UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

APPLYING THE DRIVING FORCE-STATE-RESPONSE FRAMEWORK AND EARTH OBSERVATION IN EVALUATING ENVIRONMENTAL IMPACTS OF URBAN EXPANSION: THE CASE OF RIYADH CITY, SAUDI ARABIA

by

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(1364722)

Thesis

Submitted in fulfilment of the requirements for the degree

Doctor of Philosophy

in

Geography and Environmental Studies

in the Faculty of Science, University of the Witwatersrand, Johannesburg, South Africa

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June 2022

Declaration I - Plagiarism

I declare that the research that is reported in this thesis, except where otherwise stated, is my unaided work. It is being submitted for the degree of Doctor of Philosophy within the School of Geography, Archaeology and Environmental Science at the University of the Witwatersrand, Johannesburg under the supervision of Prof. Elhadi Adam and Dr. Alex Wafer. This thesis has not been submitted before for any degree or examination at any other university.

15/06/2022

Signed by Yusuf Aina   Date

1364722

Declaration II – List of publications

1. **Aina, Y.**, Adam, E. and Ahmed, F., 2016. Examining the Spatio-temporal Dynamics of $PM_{2.5}$ in Saudi Arabia Using Satellite-derived Data: A Cluster Study. *The First Saudi Conference on the Environment*, 7 - 9 March, 2016, King Khalid University, Saudi Arabia. *Preprints, (doi: 10.20944/preprints201612.0011.v1).*

2. **Aina, Y. A.**, Adam, E. M. and Ahmed, F. 2017. Spatiotemporal variations in the impacts of urban land use types on urban heat island effects: the case of Riyadh, Saudi Arabia. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XLII-3/W2, pp. 9-14.

3. **Aina, Y.A**., Wafer, A., Ahmed, F. and Alshuwaikhat, H.M., 2019. Top-down sustainable urban development? Urban governance transformation in Saudi Arabia. *Cities*, 90, pp.272-281.

4. **Aina, Y.A.**, Adam, E., Ahmed, F., Wafer, A. and Alshuwaikhat, H.M., 2019. Using multisource data and the VIS model in assessing the urban expansion of Riyadh city, Saudi Arabia. *European Journal of Remote Sensing*, 52(1), pp.557-571.

5. **Aina, Y. A.**, Adam, E. and Wafer, A. (under second revision). Impact of urbanization on urban heat island effects: Analysis with urban density, traffic, and social media data. *Remote Sensing*.

6. **Aina, Y.A.,** Adam, E., Wafer, A. and Al-Shuwaikhat, H. M. (Submitted). Applying the DSR framework in assessing urban sustainability by incorporating remote sensing technologies: A review. *Environment Development and Sustainability*

7. **Aina, Y.**, Adam, E. and Wafer, A. (under preparation). Re-examining the spatiotemporal dynamics of $PM_{2.5}$ in Saudi Arabia using satellite-derived data: a multi-scale study.

Abstract

The rate of urbanization is unprecedented. Over half of the global population is already residing in urban areas. Future growth is expected to occur in Africa and Asia. Therefore, African and Asian cities are gaining attention on how to monitor and accommodate the impending growth in a sustainable way. Different models have been developed for benchmarking and monitoring sustainable development. However, most of them require adequate spatial data for developing an effective monitoring system. Remote sensing has intensively been used to contribute, with up-to-date data, towards urban sustainability. This study explored the use of the Driving force-State-Response model with satellite-derived data in assessing environmental sustainability. The Riyadh city of Saudi Arabia was used as a case study because it is a region that has not been adequately investigated in the literature and one of the fastest growing cities in the Middle East.

First, the study provides an overview of the different urban sustainability assessment models and the use of remote sensing data to bridge the data gap as well as the challenges and possible areas of future research. The results indicated the need to address the challenges of uncertainty, getting a "one size fits all indicator" and linking with SDG.

Second, the study provides an overview of the urban governance and policies that shaped the development of Riyadh city and the effects of the policies on the sustainability of the city. It examined the recent changes in urban governance in Riyadh and how they might promote urban sustainability in the city. This was carried out by a review of the literature and government publications on urban governance and policy changes in the city. The results highlighted gaps in urban governance, which need to be bridged.

Third, the study explored the techniques of land use classification by comparing spectral angle mapping (SAM), band ratioing and spectral mixture analysis (SMA). The results indicated that the SMA was the most accurate technique and was more amenable for use in the Vegetation-Impervious Surface-Soil model compared to SAM or band ratioing. The usefulness of the Urban Field Percentage of Landscape (UFPLAND) metric in analysing the diffusion and coalescence process of urban expansion was also explored. The results of the analysis revealed that UFPLAND was suitable for the monitoring of the urban process. Riyadh city's spatial growth followed the diffusion process from 1972 to 1995 and thereafter, the urban expansion in Riyadh has been going through the coalescence process.

Fourth, the study examined the environmental impacts of urbanization in Riyadh by testing and comparing the outputs of normalisation methods and a geographical random forest algorithm. The results indicated that one of the normalisation methods (normalised ratio scale) was not successfully computed and the mean normalised LST values in Riyadh had a decreasing trend contrary to the increasing minimum LST values (15°C in 1985 to 32°C in 2015). The results of the geographical random forest showed the influence of land use types and socioeconomic factors on LST in Riyadh.

The study concludes that the DSR framework is suitable for urban sustainability assessment, but further research is needed in providing more remote sensing-based data to further reduce the data gap and in standardizing the indicators for usage across different locations and times.

Keywords: driving force-state-response framework, land-use/-cover change, sustainability assessment, urban governance, urban heat island, particulate matter

Acknowledgements

I give thanks to Allah for giving me the strength and good health to finish the thesis successfully.

I acknowledge the invaluable support of my supervisors, Prof. Elhadi Adam and Dr. Alex Wafer. They gave the needed guidance and encouraged me to reach the finishing line.

I appreciate the support given by Prof. Alshuwaikhat in completing the thesis and the help in getting the needed data for the analysis. The study would not have been possible without the support and access to free data granted by ArRiyadh Development Authority, King Fahd University of Petroleum and Minerals, King Abdulaziz City of Science and Technology, and United State Geological Survey.

I am grateful to the staff and students at the School of Geography, Archaeology and Environmental Studies at Wits for their support. I also appreciate the brotherly environment provided by the Muslim and Nigerian communities at Wits.

Finally, I acknowledge the great sacrifice by my family, especially my wife and children, while I was “always playing with my computer” as one of them said. I thank my dad for always asking “what about South Africa?” I am grateful to other family members and friends for their support.

Table of Contents

List of figures

List of tables

CHAPTER ONE

General introduction

Abstract

This chapter presents the background of the challenge of rapid urbanisation and the need to curb the negative impacts of urban development to promote sustainability. This chapter emphasize the need to monitor and benchmark the process of urban development to ensure sustainability. It identifies the challenges of monitoring rapid urbanisation as paucity of data, the development of indicators, and the development of an integrated approach to urban change monitoring. It examines the impacts of urban development in Saudi Arabia and highlights the need to study Riyadh city as a case urban sustainability assessment. Furthermore, this chapter discusses the objectives and scope of the thesis and provides information about the study area (Riyadh city).

Keywords: urban sustainability, DSR framework, sustainability indicators, sustainability assessment, geospatial techniques, Riyadh

1.1 Background

In recent years, the scale of urbanisation, especially in developing countries, has been unprecedented. Presently, half of the world's population is living in urban areas and the percentage could rise to 66% by 2050 (UNFPA, 2007; UN DESA, 2015). By 2050, almost 90% of the world’s urban population growth will be in the urban areas of Asia and Africa (UN DESA, 2015). The urban population in the less developed regions rose from 18% in 1950 to 35% in 1990, then 40% in 2000 and 51% in 2018 (United Nations, 2006; UN DESA, 2019). The challenge of urbanisation in developing countries is not in the rate of urban growth, it is however in the absolute size of the urban population; because the rate of urban growth is already declining (UNFPA, 2007). Consequently, there is an increasing concern about providing adequate infrastructure, employment and resources (food and water) for the urban populations. There is also increasing focus on the need to curb the negative environmental impacts of rapid urbanisation (Liu et al., 2019; Ahmed et al., 2020). These negative environmental impacts tend to undermine urban sustainability (Huang et al., 2015). The concept of sustainable development emerged to improve the consideration of the environmental impacts of economic development, and it has been broadened to mean balanced consideration of social, economic, and environmental aspects of development (Alshuwaikhat and Aina, 2006; Moldan et al., 2012; Huang et al., 2015). However, some recent studies have restated the need for more attention to the environmental dimension of sustainability thereby giving rise to the theme of environmental sustainability (Ekins, 2011; Moldan et al., 2012; Baynes & Wiedmann, 2012; Leemans & Solecki, 2013).

