drivers of urbanisation and reflection of environmental degradation in terms of biodiversity loss in vegetation. None of the methods were developed for measuring the source of emerging contaminants. Population growth and climate variables such as temperature and precipitation were considered by all the sustainability methods.

Table 8.1: Parameters considered under the three sustainability methods in this research

Parameters	Urban health sustainability	Environmental Vulnerability Index	Comprehensive Environmental Pollution Index
Water quality	+	+	+
Land use	+	+	–
Vegetation cover	+	+	–
Air quality	+	–	+
Isotopes	–	–	–
Soil	–	+	+
Population	+	+	+
Built-up	+	–	–
Emerging contaminant	–	–	–
Temperature	+	+	+
Precipitation	+	+	+
Water level	–	+	–

The CEPI and UHS show significant correlation in terms of the pollution index and sustainability index. The area with high a pollution index indicates areas of low sustainability (Figure 8.7). All the methods classified the area ranging between low to high vulnerability, pollution and sustainability, respectively. The EVI shows a larger percentage of the area classified as high. The high vulnerability of the area observed from the EVI was due to the rapid growth of informal settlements (urban slums) and agricultural activities in the eastern and south-eastern region of the study area. Consequently, the area classified as moderate and low vulnerability, were lower. This can be said as an area with moderate sustainability and high sustainability.

Table 8.2: Sustainability classification and range

Methods	Very low	Low	Moderate	High	Very high
UHS	<30	30–50	50–65	65–80	>80
EVI	<10	10–15	15–25	25–35	35–45
CEPI	–	<25	25–45	45–65	>65

According to the CEPI map and method, the study area classification ranged from a low to high pollution index. About 45% of the area are characterised by the high pollution index. These areas are characterised by densely populated areas in the MMM. These areas also have high rapid urban slums, inadequate sanitation and generated contaminants that flow to the surrounding stream and river system. Furthermore, about 35% of the area are characterised by a moderate pollution index. These areas are represented by urban and suburban areas and agricultural activities. The southern region falls under the low CEPI score and represent about 20% of the study area. The southern region was the least populated region and generated less environmental contaminants.

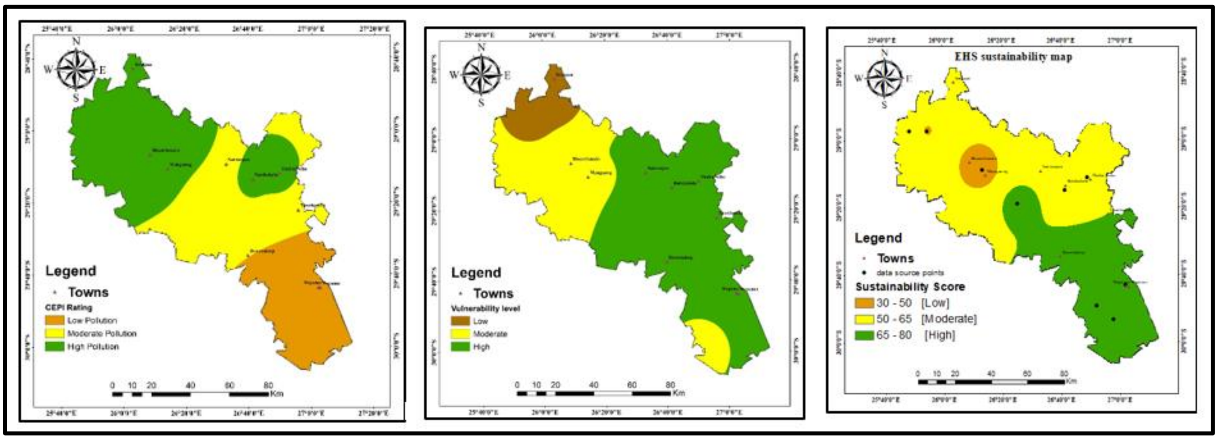

Figure 8.7: Comparison of sustainability classes and maps

8.7 Conclusion

The aim of this chapter was to validate the UHS index map produced to assess the impact of urbanisation on environmental health sustainability of the MMM. Validation was performed to analyse the MMM which lies in the Caledon–Modder River subcatchment, using other methods and maps compared with the final UHS map of the study area. An attempt was made to use comparison and correlation charts and maps, where possible, to highlight the strengths and weaknesses of the UHS map.

This study has classified the LULC of the study area into built-up areas, waterbodies, agricultural land, open land and vegetation cover. Built-up areas and agricultural land has experienced an increase within the last 40 years, while waterbodies and vegetation cover has been reducing in the MMM. It is worthy to note that reduction in waterbodies and vegetation cover are due to increase in built-up areas as a result of population growth, thereby necessitating an increase in agricultural/farmland to meet up with the growing population and for food security. This has exacerbated changes in climate conditions that accelerate climate change impact on the municipality and its environment.

Validation of a model is an important aspect of environmental studies. The significance of a model should be judged by its suitability for a specific purpose. The validation performed in this study was a process executed to determine if the model accurately represents the actual environmental conditions. The findings corresponded to the presentation and results of the UHS map.

This chapter concluded that a model is sound and dependable if it accomplishes what was expected. In addition, it can be said that the UHS of the study area depended more on human driven factors that are determined by the LULC pattern and population growth in the MMM. In summary, it would be interesting to use recommendations from this study in future studies to support claims that the low UHS of the central region is due to human activities in urban areas of the municipality.

Chapter 9

SIMULATING FUTURE PREDICTION OF LAND USE / LAND COVER OF THE MANGAUNG METROPOLITAN MUNICIPALITY

9.1 Introduction

LULC change is significantly increasing and primarily stimulated by natural phenomena and human activities (Alam et al., 2019; Javed et al., 2012). Information and time series of LULC change can be observed using satellite data and ground surveys (Gallego, 2004). Prediction of LULC using remote sensing data is important for the future management plan of LULC (Gashaw, 2017), and it is regularly employed for an environmental sustainability measure as a proxy of human influence on land cover change processes.

A common approach to tracking changes in the local environment and vegetation is to conduct LULC surveys (El-Tantawi et al., 2019). Hydrological processes, such as runoff patterns, peak flow characteristics and water quality are affected by changes in the LULC of a region (Ashaolu et al., 2019). LULC is regarded as a significant component in streamflow shift because it has the potential to influence the hydrological processes within the catchment (Msovu et al., 2019). Indirectly or directly, humans have had an impact on and affected the landscape (Buday & Buday, 2019).

As a result of direct management activities, such as farming, forestry, and other related activities, the land's usage is determined by its position in the community. The earth's surface and near subsurface environment are referred to as land cover (Srivastava et al., 2020; Wang et al., 2021). Soil erosion, desertification, and other forms of environmental degradation are all a result of shifting land uses and coverings due to climate change (Bhattacharya et al., 2020). The ideal instrument for managing land use change research and natural resources is the combination of remote sensing and a GIS instrument. Scientists, environmentalists, agriculturalists, policymakers, and urban planners gain from analysing and tracking regional and temporal LULC shifts (Guidigan et al., 2019). As a result of the use of remote sensing, land management and long-term change dynamics, tracking can be more effectively accomplished (Bhattacharya et al., 2020; Bokaye et al., 2018).

On the other hand, LULC transition models seek to predict how often and when these changes will occur. Researchers worldwide are using land prediction models such as IDRISI's CA MARKOV, CLUE-S / Dyna-CLUE, DYNAMICS EGO, and Land Change Modeler. Future prediction models proved to be incredibly useful in determining how past and future LULC changes may affect soil erosion, particularly on farming (Perovi et al., 2018).

The CA-Markov model is one in which the future state of a system can be predicted purely based on the proximately preceding state. CA models are also increasingly being used in urban planning studies. Urban sprawl and deforestation caused by natural disasters and human activities can be simulated using the CA-Markov model (Saputra & Lee, 2019). In this study, predicting future change was accomplished by developing a transition probability matrix of LULC change from 2018 to 2038. Furthermore, the researcher employed multispectral satellite imageries and the CA-Markov chain model to estimate the LULC change in the MMM.

9.2 Processes and methods of land use / land cover simulation

Methods for land use change evaluation (MOLUSCE) plugin in Quantum GIS 2.18 software was used for the simulation of the LULC 2028 and 2038 in the MMM. MOLUSCE is a QGIS plugin for land use change evaluation. The model is an algorithm used for prediction of land use changes and has featured six LULC prediction phases (Hakim et al., 2019). QGIS was used to predict spatiotemporal changes and compute the LULC transition between the research intervals (2028 and 2038) using the MOLUSCE plugin. Matrix of change and transition probabilities are based on LULC data and contextual elements, including rows and columns of landscape categories at the beginning and end of each year. The ANN multilayer perceptron technique was utilised to model transition potentials in the land use classification analysed. The DEM and drainage map were examined as explanatory elements. Data on physical and human influences on LULC dynamics is provided by these variables, which are frequently used for study. The following flow chart explains the analytical procedure for carrying out this research work (Figure 9.1)

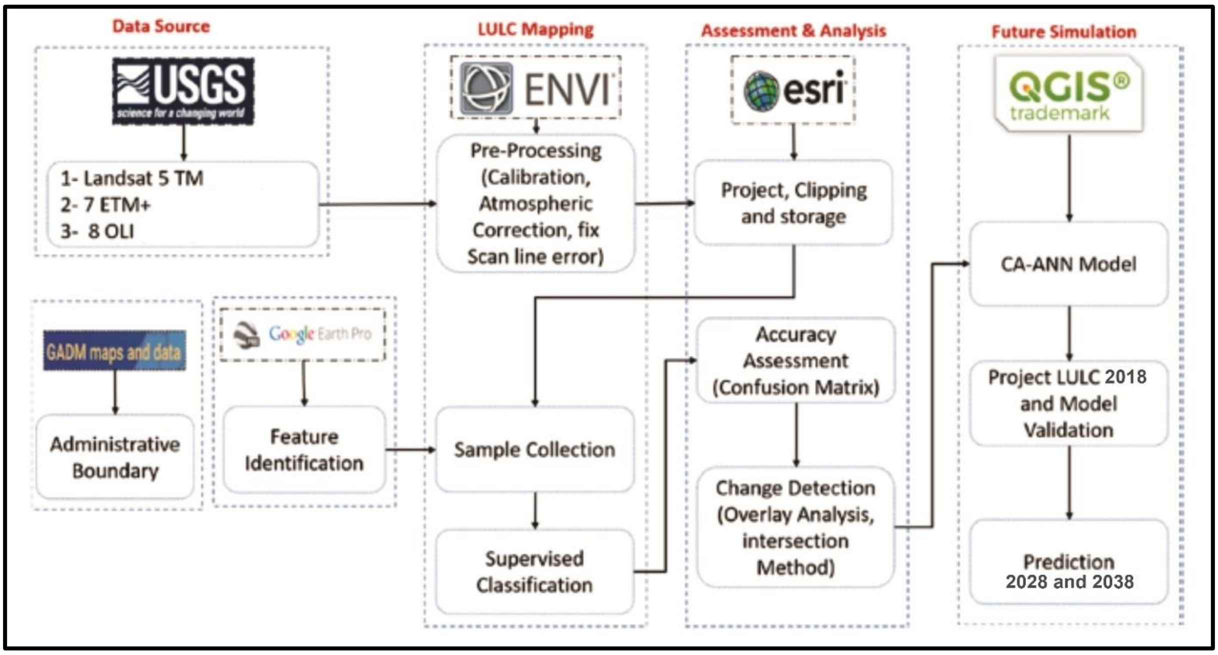

Figure 9.1: Processes and methodological flow chart

In summary, the MOLUSCE plugin implements the processes listed below:

- Takes raster of land use categories for the past time period with raster of land use categories for the present time period and raster of explanatory variables to predict the future scenario.
- Trains a model to forecast changes in land usage from the past to the present.
- Forecasts future land use changes based on a developed model to simulate past land use, and current circumstances.

9.2.1 Data input and validation

The image of the satellite Landsat dataset that has been processed was placed into MOLUSCE, along with the variables of LULC modifications that have also been processed in accordance with the map extent. The initial stage of the model was to add LULC maps for the start (1978) and end years (2018). Land cover change maps for the research region between 1978 and 2018 were created using spatial variables such as DEM, river, and built-up. A 30-m pixel size is used to extract the attributes of the explanatory maps from all datasets, using the same geographic projected coordinates of the UTM 35S.

Using this plugin, it can be established how land use has changed in a particular year and how many pixels have changed from one land use cover to another. All five classifications of built-up areas, farmland, vegetation, open land and waterbodies are shown in the area change map created by the plugin. The ANN-(Multi-layer perception) plugin was utilised to project the change in LULC (Buday & Buday, 2019; Msovu et al., 2019). It was also expected that in the years 2028 and 2038, LULC shifts will take place. If the current LULC pattern and dynamics persist, future LULC maps can be projected.

Validation is carried out by determining the overall kappa value between the reference map (LULC 2018) and the simulated map (LULC 2018) with an accuracy of 75%. Returning to the cellular automation simulation step after the overall kappa value is in agreement with the assessment standard. The kappa coefficient is commonly used to assess LULC change (Alawamy et al., 2020; Ullah et al., 2019). The aggregate kappa value was used to validate the projected and actual 2018 LULC maps. The formula for calculating the Kappa coefficient is given below (Alawamy et al., 2020; Satya et al., 2020; Ullah et al., 2019).

9.3 Predicted land/use land cover 2028 and 2038

The projected land use/land cover of 2028 and 2038 were computed using the CA-Markov model as presented in Figure 9.2, while their area is given in Table 9.1. The predicted area of vegetation decreases from 99km^2 in 2028 to 92 km^2 in 2038, waterbodies from 38.2 km^2 in 2028 to 31.2 km^2 in 2038 and barren surface decreases from 4 051.1 km^2 in 2028 to 3 421

Central University of Technology, Free State

km^2 in 2038. Nonetheless, a continuous increase in agricultural land area was predicted from 2 798 in 2028 to 2 995 in 2038, while the built-up area will experience the same increase from 2 894.2 in 2028 to 3 341 in 2038. In addition, as compared to LULC 1978–2038, agricultural land and built-up will increase by 26% and 25%, respectively, while waterbody and vegetation will decrease by 5.5% and 14.2%, respectively. The expansion of the urban centre observed in this research was expected to increase at the expense of barren surface area and vegetation cover.