Some of the environmental effects of urban growth and expansion have spatial dimensions. That is, the effects do vary over space. To curb the negative environmental impacts of expanding cities, there is a need to spatially understand the processes that have led and will lead to environmental change in urban areas (Liao et al., 2020). That is, the investigation for understanding the processes must incorporate the spatial dimensions into its analytical framework. This underscores the requirement for adequate spatial data and information on the causes and effects of urban growth and expansion. The paucity of spatial data on environmental sustainability in most developing countries has been one of the major limitations confronting the development of environmental policy (Baynes & Wiedmann, 2012). However, recent developments in remote sensing and GIS (Geographic Information Systems) offer new opportunities for collecting environmental and climatic data such as land cover, soil moisture, NOx, and particulate matter data, on the one hand, and analysing information about urban areas such as urban growth patterns on the other (Aina, 2012). The challenge now is to develop techniques for accurately monitoring urban environmental change and incorporating this information into operational sustainability frameworks (Herold et al., 2002; Blaschke, 2006).

In Saudi Arabia, little research has been undertaken in assessing the environmental impacts of urban growth in the cities of the Kingdom. The studies have been constrained by the lack of adequate spatial data. The study by Mubarak (2004) and Aina et al. (2008) indicated that the political-economy of Saudi Arabia has contributed to the development of urban sprawl. They also reported that the Urban Growth Boundary Policy (UGBP) initiated in 1989 to curb sprawl has not been adequate in limiting suburbanisation. Choguill (2006) computed the ecological footprint of Riyadh by comparing its carrying capacity with the resource demand of its population and concluded that Riyadh requires an area 114 times its size to maintain its current lifestyle. Comparatively, the size of the ecological footprint of Riyadh is larger than the size of Syria, twice the size of Jordan and about thrice the size of Ireland (Choguill, 2006). At the national level, Aina (2014) observed that the resource demand of the Saudi Arabian population is three times greater than the carrying capacity of the country. Alshuwaikhat and Aina (2006) carried out a GIS-based assessment of urban sustainability of Dammam City and noted low performances in environmental and social sustainability of the city. The test of a satellite-based Driving force-State- Response (DSR) framework in Riyadh could provide informative insights into the usage of the framework in assessing the sustainability implications of urbanisation and the attendant land-use changes in Saudi Arabia.

1.2 Rationale and problem statement

1.2.1 The paucity of data for urban monitoring: opportunities for remote sensing

The task of monitoring urban expansion processes is constrained by the huge volumes of data that need to be collected and analysed especially for indicator-based assessment whereby each indicator requires specific data. The increasing availability of remote sensing data sources (Taubenbock & Esch, 2011; Aina, 2012) and data processing techniques in the fields of remote sensing and GIS (such as machine learning methods, sub-pixel analysis, cluster analysis and spatial autocorrelation) offer opportunities for urban researchers to timely provide useful information. These opportunities are particularly significant in developing countries, where data collection and storage techniques are often not well developed. However, there is still a gap in the development of common standardised indicators for monitoring and assessment of sustainability (Pires et al., 2014, Xiang, 2017) and the possible contribution of satellite-derived data to the development of sustainability indicators is yet to be tested (de Sherbinin et al., 2014). The development of standardised indicators could help in comparing cities across countries and globally rather than just computing percentage changes.

To overcome the problem of wide-spread lack of suitable data for sustainability assessment, some authors have proposed the use of indicators based on satellite-derived data (Taubenbock & Esch, 2011; Musakwa & van Niekerk, 2013, 2015; Chrysoulakis et al., 2014; de Sherbinin et al., 2014; Andries et al., 2018). The pilot study by de Sherbinin et al. (2014) used satellite-based indicators of three environmental issues (air pollution, coastal eutrophication and biomass burning) to monitor environmental change. The study highlighted the challenge of selecting sustainability indicators that will be meaningful to scientists and policymakers, since "indicator" is a broad term whose exact meaning is controversial. Musakwa and Van Niekerk (2015) suggested that a shift to approaches that can be easily used by planning professionals rather than scientists is required. They also urged further investigation of satellite-based urban sustainability indicators and their applications. Andries et al. (2019) showed that data derived from earth observation have an important role to play in monitoring the progress in achieving the Sustainable Development Goals (SDGs). They reported that earth observation can be used to address the paucity of spatial data. In addition to the challenge of selecting appropriate indicators, is the difficulty of achieving acceptable levels of classification accuracy. In the arid region for example, there is the challenge of accurately discriminating between the signatures of barren desert and urban areas (Zhang et al., 2015a).

1.2.2 The environmental impacts of urbanisation and possible indicators

One of the environmental impacts of urbanisation is the urban heat island effect (UHI) whereby the temperature of an urban area is higher than the temperature of the surrounding areas (Deilami et al., 2018). UHI can be monitored through satellite data and can be used as an indicator for measuring the environmental impacts of urbanisation (Grimmond, 2007; Cui and Shi, 2012; Chrysoulakis et al., 2014; Peng et al., 2016). Lazzarini et al. (2015) have reported that the investigations on the effects of rapid urbanisation on local climate have been carried out mainly in the temperate regions with limited attention on arid regions. Ngie et al. (2014) in their review of trends in urban heat island studies observed that UHI studies need to investigate the effect of urban structure and morphology on UHI. Zhang et al. (2015b) in their study of using landscape metrics and impervious surface area for urban structure concluded that the amount of impervious surface and the spatial structure of the surface affect urban land surface temperature (LST). They suggested that local micro-climatic zones like industrial areas, high-density areas and low-density areas can be investigated. Lazzarini et al. (2015) in their study of eight desert cities, including Riyadh, used only three sites; city centre (with low vegetation), suburban and urban + vegetation area. Deilami et al. (2018) highlighted the challenges of monitoring UHI as an indicator, as getting relevant multidate data and the different ways used in computing UHI.

Particulate matter is another indicator that can be used to monitor the environmental impacts of urban expansion. Particulate matter can be derived from satellite images such as MODIS through the derivation of aerosol optical depth (AOD). Aina et al. (2014) performed cluster analysis of satellite-derived multi-year $PM_{2.5}$ data of Saudi Arabia and observed an increasing trend of $PM_{2.5}$ concentrations in some Saudi cities. The spatial resolution of the analysed data is 50 km (Aina et al., 2014). The coarse resolution of satellite-derived data has been a limitation to its application at the city scale. However, recent studies by Amanollahi et al. (2013) and by Sun et al. (2015) have been able to retrieve AOD and PM_{10} from Landsat data. Also, the Center for International Earth Science Information Network (CIESIN) has, in 2013, released global satellite-derived $PM_{2.5}$ data (1998-2012) with a spatial resolution of 10 km. These data are more suitable for city-scale analysis than the 50 km data used by Aina et al. (2014) which has only two pixels covering Riyadh city.

1.2.3 Towards an integrated analysis of urban environmental change

Different studies have investigated the causes and effects of urban growth and land-use changes (Lambin, 1997; Seto & Kaufmann, 2003; Li & Yeh, 2004; Guneralp & Seto, 2013; Yu et al., 2013; Musakwa & Niekerk, 2013). A few of the studies have carried out a comprehensive investigation of the spatial impacts of urban growth; for instance, the study by Li and Yeh (2004) addressed some aspects of spatial impacts such as loss of agricultural land and compactness (using the compactness index and entropy). Some studies have addressed other impacts such as open space and urban green areas (Gatrell, 2002; Jim, 2004), landscape fragmentation (Southworth, 2004), urban sprawl (Batty, 2003), agricultural land and vegetation (Liu et al., 2019) and environmental factors (Chen et al., 2014a). Though the study by Liu et al. (2019) applied a DSR framework, it focused mainly on the loss of farmland and ecological changes through vegetation loss. Similarly, Chen et al. (2014a) in implementing their assessment framework used mainly field data, which might not be readily available in contexts with limited data. These limitations demonstrate the need to study the impacts of urban growth on sprawling, landscape fragmentation and urban greening in an integrated manner in order to enhance our understanding of their effects. The studies by (Batty, 2003; Newman, 2001) have shown that there are linkages between the environmental/sustainability performance of cities and these critical determinants of urban growth and expansion. Lautso et al. (2002) and Baredo and Demicheli (2003) have tried to integrate sprawl indices and landscape fragmentation into urban growth modelling and impact assessment. However, these studies are mainly based on data from tropical and temperate environments (Millington,

2004) and such a study in a dry land environment might lead to a different conclusion. Moreover, He et al. (2017) argued that one of the gaps of the research using remote sensing to investigate the urban environment is that most studies focused on one aspect of environmental change in urbanised areas.

1.2.4 Urbanisation in Saudi Arabia

The urban population in Saudi Arabia is growing at a rate of 2.1% per annum and increased from about 6.5 million in 1980 to about 14.6 million in 1995 and 25 million in 2015 (UN DESA, 2015). Rapid urbanisation has far-reaching implications on the sustainability of Saudi cities in terms of the loss of urban green areas and agricultural land, urban sprawl and changes in land-use patterns. Urban planners and policymakers are faced with the dilemma of either encouraging growth and accepting or trying to mitigate the environmental effects or limiting growth and thereby reducing the economic viability of the city. This research used a case study of Riyadh to demonstrate how remote sensing can be used to acquire data about growth-related impact indicators such as vegetation change, particulate matter concentrations and changes in thermal regime within the context of the DPSIR framework. The motivation to study the city of Riyadh in Saudi Arabia is driven by the fact that Saudi cities present a case whereby urban development is mainly influenced by centralised government policy in terms of land distribution, provision of infrastructure and legal framework. Also, the urban growth and development of Saudi cities are mainly driven by the oil-based economy. This is in marked contrast to many cities in the global South, where urban growth often exceeds the capacity of municipal and central authorities to control it. So, Saudi urban development can be evaluated in this centralisation context and compared with other urban development scenarios.

1.3 Research aim and objectives

This study aimed to apply the Driving force-State-Response framework in evaluating the environmental impacts of urban expansion in Riyadh, Saudi Arabia using remotely sensed data as the basis for undertaking urban environmental management and policy decisions in the context of scarce or inadequate ground data.

Specific objectives were to:

1. Explore the use of indicators based on the Driving force-State-Response framework for urban environmental sustainability assessment.
2. Examine the changes in urban governance and policies in Saudi Arabia and how they affect changes in sustainable urban development.
3. Analyse land-use change and urban expansion in Riyadh by using remote sensing and GIS-based spatial metrics that include Vegetation-Imperviousness-Soil model, Annualized Sprawl Index and Percentage of Landscape.
4. Examine the environmental impacts of urban expansion in Riyadh by using a set of indicators including urban heat island effect, particulate matter concentrations and changes in the spatial distribution of vegetation based on satellite-derived data and GIS analysis and identifying the effects of different land-use types on the impacts.
5. Determine the linkage between the environmental impacts and urban expansion by using satellite-based indicators and multivariate analysis.

Figure 1.1 shows the analytical framework adopted by this study. It highlights the steps that were taken in carrying out the analysis including image acquisition, classification of images, compilation of indicators and the evaluation of environmental impacts. Within the framework, the following research questions were investigated; (1) What are the spatial indicators of environmental impacts of land use change?, (2) What are the spatial implications of rapid urbanization in Riyadh?, (3) What are the determinants or factors influencing environmental impacts?, (4) What policies and measures had been put in place to curb/manage growth and what has been the success of these?, (5) How can the effectiveness of the measures and policies be improved?

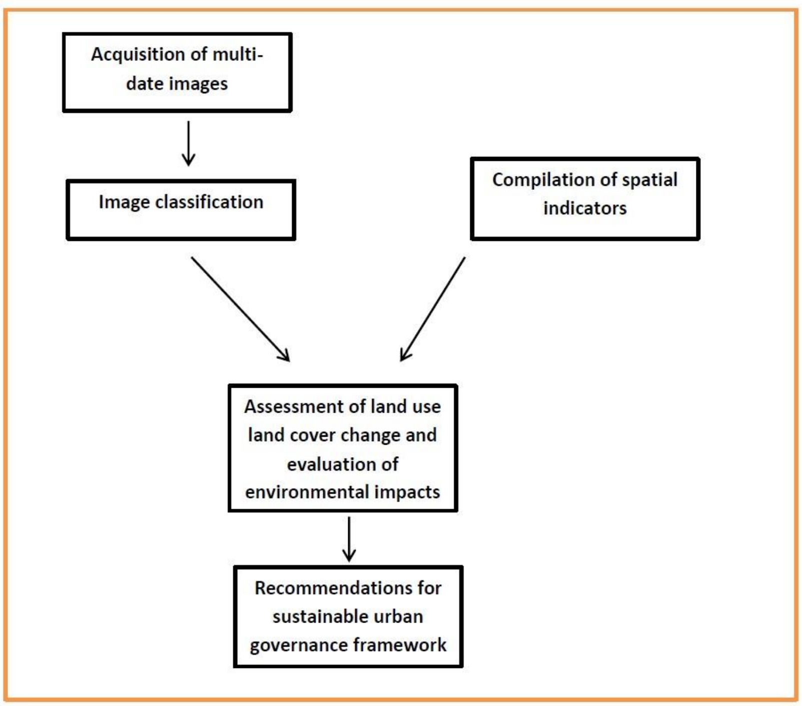

Figure 1.1. Flow chart of the study.

1.4 Scope of the study

The scope of the study was mainly the analysis of environmental sustainability of Riyadh city with limited or no consideration of the social and economic aspects of sustainability. This was due to shortage of socioeconomic data and the capture of socioeconomic data by remote sensing is still evolving. Also, indicators that are related to three main issues of land consumption during urban expansion, changes in UHI and the concentrations of $PM_{2.5}$ were considered.

1.5 Study area

Riyadh is the capital city of Saudi Arabia. It has historical, administrative, economic and global significance. It is in the central region of Saudi Arabia (Figure 1.2). The altitude of Riyadh is about 600 m. Due to its desert climate; summer months are usually hot and dry while winters are cold with sparse rainfall. The minimum temperature in winter is as low as 10 °C while the maximum temperature is over 40 °C in summer. The highest average monthly rainfall (~20 mm) is in April and the lowest average monthly rainfall (0 mm) is in June and September (0 mm) (Vincent, 2008). Riyadh is situated in a valley that is bounded in the west and east by the Tuwaiq and Al Aramah escarpments respectively (Vincent, 2008). Due to the physical setting, the city tends to expand from the north to the south to avoid development on the high escarpments.

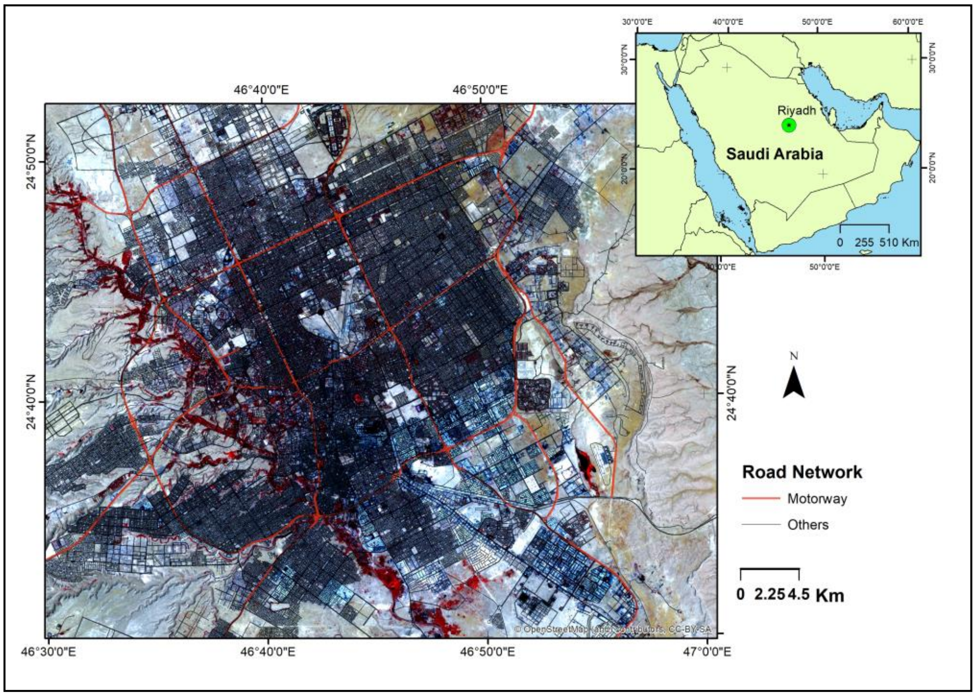

Figure 1.2. Location of Riyadh city in Saudi Arabia.