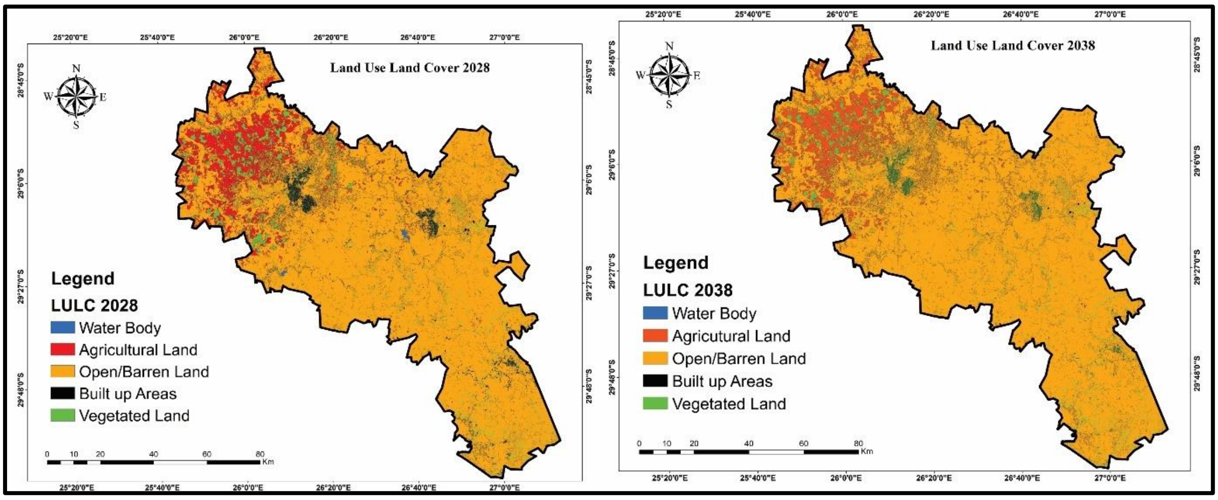

Figure 9.2: Predicted land use / land cover maps for the years 2028 and 2038

Table 9.1: Projected land use / land cover of 2028 and 2038 area distribution

Land use / land cover classes	2028		2038		1978-2038	
	Area (m^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Built-up areas	865.5	8.760121	1 024.4	10.36842	2 475.5	25.05567
Waterbodies	575.4	5.823887	541.2	5.477733	−544.2	−5.5081
Vegetated areas	1 501.3	15.19534	1 281.3	12.96862	−1 409,.3	−14.2642
Agricultural areas	410.7	4.156883	702.2	7.107287	2 584.3	26.15688
Barren surface areas	6 527.1	66.06377	6 330.9	64.07794	−3 106.1	−31.4383
Total area	**9 880**	**100**	**9 880**	**100**		

9.3.1 Simulated land use / land cover (2018) and model validation

The MOLUSCE plugin integrates some well-known algorithms for transition potential modelling, such as the ANN (multilayer perceptron), weights of evidence, multicriteria evaluation, logistic regression, and CA algorithms for future simulation. Cramer's coefficient was used to select the geographical variables for model calibration based on their relatively significant association with LULC. In addition, the researcher employed the CA-ANN method for transition potential modelling and prediction.

In this study, simulated and actual LULC in the MMM was established for the year 2018. Thus, the actual and simulated LULC maps of the year 2018 revealed a similarity in built-up areas and the waterbody area with slight differences in other LULC classes (Figure 9.3). The area coverage of the two maps showed that all LULC classes had the best range of agreement with a rate of difference lower than 5% (Table 9.2).

Validating the model, kappa index of agreement (KIA), a comparison was made between the actual and simulated LULC maps of 2018. The validation of the model or KIA statistics and the actual and predicted LULC change of the 2018 period result (Table 9.2) showed a good similarity between the actual and predicted maps of 2018. The accuracy and overall kappa value was 65%, which represents a strong agreement between the two map categories. Such a validation process was evaluating the agreement of the two maps (predicted and actual) in terms of the number of pixels in each LULC class and in terms of their location of the pixels.

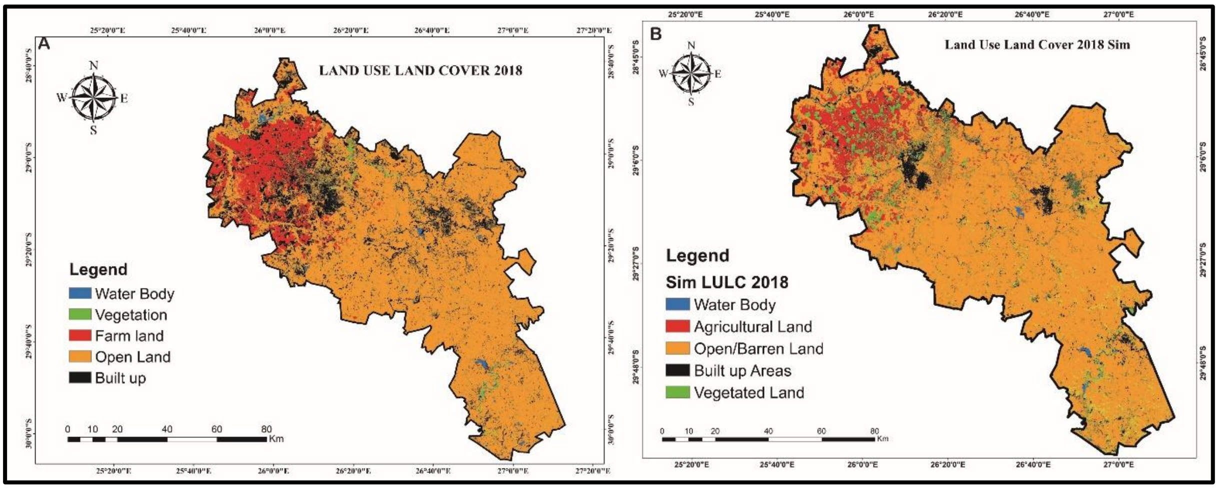

Figure 9.3: Model validation using actual and simulated land use / land cover (2018)

Table 9.2: Comparison of actual and simulated land use / land cover changes in 2018

Land use / land cover classes	Actual 2018		Simulated 2018		Change	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Rate of change	Percentage of change
Built-up areas	2 545.7	25.76619	2 437	24.66599	−108.7	−1.1002
Waterbodies	42.9	0.434211	49.0	0.495951	6.1	0.061741
Vegetated areas	115.5	1.169028	143.0	1.447368	27.5	0.27834
Agricultural areas	2 645.0	26.77126	2 991	30.27328	346.0	3.502024
Barren surface areas	4 530.9	45.85931	4 260	43.11741	−270.9	−2.7419
Total area (km^2)	9 880	100	9 880	100		

9.4 Impact of land use / land cover changes on environmental health sustainability of the Mangaung Metropolitan Municipality

The LULC shift of the MMM has a substantial impact on environmental health and social environmental issues such as livelihood vulnerability and internal migration. The result of land cover classification and built-up area reflects on the rapid urbanisation in an agricultural-based economy which is the major issue of socio-economic development. As a result of rapid urbanisation in the last decade, agricultural farming has increased in the MMM in order to meet the demand of food by the population and for food security and sustainability. This has resulted in an increase in usage of fertilisers and pesticides, which in turn increased pollution in soil and water sources. The incessant pollution of water sources has led to poor water quality supply in the MMM, which has resulted in poor quality municipal water supply and impacted environmental health sustainability. A period of drought was recorded in 2015 and 2016 in the MMM due to climate change (Oke & Ruzvidzo, 2021). Climate change impact has been aggravated by human activities as the population increased uncontrollably.

Climate change, groundwater depletion, and water scarcity have major effects for soil fertility, crop failure, and agricultural activity, with severe effects on quality of lives and livelihood. Furthermore, vegetation has been highly impacted due to rapid urbanisation in the MMM. Many vegetated cover areas have been converted to informal settlements in the suburbs of major cities. Urban slums have, therefore, increased with low quality lifestyle and livelihood.

The agricultural inputs have worsened the constraints for cultivation methods since land degradation has occurred. As a result, local farmers have attempted to diversify their primary source of income through non-crop economic activities. Farmers have used a variety of measures to create resilience, including agroforestry, riparian resource reliance, and riverbank cultivation. Due to the lack of appropriate infrastructure to meet the rapid urbanisation and lack of government support, the people could not manage an upgraded livelihood. Hence, the impact of climate change, rapid urbanisation, poor water quality supply have exacerbated service delivery to the people of the MMM. People suffered from acute poverty, loss of identity and displacement, resulting in the degradation of land and quality of life.

9.5 Significance and contribution of the current research

The major significance and contribution of this research to scientific knowledge was the development of an UHS index. The UHS was designed to assess the impact of urban development on environmental health sustainability of the MMM in the Free State province of South Africa. The UHS techniques explored independent and non-independent variables related to the environment and human health. The UHS index variables for evaluation were simplified to collect available data specified and calculated the sustainability mark to decipher the environmental health conditions. Hence, the designed UHS tool may be used to evaluate the environmental health sustainability of any region across the globe.

The UHS index has proven its applicability in assessing the environmental health sustainability depicting the sustainability condition in the face of rapid urban development and environmental disasters ravaging planet earth in the twenty-first century. The developed UHS index was applied to evaluate sustainability of the MMM in the central region of South Africa. The urban development and land cover landscape was mapped as part of the basis for the index modelling using a GIS and remote sensing platform. Consequently, climatic conditions, social environmental, water quality, ecological factors and sustainability factor maps were produced, and a final UHS map was generated using ArcGIS 10.2 software. The sustainability class observed in the MMM ranged from low sustainability to high sustainability. The low sustainability class is typical of areas with high discharge of pollutant from agricultural and human activities, while the high sustainability class is typical of areas with low generating polluting media to the atmosphere and water sources (Figure 9.4).

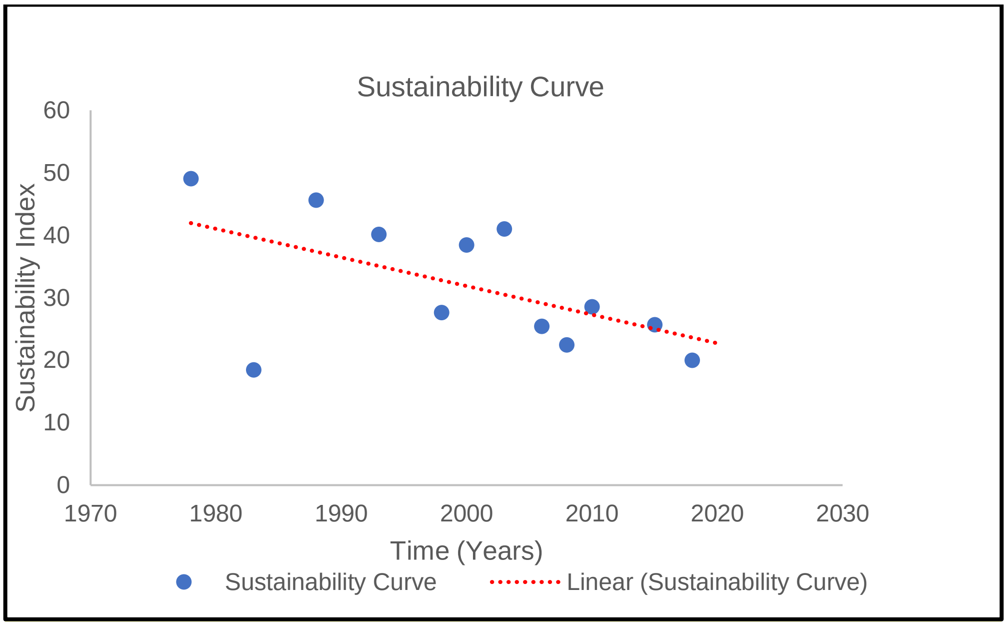

Figure 9.4: Sustainability curve of the Mangaung Metropolitan Municipality

The GIS and remote sensing investigation of the MMM revealed increase in urban areas in terms of built-up assessment from the satellite imagery analysis. The study also revealed an increase in agricultural land areas. This is an indication of rapid urban development, population growth and high demand on agricultural activities to combat food insecurity. The LULC analysis using a remote sensing method has significantly proven that urbanised areas reduce the availability of water sources, poor water quality supply and contribute to environmental degradation by loss of vegetation.

The UHS index is an applicable tool like other environmental sustainability methods for environmental assessment and management. This method may be used to investigate environmental conditions in a similar rapidly urbanising locality with limited available data. The study explored water quality analysis, built-up expansion, ecological assessments, focussing on vegetation pertaining to environmental sustainability as factors for the UHS index method. The scores and ranking of the factors were necessary to achieve the objectives of this research. The application of the UHS to evaluate and monitor the environmental conditions of the study area was considered successful. This is what this study sought to achieve, and which has been the achievement of this study and contribution towards the environmental sustainability goal.

The study further investigated the future LULC to observe the potential impact of urban development on environmental sustainability. The future simulation of LULC used the MOLUSCE plugin in Quantum GIS software. The model is an algorithm used for prediction of land use changes and has featured six LULC prediction phases (Hakim et al., 2019). QGIS was used to predict LULC changes and compute the LULC transition between the research intervals (2028 and 2038) using the MOLUSCE plugin. The results of the future simulation revealed the impact of urban development on the environment which was also an achievement of this research.

The CA-Markov model is inappropriate when the time interval observed is short; thus suggesting that the Markov models are generally inappropriate over sufficiently short time intervals (DelSole, 2000). Furthermore, the Ca-Markov plugins does not operate with the latest version of QGIS 3.20, which necessitate the use of QGIS 2.12 in this study. In this study, the model was used to predict LULC classification with an accuracy of 65%.

9.6 Conclusion

Changes in LULC act as global environmental drivers to climate change. Hence, a LULC change study has become a top priority for monitoring environmental degradation for sustainability around the world. This chapter predicted future LULC classification of MMM by analysing the change rate in the past and predicting the near future scenarios. The natural land resources are undergoing adverse changes to meet the growing demands of urbanisation and industrialisation in the MMM, causing an undesirable impact on the environment. A maximum likelihood LULC classification technique was performed on a series of Landsat imageries on the current and future LULC.

This chapter forecasted LULC scenarios in 2028 and 2038 using MOLUSCE in QGIS. The model simulated LULC was validated by comparing the observed LULC 2018 with the simulated LULC 2018. The model demonstrated acceptable LULC dynamics with an overall accuracy of 65%. The simulated future LULC scenarios illustrated an increase in the built-up lands and shrinkage of natural land covers such as vegetated lands, barren surface lands, and waterbodies.

The urban growth indicator based on the literature and land cover observed in this study confirmed the extreme transformations of barren surface and vegetated areas in terms of urbanisation. The negative impact of urbanisation on the natural land cover will likely be more concerning in the near future. Mapping land cover changes, using Landsat images, provided crucial information for policymakers and planners in understanding the consequences of urban growth, especially towards the environment. Thus, for long-term environmental preservation, the author maintain that policymakers must adopt sound urban design and management practices for sustainable environmental health of the Mangaung Metropolitan Municipality.

Chapter 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Introduction

This final chapter summarises the research findings with adequate conclusions and recommendations based on the findings from the results. It also makes suggestions for additional effort and investigation towards sustainable urban environment in the phase of rapid urbanisation and climate change. The research aims and objectives for this study were substantively met. The research goal was to analyse and characterise urban development influencing land use in the Mangaung Metropolitan Municipality in the Free State province of South Africa.