As regards socioeconomic importance, most Saudi government institutions are in Riyadh (AlAhmadi and Atkinson, 2019). Riyadh accounts for about 35% of national employment (MOMRA, 2019). The population of Riyadh city was about 6.5 million in 2016 (ADA, 2016). It is one of the five cities (Riyadh, Jeddah, Makkah, Madinah, and Dammam) that harbour about 45% of the Saudi population. The population of Riyadh is expected to grow to about 8.5 million by 2030 and the five largest cities are expected to accommodate about 50% of the Saudi population in the same year (MOMRA, 2019). Riyadh is facing some development challenges due to its fast population growth and spatial expansion. The city's spatial extent grew from 300 km^2 in 1990 to about 1000 km^2 in 2014 (MOMRA, 2019). This has affected infrastructure and service provisions resulting in gaps in electricity and water services (ADA, 2003a; Gazzeh and Abubakar, 2018). The city largely depends on private transport. This has led to traffic congestion and environmental pollution. The carbon emission per capita in Saudi Arabia was about 19 tons in 2015, which was higher than the emission per capita (about 17 tons) in the United States (MOMRA, 2019). These challenging environmental issues hinder the achievement of environmental sustainability in Riyadh. Recently, the government developed environmental sustainability strategies as part of the Saudi Vision 2030 (www.vision2030.gov.sa). This scenario justifies why it is necessary to investigate the environmental challenges facing the city of Riyadh. However, the peculiar challenges of such a study in an arid environment should be considered. For instance, in the tropical forest areas, urban expansion is associated with a reduction in vegetation cover while in the desert area, the vegetation cover might increase in the urban centres as there is little or no existing vegetation. Thus, there is a challenge in interpreting the result and distinguishing between the various urban features during image classification.

1.6 Thesis outline

The remaining six chapters (chapters 2-7), are written as independent scientific papers published in/or submitted to peer-reviewed journals. Each of these chapters consists of an introduction, and the methodology, results and discussion sections, which can be read separately from the rest of the thesis. Each chapter draws a different conclusion that directly links to the overall research aim and objectives. Though some sections of the chapters, such as “Introduction”, “Study Area”, and “Methodology”, may overlap, it is deemed to be of little significance since the main issues addressed by the chapters are different. However, efforts have been made to minimize such duplication.

Chapter 2 reviews the literature on the use of the DSR framework in urban areas by providing a detailed exposition of how remote sensing can be used as a supplementary source of information. The review evaluates possible indicators for assessing urban environmental change and examines the potential of using indicators based on the Driving force-State-Response framework for urban environmental sustainability assessment in the light of the existing literature.

Chapter 3 examines sustainable urban governance in Saudi Arabia. It investigates the top-down approach of urban governance in Saudi Arabia and its performance in addressing the environmental challenges of Saudi cities. It also highlights the recent transformations in urban governance. Overall, the chapter examines the changes in urban governance and policies in Saudi Arabia and how they affect changes in sustainable urban development within the context of the DSR framework.

Chapter 4 assesses the urban expansion of Riyadh city using multidate and multisource remote sensing data. It highlights the role of the urban growth boundary and increasing urban population in driving spatial expansion in Riyadh. This is done by analysing land-use change and urban expansion in Riyadh by using spatial metrics and the V-I-S model. It addresses the Driving force and State aspects of the DSR framework.

Chapter 5 examines the spatial and temporal dynamics of PM2.5 in Saudi Arabia using satellite-derived data. It also highlights the PM2.5 concentrations in some selected Saudi cities including Riyadh. The chapter also examines the influence of urbanization on the changes in $PM_{2.5}$ concentrations.

Chapter 6 examines the effects of land-use change on land surface temperature in Riyadh. It also highlights the impacts of urban density and road traffic on LST. It highlights that the urban heat island of Riyadh is driven by industrial and urban land use. The chapter uses multivariate analysis to determine the impacts.

Chapter 7 provides a synopsis of the thesis and highlights possible future studies.

The next chapter is the literature review (Chapter 2), which provides an overview of the literature relevant to this study.

CHAPTER TWO

Literature review

This chapter is based on:

Aina, Y.A., Adam, E., Wafer, A. and Al-Shuwaikhat, H. M. (Submitted). Applying the DSR framework in assessing urban sustainability by incorporating remote sensing technologies: A review. *Environment Development and Sustainability*

Abstract

The DSR framework has been mainly applied in agriculture and water domains with limited applications in urban areas. The limited use of the framework in urban areas has been due to some shortcomings such as simplification of the complex urban system, focus on a single dimension of sustainability and difficulty in categorizing indicators. This paper revisits the adaptation of the DSR framework for urban sustainability assessment. It reviews the advantages and limitations of different frameworks (such as ecological footprint) for assessing urban sustainability and highlights the merits of the DSR framework over others in assessing sustainability. This paper further highlights indicators that could be used in the framework to foster urban sustainability by incorporating remote sensing-based indicators. Despite its shortcomings, the DSR framework could serve as a simplified way of linking the impacts of urbanization with urban policies. It can also be adapted to the emerging spatial indicators. The spatial indicators are developed to overcome the problem of data scarcity by using remote sensing technology to monitor the urban environment. An example is the spatial metrics that are developed to monitor changes in landscape due to human activities. There are efforts to also link the indicators to environmental processes rather than measuring a fixed state of the environment. This development could make the DSR framework a useful tool for the developing countries where scarcity of data and complexity of urban systems have been the bane of sustainability assessment.

Keywords: urban sustainability, DSR framework, ecological footprint, sustainability indicators, sustainability assessment, geospatial techniques

2.1 Introduction

The scale of urbanization, especially in developing countries, has been unprecedented. A high percentage of urban growth in the coming years will be in developing countries (UN DESA, 2019). Urban sustainability has gained research focus due to the fact that a large percentage of the world's population lives in urban areas and urbanization influences global environmental change. The unsustainable development of urban areas has implications that undermine global sustainable development. There have been recurring urban sustainability debates about developing an operational framework for measuring and benchmarking the sustainability of urban areas. The United Nations (UN) sustainable development goals (SDGs), especially goal 11 which covers urban sustainability, have focused more attention on benchmarking progress on sustainability. The SDGs have targets that serve as benchmarks that governments are encouraged to achieve (United Nations, 2015).

The targets of SDG 11 include the reduction of the urban slum, managing solid waste, reducing air pollution, universal access to adequate housing and green spaces, disaster risk reduction and sustainable urban planning (United Nations, 2018; Abubakar and Aina, 2019). The 2021 SDG report shows that the proportion of the global urban population living in slums increased from 23% in 2014 to 24% in 2018 (United Nations, 2021). In addition, according to the 2019 data, only 50% of the global urban population had access to public transport and only 16% of urban areas were allocated to open spaces and streets in 2020 (United Nations, 2021). The report shows that more global efforts need to be made to improve the conditions of slum dwellers and provide adequate public transport and open spaces in urban areas.