Rapid urbanisation in MMM has impacted land use change and exacerbated poor water quality supply. Human activities and dilapidating urban infrastructure accelerate environmental degradation and climate change. The negative impact of climate change and the rising urban population in the municipality caused a need to design a framework for sustainable environmental health and management by modelling land cover changes, water quality, social environmental and climatic factors affecting environmental health sustainability of the rapidly urbanising MMM environment.

10.2 Conclusion

Two main aims were set to accomplish the specific objectives of the study as discussed in section 1.4. Monitoring and characterisation of urban development as well as model index development were sub-aims set to achieve the specific objectives in this research. Therefore, the conclusions are further presented in the following sub-sections.

10.2.1 Rate of urbanisation and future prediction in the Mangaung Metropolitan Municipality area using remote sensing and a geographic information system

Urban classification using remote sensing was carried out in the MMM to observe the relationship between urbanisation and environmental sustainability. Remote sensing and GIS are extremely effective techniques for examining the dimensions of rapidly expanding metropolitan areas (Oke & Ruzvidzo, 2021; Sansare & Mhaske, 2020; Senbore and Oke, 2021).

The rate of urbanisation has been observed in the MMM using remote sensing and GIS techniques from 1978 to 2018. The assessment of LULC observed between 1978 and 2018 revealed rapid expansion of built-up areas throughout the years. The agricultural area increased by 22.6% between 1978 to 2018. As a result of urban expansion and population growth, there have been a need to increase agricultural activities to combat food insecurity in the MMM, which increased the level of environmental contamination. Increase in agricultural activities has contributed to an increase in contaminants that polluted the urban water system (Senbore & Oke, 2021).

Consequently, the research revealed that waterbodies in MMM have experienced a shortfall by 5.4%, while 14% of the vegetation cover were lossed through the years, which had negative effect on environmental sustainability and mitigating the effect of climate change. Evidently, loss of vegetation, environmental degradation and rapid urbanisation have impacted environmental sustainability based on the results from this research.

Future prediction of LULC, using the CA-Markov model revealed that there will be future loss of waterbodies, vegetation and an increase in built-up area. The area covered by vegetation will decrease from 99 km^2 in 2028 to 92 km^2 in 2038. The area covered by waterbodies will decrease from 38.2 km^2 in 2028 to 31.2 km^2 in 2038. The barren surface area will decrease from 4 051.1 km^2 in 2028 to 3 421 km^2 in 2038. Nonetheless, agricultural land area will increase continuously from 2 798 km^2 in 2028 to 2 995 km^2 in 2038, while built-up areas will increase similarly from 2 894.2 km^2 in 2028 to 3 341 km^2 in 2038.

Furthermore, compared to LULC 1978–2038, agricultural land and built-up areas will rise by 26% and 25%, respectively, while waterbodies and vegetation will decline by 5.5% and 14.2%, respectively. The observed development of urban centres in this study is projected to continue at the expense of barren surface areas and vegetation cover.

10.2.2 Surface water quality of the study area

Generally, the water quality observed in the study was suitable for drinking and irrigation purposes. However, the water quality rating observed in 1978 fell withing the class 1 bracket and compared with 2018, representing class 2. The average WQI scores ranged between 19.98 and 56.56 from 1978 to 2018, suggesting excellent and an undesirable water quality for drinking and irrigation supply, irrespectively.

Physicochemical parameters observed in the research area revealed an increase in NO_3, phosphate and chloride content from 1978 to 2018. An increase in NO_3 content indicated a level of contaminants from human activities.

The WQI values in 1988 for all the samples observed in the study area scored 20.12, 27.47, 23.21, 24.98, 20.27, 24.88, 40.16, 18.69, 43.32, 39.71, and 22.16. All the samples were of excellent quality, except for Kgabanyane and Renosterspruit which were of lower quality with a rating as *good*. The water quality rating for 1988 consisted of a good and poor quality rating with the values ranging from 26.05, 27.64, 2.86, 31.67, 27.45, 46.83, 31.64, 37.80, 53.49, 40.99, and 22.16. This suggests that the water observed in the study area deteriorated more in 1998 as compared to 1978. Succinctly, most of the water quality ratings of the samples observed in 2018 were represented as good, with the following index score: 19.98, 25.69, 28.53, 22.47, 25.42, 41.01, 38.43, 27.62, 45.64, 18.44, and 49.07, compared to the observed water quality rating in 1978 that represented an excellent class.

The deterioration in water quality from excellent in 1978 with a little drop in quality to good in 2018 suggest the impact of urbanisation and human activities is reflecting on the water quality across the rivers and dams in the study area.

10.2.3 Historical urban water cycle component

Meteorological data, such as precipitation, humidity, temperature, and cloud cover were gathered from the SAWS for this research to estimate the urban water cycle for the purpose of environmental sustainability assessment in the MMM. The mean average rainfall of 720 mm was recorded as 1 978 mm and 419 mm in 2018, while evapotranspiration also varied considerably across the study area from 1 700 mm in 1978 to 1 400 mm in 2018. The amount of rainfall was considerably lower than evapotranspiration in 1978 and the same scenario was observed in 2018 that evapotranspiration was higher than the amount of rainfall received.

The study revealed a higher level of cloud cover, reduction in the amount of rainfall and an increase in temperature in 2018. This is a clear indication of water loss and imbalance in the hydrological cycle, which is an element of extreme weather that accelerate drought and other climate change effects on the urban environment. This validated the drought experience in 2016 as reported by the DWS.

10.2.4 Development and application of indices to model environmental health sustainability of the Mangaung Metropolitan Municipality

UHS was developed and applied to assess the environmental health sustainability of the MMM in the Free State province of South Africa. The conceptual framework and selected parameters chosen was discussed extensively in Chapter 5 and the production of maps for all the factors considered under study in this research were presented. There has been a high demand for residential space to meet the rapid urbanisation in the MMM, which in turn has been impacting environmental sustainability. The UHS index measured the overall progress of the MMM toward environmental sustainability. The UHS index developed observed the relationship between urban sprawl, LULC change, climate variables, vegetation and water quality in terms of its sustainability to the population of the MMM.

The climate factor as well as historical water quality in environmental sustainability conditions were important parameters considered in this research; likewise, the ecological factor plays a vital role in our natural ecosystem and also supports the biosphere in various ways for its sustainability. Finally, the final factor was the social environmental factor that encompasses all interactions between humans and the earth, such as personal and societal connections, institutions, cultural practise and physical impacts arising from human activity and interaction within the planet.

Rating and weighting limit conditions for all factors in developing UHS were based on the global highest and lowest values recorded. This was adopted so that the UHS would be applicable to any other municipality in South Africa or any part of the world. This method was based on using various factors of the environment to understand a set of selected parameters, such as climate variabilities, ecological, water quality and social environmental indicators. Chapter 6 furthermore presented that urban and built-up expansion contribute to increasing environmental degradation and pollution, thus accelerating climate change in the MMM. The sustainability classes that were derived followed other methods of analysis of complex sustainability challenges around environmental and urban management. These methods offered a range of sustainability classes from very high to very low. The resulting sustainability index was easy to collate and use. It was designed for zones such as the rapidly urbanising areas in the MMM, as well as other urban centres in South Africa and across the globe.

The application of the UHS index concept of environmental and ecological assessment for sustainable environmental health of the MMM was presented in Chapter 6. This chapter detailed the production of maps for all the factors under study in this thesis. The climatic conditions factor, water quality condition factor, ecological factor as related to vegetation and built-up, social environmental conditions and the environmental health sustainability maps of these factors were produced using the data from the developed factors.

Finally, the UHS class in the MMM ranged from low sustainability to high sustainability. The low sustainability class is typical of areas with high discharge of pollutant from agricultural and human activities, while the high sustainability class is typical of areas with low-generating polluting media to the atmosphere and water sources.

10.3 Recommendations

The impact of rapid urbanisation on water sources and environmental sustainability has been confirmed and evidence was presented from the MMM. The UHS map of the MMM presented a low sustainability condition in the most densely populated region in the study area. Thus, it calls for future concern for environmental health sustainability as urbanisation continues to sprawl in the MMM. The sustainability assessment presented a risk taken on the environmental ecosystem in the catchment if urbanisation remained uncontrolled and unplanned. Restrictions are needed to control internal emigration of people from rural to urban centres in order to avoid overstretching on the infrastructure and reducing urban activities that contribute to environmental degradation.

The recommendations suggested in this research thesis were based on the findings and challenges encountered during the research for the sustainability of the MMM. These recommendations are presented under the following categories.

10.3.1 Recommendation for future studies

- The future studies on impact of rapid urbanisation on environmental sustainability need to focus on urban classification and major sources of urban pollutants to assess and evaluate any possible future impact on the environment, water resources and human health that would arise from unplanned urban growth.
- Also, an environmental geochemistry investigation should be conducted in the urban and suburban centres to trace the sources of emerging contaminants contributing to water and environmental contaminants.
- It is also advisable to conduct research based on an increased number of particulate matter, cloud cover and other air quality parameters to determine the source of air pollutants.
- The UHS methodology evaluation will be useful for environmental sustainability assessment. This index, with available data and the right approach, can examine environmental sustainability in a similar urban setting.
- Future seasonal data collection and evaluation of urban health is imperative in the study area. This will inform researchers on the season that is most susceptible to unsustainable urban health.
- Further improvement on the UHS method should be considered to include contaminant type and diseases affecting human health.

10.3.2 Recommendation

This research has shown that some causes of environmental degradation due to rapid urbanisation in the MMM lie in the legislation and the regulating agencies.

- It is therefore recommended that policymakers in the study area should curtail increases in unplanned settlements and control internal migration. This is to allow for the urban sustainability goal by 2050 as campaigned by the UN.

- Attention should be given to the townships to reduce the generation of solid waste at the sources through mandatory standards and regulations, education and voluntary compliance.
- Adequate steps should be taken to prevent environmental and water pollution to improve the quality of life of the inhabitants by providing facilities and quality service delivery; otherwise, the urban dwellers in the MMM may become susceptible to devastating health and environmental hazards.
- The standard of living in urban centres has led to the growth of informal settlements and slums near the urban centres that constitute unhealthy living and working environment.
- Sustainable urban growth and urban planning for a sustainable urban development is to ensure that all socio-amenities is available to urban inhabitants without imposing any negative effects on the environment.

10.4 Final conclusion

The study was conducted in the MMM of the Free State province with the aim of investigating the impact of rapid urban development on climatic and river systems on environmental health sustainability conditions. The major urbanising areas in the MMM include Bloemfontein, Botshabelo and Thaba 'Nchu. There were significant changes in LULC, NDVI, NDWI, and WQI among other observed variables and parameters. Water quality deteriorated over the period. Likewise, surface waterbodies decrease as land use increases. Land use and land cover estimations were done with remote sensing techniques, using Landsat imagery dataset.

Climatic indices such as drought, temperature and rainfall were severely affected over the period under study. The temperature increases and low amount of rainfall in recent years may have been responsible for the drought experienced in 2016. The rainfall amount in 1978 was about double what was experienced in 2018. This affected the greenest areas and survival of vegetation. The sudden increase in urban areas in the MMM has tripled since 1978.

Rapid urban development has reduced the surface water areas as well as vegetation cover in the MMM. This was responsible for the low evapotranspiration with the subsequent reduction in the amount of rainfall. Low rainfall and surface waterbodies meant low surface water volume and a decrease in water quality because of the increase in compounds and contaminants that where once diluted.

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Appendix A

HYDROCHEMICAL DATA FROM THE MONITORING STATIONS ACROSS THE STUDY AREA

Longitude	Latitude	Station	Year	Ca	Cl	DMS	EC	F	K	Mg	Na	NH_4	NO_3	pH	PO_4	Si	SO_4	Total Alkalinity ($CaCO_3$)
26.573333	-29.160278	C5H003Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.573333	-29.160278	C5H003Q01	1988	15,89	11,71	149,1	20,02	0,273	3,861	6,82	12,14	0,251	0,87	6,942	0,1376	5,216	7,57	70,4
26.573333	-29.160278	C5H003Q01	1998	34,5375	24,5875	358,438	45,1146	0,26688	5,63833	16,3563	33,9688	0,04175	0,16306	8,28146	0,12508	4,25104	24,3792	178,381
26.573333	-29.160278	C5H003Q01	2008	32,8083	38,648	207,344	41,9867	0,26793	6,98254	15,9727	32,4288	0,08382	0,15678	8,10887	0,22478	4,27377	22,933	146,47
26.573333	-29.160278	C5H003Q01	2018	32,95	41,6635	330,787	58,22	0,196	8,3884	11,8	40,4672	1,962	9,3824	8,3688	1,1258	5,24125	28,8653	148,099
26.341944	-28.984722	C5H006Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.341944	-28.984722	C5H006Q01	1988	37,6	51,15	373	54	0,235	6,18	22	38,5	0,06	0,135	7,405	0,864	3,44	28,6	152,05
26.341944	-28.984722	C5H006Q01	1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.341944	-28.984722	C5H006Q01	2008	32,2	35,697	-	41,2	-	5,907	17,981	20,882	0,025	-	8,431	0,005	3,033	22,048	160,445
26.341944	-28.984722	C5H006Q01	2018	-	12,9	-	23,4	0,025	4,5	-	11,2	0,05	0,483	8,3	0,034	4,8	14,1	72,8
26.318056	-29.144444	C5H007Q01	1978	31,3	13,2	-	37,2	0,23	-	15,1	22,3	-	0,02	7,9	-	-	13,8	137,3
26.318056	-29.144444	C5H007Q01	1988	39,66	37,3	438,8	60,12	0,444	3,024	23,9	47,04	0,076	0,268	7,82	0,0174	4,066	41,16	200,9
26.318056	-29.144444	C5H007Q01	1998	31,7385	41,4923	379,923	48,5231	0,30923	7,36808	18,3423	42,2692	0,07992	0,59404	8,00538	0,47354	4,41077	30,2692	167,296
26.318056	-29.144444	C5H007Q01	2008	42,1017	60,061	385,794	63,5771	0,27429	12,1512	18,3135	59,1315	0,58652	11,0263	7,67591	4,96026	7,55797	41,4242	128,614
26.318056	-29.144444	C5H007Q01	2018	24,8	36,92	291,73	43,9833	0,197	8,08333	8,4	36,3667	0,05	10,4848	8,33333	1,87167	6,84	27,48	98,55
26.112222	-28.8075	C5H015Q01	1978	23,9476	22,7952	237,619	33,5667	0,27905	4,54476	10,2333	24,6238	0,13048	0,12524	6,97286	0,09724	6,45143	9,2	115,838
26.112222	-28.8075	C5H015Q01	1988	18,8	10,1	116	16,9	0,3	2,57	5,6	5	0,02	0,36	6,66	0,064	4,58	4,3	55
26.112222	-28.8075	C5H015Q01	1998	40	93,7	536	81,5	0,32	3,58	29,7	81,4	0,042	0,895	8,28	0,019	7,07	95,3	154
26.112222	-28.8075	C5H015Q01	2008	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.112222	-28.8075	C5H015Q01	2018	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.921944	-29.285556	C5H022Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.921944	-29.285556	C5H022Q01	1988	34,8	25,6	381	43,7	0,44	3,76	22,5	32,8	0,06	0,2	8,65	0,013	1,3	20,4	196,8