The task of monitoring urban land-use change processes is complicated by the volume of data that needs to be collected and analyzed. In order to reduce the problem of inadequate data for sustainability assessment, some authors (Taubenbock & Esch, 2011; Musakwa & van Niekerk, 2013; de Sherbinin et al., 2014; Chrysoulakis et al., 2014; Musakwa & van Niekerk, 2015; Stokes and Seto, 2019) have proposed the use of indicators based on satellite-derived data. Remote sensing data have been successfully used to monitor electricity coverage and the growth of slums in urban areas (Stokes and Seto, 2019). Satellite-derived data can be used in developing urban sustainability indicators (Chrysoulakis et al., 2014). Remote sensing has the potential of being an enabler for achieving the SDGs (Kavvada et al., 2020). However, there is a need for further study on satellite-based urban sustainability indicators and their applications (Musakwa & van Niekerk, 2015; Kavvada et al., 2020). The aim of this chapter is to review the DSR framework in the context of remote sensing technologies, and to identify relevant indicators and the challenges confronting their use in sustainability assessment.

2.2 Frameworks for assessing urban sustainability

2.2.1 Carrying capacity

Carrying capacity is one of the basic benchmarking criteria. It is based on the concept that an area has a capacity beyond which the environment starts to degrade. It is the threshold beyond which an environment ceases to have the capability to support natural and human activities (Wei et al., 2015a). The concept premised on the realization of the fact that the earth's resource base is finite while the human population increases over time thereby undermining its capacity to support the growing population (Arrow et al., 1995). The carrying capacity of an area can be used as a benchmark in determining the sustainability of development activities.

Sayre (2008) asserted that carrying capacity has been applied in many areas due to its precision and ability to provide a quantitative framework for sustainability assessment. The application of carrying capacity in urban areas is regarded as Urban Carrying Capacity (UCC) (Meng et al., 2020). Bendewald and Zhai (2013) used carrying capacity as a baseline for assessing the sustainability of buildings by modeling the amount of carbon in the buildings and carbon emissions. In a broader application, Sun et al. (2020) examined the urban land resources carrying capacity in the Yangtze River Delta in China. They considered multiple factors influencing urbanization (population, economic, industry, environment, and technology) and urban land resources carrying capacity (population, food production, construction, economy, and environment). Despite the wide utilization of the carrying capacity model, there is a lack of a common framework for getting more knowledge about interactions between different environmental factors within an area (Chapman and Bryon, 2018). Moreover, carrying capacity applications tend to focus on a single factor (water, transport, land resource or tourism) and mainly consider the environmental dimension of sustainability (Sayre, 2008; Wei et al., 2015b; Meng et al., 2020).

2.2.2 Ecological footprint

The ecological footprint is the amount of resources required to sustain a region. According to Wackernagel and Rees (1995), it is the "land area necessary to sustain current levels of resource consumption and waste discharge by a given population". The Global Footprint Network computes the yearly ecological footprint for countries with available United Nations data (https://www.footprintnetwork.org/). The ecological footprint is calculated in global hectares (gha) for each country and the footprint per person can be computed based on a country's population. For example, Saudi Arabia's ecological footprint per capita nearly doubled by increasing from 3.0 gha in 2000 to 5.6 gha in 2017 (https://www.footprintnetwork.org/). Conversely, the ecological footprint of the UK has decreased from 5.6 gha in 2000 to 4.2 gha in 2017 (https://www.footprintnetwork.org/). Lin et al. (2018), observed in a study of the global trend of ecological footprint, that the ecological footprint of Asia has been increasing more than that of the other regions.

In recent studies that analyzed the relationship between the ecological footprint and other socioeconomic and environmental factors, urbanization and energy use were found to lead to improvement in the environment (Nathaniel et al., 2019). Similarly, population density and energy consumption have a positive relationship with ecological footprint while foreign investment and economic growth have a negative relationship (Fakher, 2019). Solarin (2019) also observed a relationship between carbon emission and ecological footprint. The application of the ecological footprint is however limited by its computation at the global level and the exclusive evaluation of the renewable resources (Wei et al., 2015b) because of difficulties in applying it in limited data scenarios at the local level (Klinsky et al. (2009).

2.2.3 Input and output model

The input and output model is based on the concept of urban metabolism. The inputs are resources that go into the system and the outputs are the wastes. Alberti (1999) referred to the concept as “urban ecosystem” and noted that it provides an opportunity to improve the understanding of the complex interaction between the human and the natural systems within a city. The model accounts for the flow of energy and materials between an urban area and its environment and the used and unused ‘waste’ byproducts (Zhang, 2013). An urban area is regarded as a “superorganism” (Zhang, 2013). Alberti (1999) argued for the revision of the input and output model by integrating the human and natural systems more explicitly and accounting for spatial heterogeneity. It was also suggested that interdisciplinary perspectives are needed to improve the implementation of the urban metabolism model (Alberti, 1999; Broto et al., 2012, Dijst et al., 2018).

Pincetl et al. (2012) expanded the urban metabolism model by including quantitative techniques and the analysis of policies and socioeconomic factors. To widen and improve the applications of the model, Liu and Zhang (2012) and Li et al. (2018) used Ecological Network Analysis for urban studies in China by considering the complex relationships and hierarchical structures of cities. Li and Kwan (2018) further suggested that spatial and temporal scales should be considered in enhancing the application of the urban metabolism model. Moreover, policies and other dimensions of sustainability should be considered without limiting the analysis to environmental issues (Li and Kwan, 2018). However, Zhang (2013) argued that externalities are currently not sufficiently accounted for in the models.

2.2.4 Indicator-based framework

The indicator-based framework uses a set of indicators to assess and benchmark the level of sustainability of an area. Though indicators can be used in any of the aforementioned models, the indicator-based model is the only one that largely relies on indicators in its assessment. Wei et al. (2015b) reported that the model can be applied for “different purposes and specific features”. The model has been applied in assessing sustainability in the agriculture (Pacini et al., 2009), water (Juwana et al., 2012), transportation (Chakhtoura and Pojani, 2016), mining (Bui et al., 2017), and tourism sectors (Mitrica et al., 2021). In a more recent refinement of the model, Tapia et al. (2021) used an indicator-based framework to evaluate the impact of urban agriculture on sustainability and concluded that it had a positive influence on sustainability. In addition, the model was used to monitor the progress towards achieving the sustainable development goals in the Arab region (Allen et al., 2018). The studies reported that the indicator-based framework is a valuable tool for assessing, predicting, and comparing the status of sustainability in urban areas. However, the challenges of limited access to data, selection of indicators and the determination of targets were highlighted (Allen et al., 2018; Dizdaroglu, 2017).

2.3 The DSR framework

The DSR framework, developed by the United Nations Commission for Sustainable Development (UNCSD), is one of the cause-effect frameworks that use indicators to study the interactions between human activities and the environment. A set of indicators or parameters is developed for each of the three aspects of the framework – the driving force (primarily human activities driving environmental change), state (present conditions of the environment and the impacts of human activities) and response (actions and reactions taken by stakeholders) (Huang, Wu & Yan, 2015). There are other variants of the DSR that have been developed to provide more details and include more components about human-environment interactions (Burkhard & Muller, 2008).

One of these variants is Driving Force-Pressure-State-Impact-Response (DPSIR), which has added two additional components (pressure and impact) to the DSR framework. These components highlight the human-induced actions that result from the driving forces and can affect the environment by inducing changes in prevailing conditions (Carr et al., 2007; Huang et al., 2015). The other frameworks that have been developed include the Driving Force-Pressure-State-Effect-Action (DPSEA) and the Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA) frameworks. The DPSEA and DPSEEA are mainly used for assessing the environment and health through indicators (Meyar-Naimi & Vaez-Zadeh, 2012a). Though the DPSIR framework provides more explanation about human-environment interaction than the DSR, it requires more indicators and consequently more data. Thus, some of the studies that apply the framework combine two of the components such as driving force and pressure (Schober et al., 2010) or even apply only three components such as state-impact-state (SIS) (Chen et al., 2014a). Meyar-Naimi and Vaez-Zadeh (2012a, 2012b) have shown that the DSR framework might still be adopted due to its simplicity, especially in the absence of adequate data for using the more complex frameworks.

The components of the three linkages depend on the area of application or the ecosystem. An example of the components for an urban area includes population/population density as driver, sprawl and thermal regime as state and urban policies as a response. In assessing urban sustainability, a framework can incorporate the three linkages by analysing the determinants of urban growth (Drivers), evaluating environmental sustainability through spatial indicators (State) and examining urban policies (Response) over a period of time (t component) as shown in Figure 2.1.

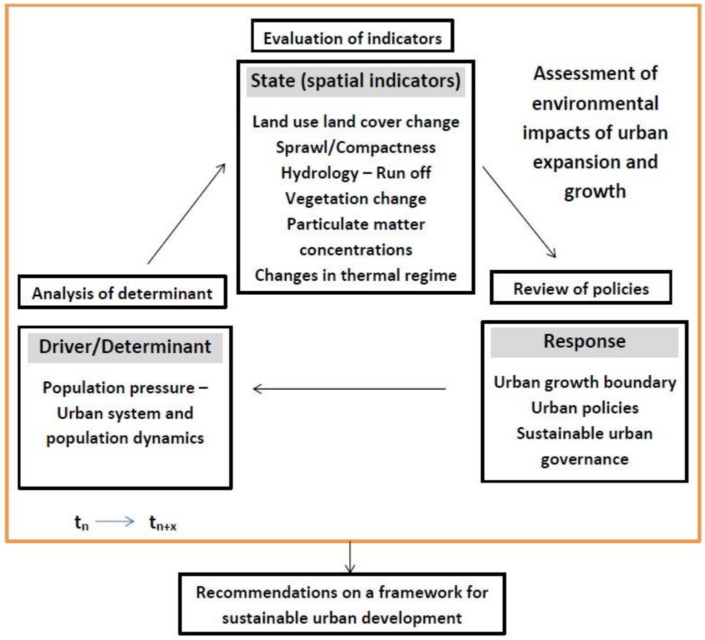

Figure 2.1. DSR of an urban area.

2.4 Remote sensing and spatial indicators

Improvements in remote sensing technologies in the aspects of spatial, temporal, and radiometric resolutions have led to increasing use and role of remote sensing in sustainability assessment. Reba and Seto (2020) asserted that the information about land-use change is very basic and vital to meeting the challenges facing urban centres. They highlighted the role of satellite data in filling the data gap. Apart from land-use change, other examples of indicators include urban land consumption, Urban Heat Island (UHI), particulate matters ($PM_{2.5}$), impervious surface, population modelling and carbon emission. Stokes and Seto (2019) highlighted the use of nighttime light data (Suomi-NPP VIIRS Day Night Band) for meeting the data need of monitoring SDG 7.1 (ensure universal access to affordable, reliable and modern energy services). Further contributions of earth observation to SDG monitoring especially SDG 6, 14 and 15 were identified by Kavvada et al. (2020). Figures 2.2, 2.3 and 2.4 show the use of remote sensing data in monitoring land surface temperature in two Saudi cities and particulate matter concentrations in Saudi Arabia. The two environmental factors are gaining importance as indicators for assessing sustainability. Moreover, particulate matter concentration ($PM_{2.5}$) is one of the targets of SDG 11. Figures 2.2 and 2.3 show that the minimum and the maximum LST have increased in the two study areas (Yanbu and Jeddah). Moreover, figure 2.2 depicted the impact of industrial land use on LST as the map shows higher LST values in the industrial zones in Yanbu. In Jeddah, a thermal plant located in the south of the city has an impact on the LST values. Also, the particulate matter concentrations in Saudi Arabia have increased between 1998 and 2010.

It is desirable to compare the results from the indicators, such as the examples stated above, at different times and locations to assess the sustainability of different cities. However, it is challenging to directly compare the values of the indicators across time and space due to seasonal and environmental differences. Indices and per capita computations have been used to facilitate comparisons between different times and places. Also, normalization is applied in comparing values of different times (Rasul et al., 2017b).

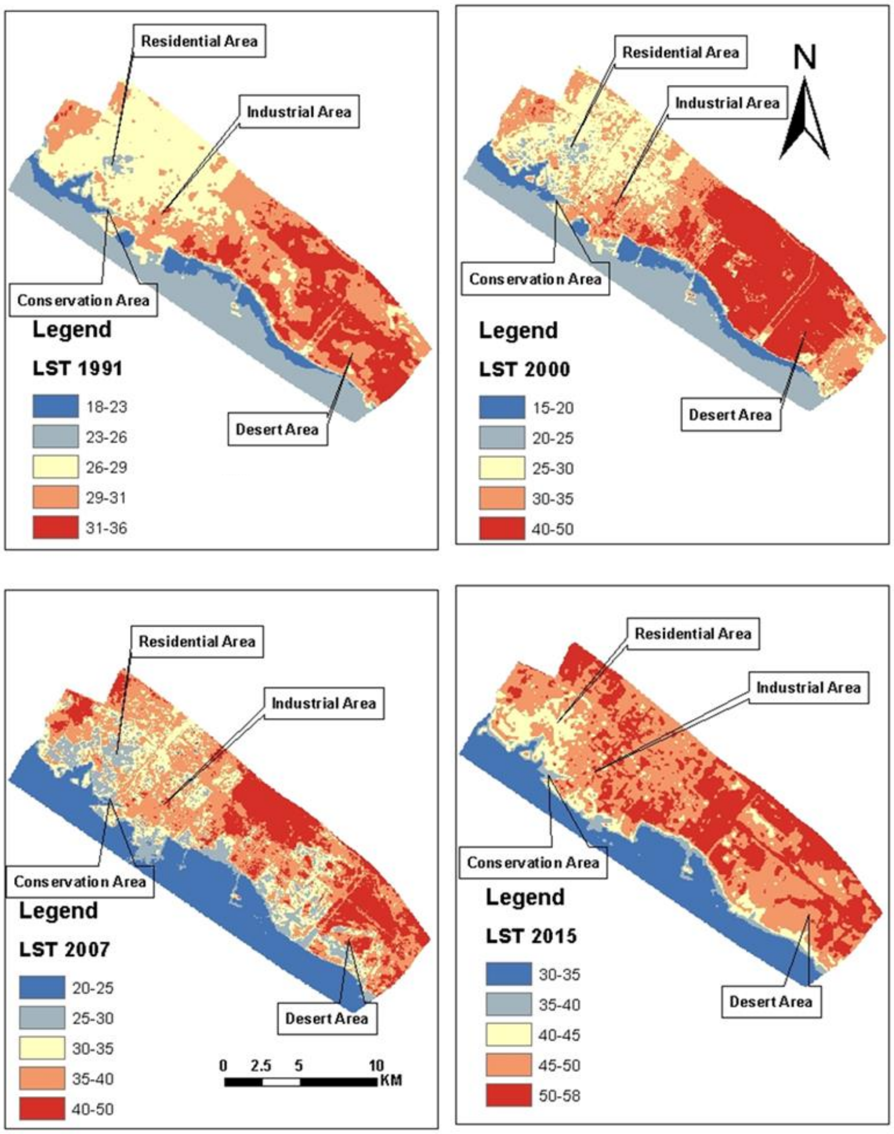

Figure 2.2. Land surface temperatures in Yanbu Industrial City: 1991, 2000, 2007, 2015 (Source: Parvez et al., 2016).