Longitude	Latitude	Station	Year	Ca	Cl	DMS	EC	F	K	Mg	Na	NH_4	NO_3	pH	PO_4	Si	SO_4	Total Alkalinity ($CaCO_3$)
26.921944	-29.285556	C5H022Q01	1998	30,8737	10,1053	364,579	41,2789	0,34316	3,86737	19,3579	30	0,02874	0,05195	8,20632	0,08921	5,70368	22,2211	202,916
26.921944	-29.285556	C5H022Q01	2008	44,691	14,6128	488,91	58,82	0,733	1,8128	29,5128	38,208	0,1056	0,0694	8,3694	0,034	10,0574	22,5904	275,743
26.921944	-29.285556	C5H022Q01	2018	21,45	7	165,586	33,4	0,241	3,36667	10,2	17,4333	0,05	0,06	8,5	0,056	8,9	6,25	154,633
25.950278	-28.883333	C5H039Q01	1978	38,2364	45,3455	422,545	57,0091	0,48545	7,01545	21,0273	47,4636	0,02455	0,26	7,68909	0,01218	0,66636	23,9455	195,091
25.950278	-28.883333	C5H039Q01	1988	21,8923	20,3077	182,923	27,0077	0,21077	3,89769	9,38462	14,2308	0,19846	0,30231	7,37231	0,02323	4,32308	9,65385	83,3615
25.950278	-28.883333	C5H039Q01	1998	24,7588	21,5059	255,941	33,9059	0,27255	6,16471	10,7314	24,2471	0,0848	0,20522	8,29686	0,06424	1,68765	18,6137	121,775
25.950278	-28.883333	C5H039Q01	2008	35,2858	63,8194	440,084	60,2667	0,35195	9,15917	21,3561	56,759	0,65729	0,18504	8,09046	0,23054	2,75004	34,8305	186,011
25.950278	-28.883333	C5H039Q01	2018	20,1	33,925	401,747	38,34	0,198	7,12	19,3	31,44	0,0958	0,726	8,4	0,1332	3,9025	15,35	132,7
26.32099	-28.94911	C5H053Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.32099	-28.94911	C5H053Q01	1988	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.32099	-28.94911	C5H053Q01	1998	38,5673	47,4469	422,98	55,3918	0,25714	7,96327	19,8653	45,9898	0,22808	2,59959	8,28265	1,51582	4,98102	40,1796	169,137
26.32099	-28.94911	C5H053Q01	2008	40,6138	52,8795	340,437	53,965	0,27173	8,52094	20,3319	48,3111	0,5386	2,16936	7,9999	2,1467	4,68326	37,5945	172,088
26.32099	-28.94911	C5H053Q01	2018	29,6	49	369,205	46,92	0,1956	6,12	13	42,48	0,3056	2,425	8,3	0,603	3,74	32	144,44
26.6161	-29.2713	C5R003Q01	1978	27,7	11,5333	300,333	36,4333	0,38333	6,11667	14,0667	25,8333	0,02	0,94333	7,52333	0,00367	0,30667	7	167,033
26.6161	-29.2713	C5R003Q01	1988	13,5118	8,74706	120,941	17,6176	0,21412	4,12588	6,27059	8,65882	0,05941	0,28941	7,20588	0,03882	5,62353	5,63529	59,3
26.6161	-29.2713	C5R003Q01	1998	21,1038	7,07692	207,269	24,9635	0,26327	4,80635	9,03077	14,3673	0,09177	0,138	8,26538	0,0461	1,54808	12,7769	112,321
26.6161	-29.2713	C5R003Q01	2008	27,3497	13,2997	281,383	35,0574	0,31543	6,79891	13,057	20,4206	0,4193	1,86444	7,93963	0,46627	2,78307	14,0372	140,084
26.6161	-29.2713	C5R003Q01	2018	21,4667	8,25	196,853	21,8	0,2396	4,12	7,6	12,72	0,05	0,141	8,3	0,037	3,19	11,4	79,86
26.408333	-29.029167	C5R006Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.408333	-29.029167	C5R006Q01	1988	21,7	10,55	184	26,95	0,32	3,905	9,35	15,15	0,08	0,175	7,635	0,0125	5,715	5,8	95,05
26.408333	-29.029167	C5R006Q01	1998	27,6212	11,7731	268,442	32,8077	0,27192	4,99654	11,925	20,6077	0,03698	0,07933	8,25538	0,03667	3,06538	14,9673	144,179
26.408333	-29.029167	C5R006Q01	2008	24,6979	16,3818	214,71	32,2676	0,25833	4,69457	11,0725	19,5745	0,08296	0,16745	8,01497	0,05284	4,69662	14,2453	122,891
26.408333	-29.029167	C5R006Q01	2018	13,8	11,4	124,64	20,18	0,212	4,06	5,13333	12,1	0,056	0,77	8,02	0,0698	4,8	9,88	64,46
26.461667	-29.050556	C5R007Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26.461667	-29.050556	C5R007Q01	1988	19,7333	9,46667	163	23,9333	0,33667	3,76	8,26667	12,9	0,06667	0,11667	7,54	0,055	5,14	2,96667	85,6
26.461667	-29.050556	C5R007Q01	1998	28,0686	14,6941	283,902	34,7275	0,27922	5,14529	12,3373	23,8647	0,03904	0,06808	8,28843	0,05012	3,21784	19,3098	147,382
26.461667	-29.050556	C5R007Q01	2008	24,3023	15,2001	237,893	33,25	0,28143	5,22807	10,4001	21,4372	0,65157	0,12079	7,96114	0,11807	4,61379	14,3569	118,885
26.461667	-29.050556	C5R007Q01	2018	15,3667	15,6	154,541	27,94	0,2262	7,88	5,86667	17,34	0,0572	2,7148	8,14	0,2976	5,4	9,76	77,12
26.889164	-29.7812972	D2R006Q01	1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Longitude	Latitude	Station	Year	Ca	Cl	DMS	EC	F	K	Mg	Na	NH_4	NO_3	pH	PO_4	Si	SO_4	Total Alkalinity ($CaCO_3$)
26.889164	-29.7812972	D2R006Q01	1988	23,3429	10,0143	200,143	27,1571	0,16571	4,31857	9,92857	13,6714	0,08	0,39143	8,47143	0,02486	6,19429	5,4	107,471
26.889164	-29.7812972	D2R006Q01	1998	25,475	5,625	210	27,2083	0,2425	3,67417	9,38333	11,6167	0,02533	0,109	8,39667	0,02367	1,88167	18,1333	110,95
26.889164	-29.7812972	D2R006Q01	2008	24,4492	9,15493	231,703	28,5733	0,223	4,88186	9,56886	14,2	0,60533	0,10433	7,94733	0,18445	4,94692	14,0223	110,22
26.889164	-29.7812972	D2R006Q01	2018	20,2	22,5	175,565	27,1	0,383	3,4	7,1	18,2	0,05	0,724	8,3	0,026	5,4	13,5	71,3
26.860556	-29.908889	D2R004Q01	1978	22,9	3,96	187,4	23,92	0,207	2,609	9,02	11,49	0,076	0,325	7,337	0,0761	7,349	5,76	106,4
26.860556	-29.908889	D2R004Q01	1988	16,12	8,68	122,8	17,2	0,266	1,864	5,64	7,24	0,078	0,81	7,31	0,0354	6,378	9,38	57,36
26.860556	-29.908889	D2R004Q01	1998	23,7231	5,62308	200,462	22,8615	0,20615	1,97846	9,20769	9,96923	0,03138	0,29554	8,12	0,02631	5,57692	19,4077	105,808
26.860556	-29.908889	D2R004Q01	2008	24,6344	11,0978	129,921	27,8	0,199	2,50262	14,273	28,321	0,051	0,20517	7,93962	0,039	4,61969	37,884	172,261
26.860556	-29.908889	D2R004Q01	2018	10,7333	8	92,0387	19,55	0,13175	1,625	4,36667	10,025	0,045	0,601	8,2	0,02075	5,83333	8,53333	65,575