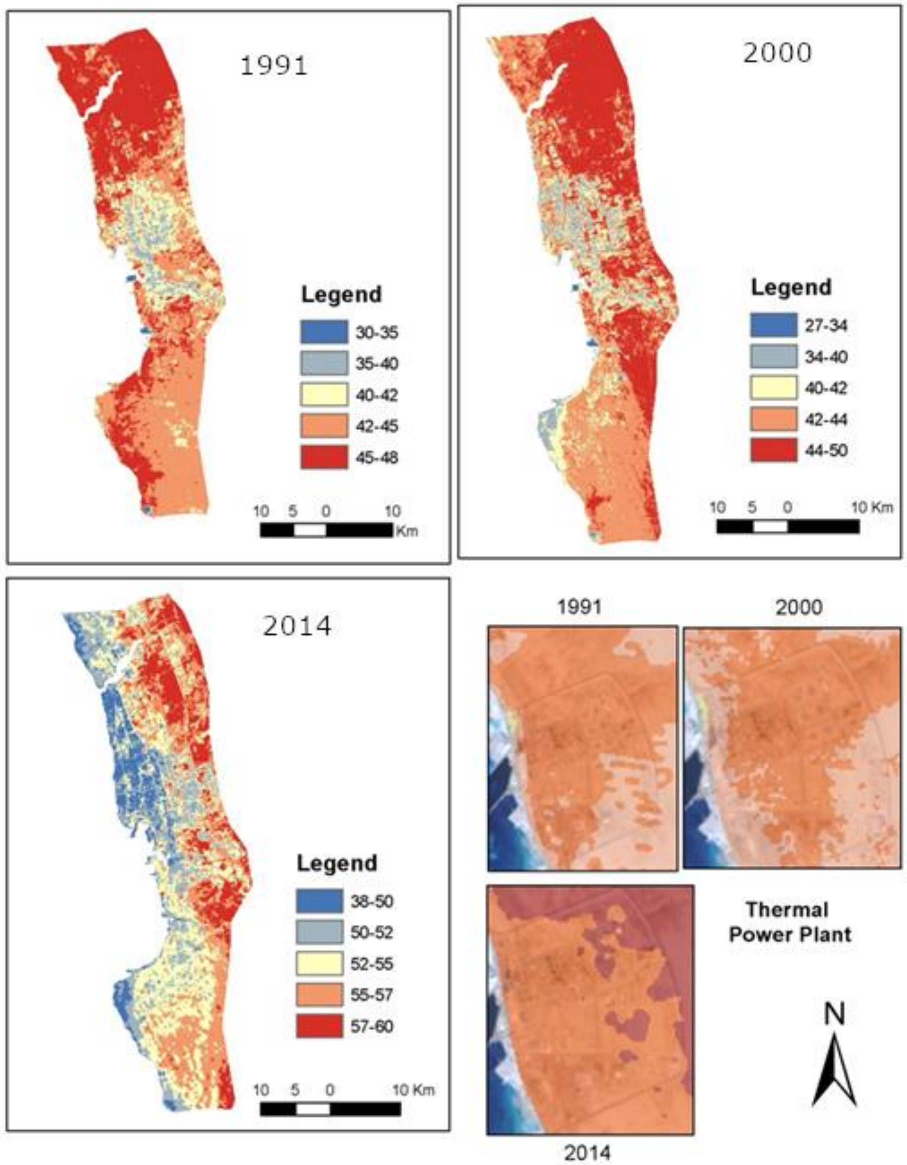

Figure 2.3. Land surface temperatures in Jeddah: 1991, 2000, 2014 (Source: Parvez et al., 2016).

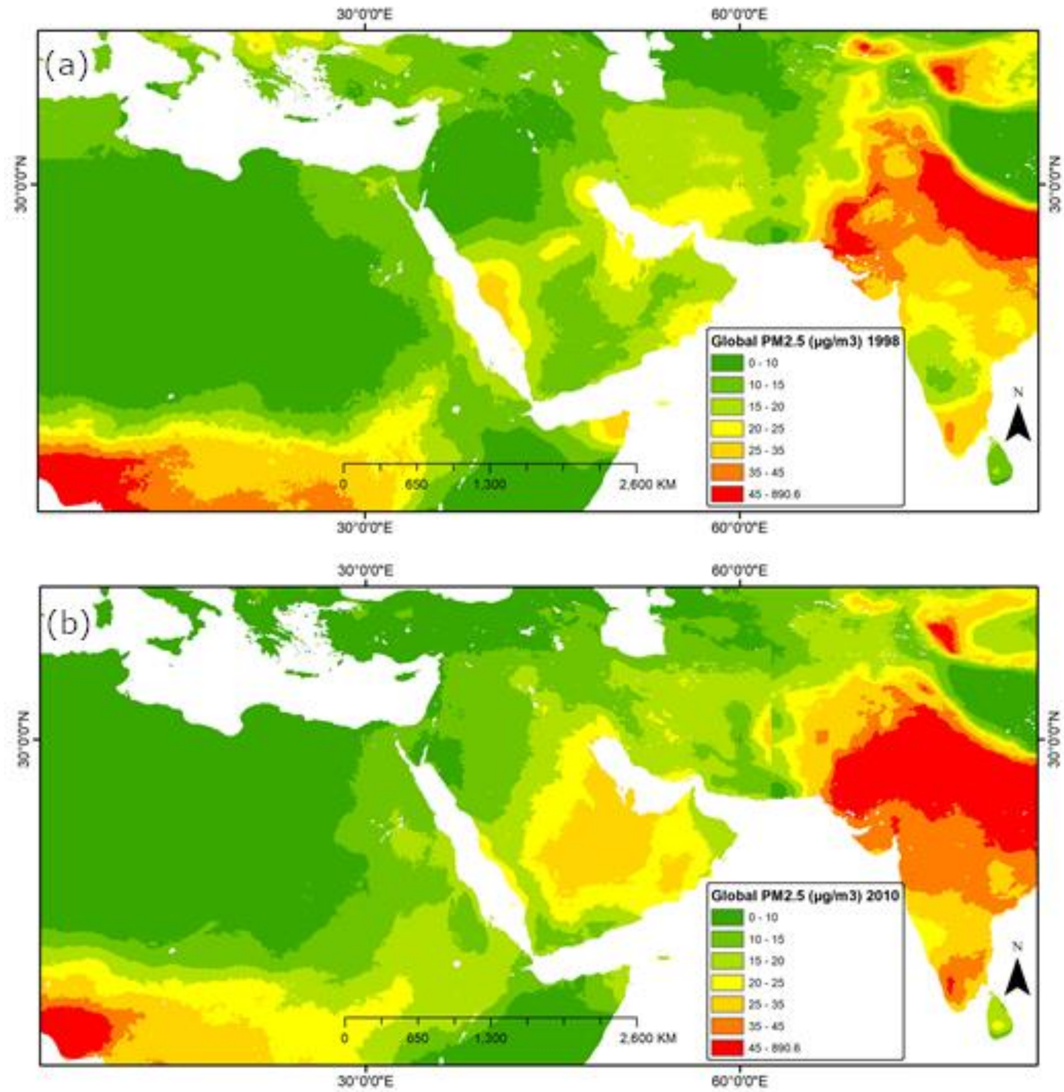

Figure 2.4. CIESIN global PM2.5 data – concentrations over Saudi Arabia (a) 1998, (b) 2010. (Source: https://sedac.ciesin.columbia.edu/data).

2.5 Challenges

To improve the use of remote sensing data in urban sustainability assessment, the challenges of integrating earth observation data into an assessment framework need to be identified and addressed. One of the challenges is the uncertainty in integrating remote sensing data into sustainability assessment. Despite the established and known improvements in remote sensing, there are still some uncertainties in terms of replacing ground data with remote sensing data. Though there are correlations between remotely sensed data and ground measurements, the gaps between them vary by location and time. Kavvada et al. (2020) argued for international guidelines in addressing the uncertainty of data. Standardizing the indicators is another bothersome issue. Researchers need to determine which set of indicators is broad enough and less complex for measuring progress towards sustainability. There is also the challenge of linking the earth observation data with the SDG targets. Though the data about some SDG targets have been derived from earth observation, the variations in the applications of satellite-derived data in computing SDG indicators are still a challenge (Adries et al., 2019). The question that remains unanswered is whether we can get a one size fits all indicator or set of universally applicable indicators?

2.6 Conclusion

There has been a major improvement in the drive towards assessing urban sustainability especially improving the role of remote sensing and related technologies. However, there is room for improvement and there are challenges of uncertainty, getting a "one size fits all indicator" and linking it with SDG. Research in this area can throw more light into the direction to take.

CHAPTER THREE

Top-down sustainable urban development? Urban governance transformation in Saudi Arabia

This chapter is based on:

Aina, Y.A., Wafer, A., Ahmed, F. and Alshuwaikhat, H.M., 2019. Top-down sustainable urban development? Urban governance transformation in Saudi Arabia. Cities, 90, pp.272-281.

Abstract

This paper focuses on transformation in sustainable urban governance by examining the prospect of fostering sustainable development through top-down urban governance. It takes a case study of urban development in Saudi Arabia, which had been administered through a centralised framework devoid of the environmental assessment of policies and plans. Urban planning documents made limited references to the environment. Consequently, Saudi cities have been ranked low on environmental sustainability. However, recently, due to the political imperative of addressing the problems, low oil prices, and the Arab Spring, there has been a remarkable transformation in urban governance. The planning of some of the major cities has been decentralised and some policies implemented to curb unsustainable development. This article reviews these changes by interrogating how top-down approaches might still be relevant in promoting sustainable development. It concludes that there is a need to implement a framework of legislation and administrative procedures integrated with strategic environmental assessment (SEA) to ensure proper sustainable institutionalised urban governance. The findings could serve as lessons for those operating under similar political contexts especially in the developing countries.