Appendix B:

DATA OF ENVIRONMENTAL FACTORS OF THE MANGAUNG METROPOLITAN MUNICIPALITY

Latitude	Longitude	Rainfall (mm)	Evapo-transpiration (mm)	Avg Temperature (Centigrade)	Elevation (m)	Climatic Zone	Water Level (m)	Use per capita in the MMM (l/c/d)	Population in the MMM	Water Uses	Land Use	Water source	Water quality	Avg Vegetation
-29.1502	26.2215	551	1478	15	1152	Arid to Semi-Arid	31.4	490,3	861,651	Domestic	Urban	Surface water	Good	Moderate
-28.9565	25.9139	534	1478	15	1152	Arid to Semi-Arid	31.4	137,36	861,651	Domestic	Urban	Surface water	Good	Moderate
-28.958	25.8136	534	1478	15	1152	Arid to Semi-Arid	31.4	82,42	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.1908	26.8158	534	1478	15	1152	Arid to Semi-Arid	31.4	48,61	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.2519	26.6891	534	1478	15	1152	Arid to Semi-Arid	31.4	865,38	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.3187	26.4206	534	1478	15	1152	Arid to Semi-Arid	31.4	206,04	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.7208	27.0338	534	1478	15	1152	Arid to Semi-Arid	43.8	924,51	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.8263	26.8704	534	1478	15	1152	Arid to Semi-Arid	43.8	67,09	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.8912	26.9637	534	1478	15	1152	Arid to Semi-Arid	43.8	118,68	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.78129	26.8891	534	1478	15	1152	Arid to Semi-Arid	43.8	2,75	861,651	Domestic	Urban	Surface water	Good	Moderate
-29.9088	26.8605	534	1478	15	1152	Arid to Semi-Arid	43.8	39,46	861,651	Agriculture: Irrigation	Urban	Surface water	Good	Moderate
-29.067528	25.850528	534	1478	15	1152	Arid to Semi-Arid	43.8	820	861,651	Agriculture: Irrigation	Urban	Surface water	Good	Moderate
-29.182341	26.110765	534	1570	15	1152	Arid to Semi-Arid	43.8	13,74	861,651	Agriculture: Irrigation	Urban	Surface water	Good	Moderate
-29.239611	25.857694	534	1570	15	1152	Arid to Semi-Arid	43.8	521,7	861,651	Agriculture: Irrigation	Urban	Surface water	Good	Moderate
-29.283324	25.811056	534	1570	15	1152	Arid to Semi-Arid	43.8	1068,18	861,651	Agriculture: Irrigation	Vegetated	Surface water	Good	Moderate
-29.332056	25.994028	534	1570	15	1233	Arid to Semi-Arid	43.8	64,48	861,651	Agriculture: Irrigation	Vegetated	Surface water	Good	Moderate
-28.519876	26.116667	534	1570	15	1233	Arid to Semi-Arid	43.8	1662,09	861,651	Agriculture: Irrigation	Vegetated	Surface water	Good	Moderate
-28.896223	25.991389	534	1570	15	1233	Arid to Semi-Arid	43.8	160,81	861,651	Agriculture: Irrigation	Vegetated	Surface water	Good	Moderate

Latitude	Longitude	Rainfall (mm)	Evapo-transpiration (mm)	Avg Temperature (Centigrade)	Elevation (m)	Climatic Zone	Water Level (m)	Use per capita in the MMM (l/c/d)	Population in the MMM	Water Uses	Land Use	Water source	Water quality	Avg Vegetation
-29.007389	-29.007389	534	1570	15	1233	Arid to Semi-Arid	43.8	236,51	861,651	Domestic	Vegetated	Surface water	Good	Moderate
-28.791234	25.849082	534	1570	15	1233	Arid to Semi-Arid	43.8	36,59	861,651	Domestic	Vegetated	Surface water	Good	Moderate
-29.066667	25.341667	534	1570	15	1233	Arid to Semi-Arid	49.7	142,86	861,651	Domestic	Open land	Surface water	Good	Moderate
-28.962778	25.995833	534	1570	15	1233	Arid to Semi-Arid	49.7	1050,82	861,651	Domestic	Open land	Surface water	Good	Moderate
-28.633241	26.220044	534	1570	15	1233	Arid to Semi-Arid	49.7	73,23	861,651	Domestic	Open land	Surface water	Good	Moderate
-29.223557	26.878324	534	1558	15	1233	Arid to Semi-Arid	49.7	32,79	861,651	Mining	Open land	Surface water	Good	Moderate
-29.141083	26.062083	534	1558	15	1233	Arid to Semi-Arid	49.7	134,3	861,651	Agriculture: Irrigation	Open land	Surface water	Good	Moderate
-29.425139	26.632917	534	1558	15	1308	Arid to Semi-Arid	49.7	32,82	861,651	Agriculture: Irrigation	Agriculture	Surface water	Good	Moderate
-29.262148	26.480619	534	1558	15	1308	Arid to Semi-Arid	49.7	19,78	861,651	Agriculture: Irrigation	Agriculture	Surface water	Good	Moderate
-28.973456	-28.978757	534	1558	15	1308	Arid to Semi-Arid	49.7	8798,63	861,651	Domestic	Agriculture	Surface water	Good	Moderate
-28.904639	26.462567	534	1558	15	1308	Arid to Semi-Arid	49.7	143,96	861,651	Domestic	Agriculture	Surface water	Good	Moderate
-28.880806	26.630833	534	1558	15	1308	Arid to Semi-Arid	49.7	454,95	861,651	Domestic	Agriculture	Surface water	Good	Moderate
-28.876754	26.535642	534	1558	15	1308	Arid to Semi-Arid	49.7	6,18	861,651	Domestic	Agriculture	Surface water	Good	Moderate
-29.046543	26.425678	534	1558	15	1308	Arid to Semi-Arid	49.7	16,48	861,651	Agriculture: Irrigation	Agriculture	Surface water	Good	Moderate

Appendix C:

ENVIRONMENTAL SUSTAINABILITY SCORES OF MANGAUNG METROPOLITAN MUNICIPALITY

Latitude	Longitude	UHS score		EVI score		CEPI Score	
−29.1502	26.2215	41	Low	20	Moderate	64,93224	High
−28.9565	25.9139	55	Moderate	12	Low	61,39844	High
−28.958	25.8136	59	Moderate	14	Low	52,62642	High
−29.1908	26.8158	51	Moderate	34	High	69,48961	High
−29.2519	26.6891	55	Moderate	30	High	62,93273	High
−29.3187	26.4206	48	Low	23	Moderate	68,87691	High
−29.7208	27.0338	68	High	31	High	44,33863	Moderate
−29.8263	26.8704	72	High	34	High	42,96465	Moderate
−29.8912	26.9637	69	High	22	Moderate	43,84386	Moderate
−29.78129	26.8891	66	High	33	High	32,31741	Low
−29.9088	26.8605	70	High	28	High	37,2383	Low