Keywords*:* urban governance; urban sustainability; environmental assessment; environmental policy; institutional framework; Saudi Arabia

3.1 Introduction

The awareness of the relevance of urban governance and political will to achieving sustainable development has been increasing in recent times. They are part of the institutional framework that is needed to nurture social, economic and environmental dimensions of sustainable development. The institutional framework has been recognised as an important aspect of sustainable development by the United Nations Commission on Sustainable Development (UNSCD, 1996). It is regarded as a sustainability dimension with themes such as integrated decision making, governance, disaster preparedness, capacity building and public participation (UNSCD, 1996). The report of the United Nations Conference on Sustainable Development indicated that strong political will is required in the quest towards sustainable development and efforts must be made in strengthening institutional frameworks (United Nations, 2012).

In a study of the environmental assessment (EA) procedure, as an example, Cashmore and Richardson (2013) argued, that power or politics cannot be divorced from the EA process. Power influences the EA procedures and outcomes and it needs to be considered to better understand EA practice (Cashmore and Richardson, 2013). Environmental assessment has been recognised as a procedure that can be integrated with plans and policies to promote urban sustainability (Alshuwaikhat et al., 2006; He et al., 2011). Environmental assessment is a valuable tool that decision-makers can use to evaluate proposed and existing policies, plans and programmes (PPP) and their alternatives with a view to achieving sustainable development (Alshuwaikhat et al., 2006). Whether in an EA-based process or in regular decision-making on sustainable development, the role of politics or power dynamics cannot be disregarded. Hansen et al. (2013) argued that power has a significant influence on decision making by enabling or constraining the actors involved in the process.

Despite the realisation of the importance of power dynamics and urban governance in fostering sustainable development, their roles have not been fully explored in research (Cashmore and Richardson, 2013). "In designing policies for sustainable development, the importance of the governance dimension is often either under-estimated or ignored" (McNeill, 2014). Patterson et al. (2017) reported that the governance dimension of the societal transition to sustainability has not been adequately addressed in the literature. Though governance more generally has been endlessly theorised, including in relation to urban development, sustainable urban development discussions should proceed with references to such debates. Jordan (2008) suggested that scholars should focus on the relationship between governance interventions and their outcomes rather than a simple description of the mode of governance. Also, many countries, especially in the global South, have not implemented adequate institutional frameworks and good urban governance that could engender sustainable development. It is questionable if the political will, that is fundamental to the formulation and implementation of sustainability policies, exists in many countries (Borel-Saladin and Turok, 2013).

Moreover, on the one hand, there may be a tendency to assume that 'traditional' top-down/centralised planning is at odds with Sustainable Urban Development (SUD); on the other, the role of central government policy remains important in both democratic and non-democratic contexts. Crot (2013) in a study of Masdar City, argued that the non-democratic political context of the UAE poses a challenge to the achievement of sustainability. Crot (2013) posited that non-democratic regimes, governing through a top-down approach, do pursue sustainable urban development, but the implementation is moderated by the relationship between a state and its society. The level of implementation of sustainability pursuit depends on the will of the state/leadership to incur the associated political costs (Crot, 2013). However, other studies indicated that, in certain contexts, top-down approaches might play a valuable role in sustainability planning (Cowley, 2015) and provide needed support for collective action in policy implementation and low carbon governance (Markantoni, 2016; Liu and Ravenscroft, 2017).

This paper aims to contribute to debates over the extent to which top-down approaches to governance can promote sustainability. It focuses on changes in urban governance through a case study of Saudi Arabia. Government documents and other secondary data sources such as academic literature, newspaper articles and websites were reviewed to depict the trend of sustainable urban governance in Saudi Arabia. Thereafter, the current practice in Saudi Arabia was compared with the best practices found in the literature to examine the shortcomings and make recommendations for improvement. The following sections of the paper discuss the findings. The first section highlights the role of urban governance in a sustainable development framework. The second section reviews the issues related to urban governance and sustainable development in Saudi Arabia. The third section highlights the recent changes in governance and sustainable urban development in Saudi Arabia. The final section examines the extent to which the recent changes have improved urban sustainability and presents an SEA-based urban development framework for Saudi Arabia.

3.2 Urban governance, power, and political will

3.2.1 From government to governance

According to Kjaer (2004), governance is a concept with "multiple meanings" and no agreed upon definition. The definition of governance depends on the context and the issue under consideration (Krahmann, 2003; Kjaer, 2004). In this study, the term governance is used to indicate a shift away from the traditional practices of 'government'. Some authors use the terms interchangeably and refer to the change from the 'traditional government' to governance as 'good governance' (Weiss, 2000). Kemp et al. (2005) defined governance as "how one gets to act, through what types of interactions (deliberation, negotiation, self-regulation or authoritative choice) and the extent to which actors adhere to collective decisions". Governance highlights both the formal and informal aspects of a political setup unlike conventional government that is strictly formal (Kemp et al., 2005). It is a departure from the traditional government that denotes "hierarchical and well-institutionalised forms of governance performed by a dominant bureaucratic and administrative government" (Rijke et al., 2012). "Top-down 'government' is broadly replaced by multi-actor practices of 'governance' that has been more communicative and inclusive" (Cowley, 2015). Governance is characterized by minimized bureaucracy and hierarchy (Jordan, 2008). The shift from government to governance could provide opportunities for sustainable urban governance (Kemp et al., 2005); since it has been argued that sustainability requires a governing environment that promotes “dialogue”, “partnership”, “shared responsibility” and “pluralistic public discourse” that might be difficult for traditional government institutions to achieve (Griffin, 2010; Joss, 2015; Rydin, 2010). The following paragraphs discuss the principles, components and typologies of urban governance, though not definitive, that are adopted (bulleted list drawn up with reference to cited authors) in evaluating the changes in Saudi urban governance and understanding the typology.

In an effort to develop a typology of urban governance, in a broad sense that includes ‘government’, Pierre (1999) highlighted four typical models of urban governance based on participants, objectives, instruments and outcomes: managerial, corporatist, pro-growth and welfare. The welfare model might not be economically sustainable in the long term (Pierre, 1999) especially when spending might grow bigger than income leading to budget deficits. An alternative approach for characterizing forms of governance is to classify governance based on centralization, public participation, partnerships and consensus building. An urban governance form that is characterized by centralization, limited or no public participation and private partnership is regarded as traditional ‘government’ while the one characterized by decentralization, public participation, partnerships and consensus building is regarded as modern ‘governance’ and desirable (Evans et al., 2006). This typology was also expressed by Obeng-Odoom (2012), who suggested that urban governance should be considered as “a cluster of meanings” comprising of decentralization, entrepreneurialism, and democratization (DED). The decentralization should not be simply deconcentration or delegation, partnership and collaboration among stakeholders should be emphasized (Obeng-Odoom, 2012). In order to coordinate the different levels of governance or tiers of government, a multilevel governance approach (Bulkeley and Betsill, 2005) should be considered or else local actions might work against regional/national policies. “In a world increasingly recognized as being multilevel, solutions must be as well” and “the complexities of multiple scales and multiple levels” should be addressed (Cash et al., 2006). The United Nations Economic and Social Council argued that regardless of the form of urban governance, key enablers are needed to promote sustainable urban management (UN ECOSOC, 2014). The key enablers, which are similar to the components of good governance highlighted above, include “strong leadership of local authorities, broad-based participatory mechanisms and processes of civic engagement, strong public-private partnerships, and alignment of national and local government policy objectives and interventions” (UN ECOSOC, 2014).

As regards to the components of urban governance, authors such as Kemp et al. (2005), Alshuwaikhat et al. (2006), Jordan (2008), Scott (2011), Smith and Wiek (2012) and Zurina and Hukil (2012) have highlighted the key components of good governance for promoting sustainable development. The components include:

- Public participation in decision making
- Decentralized decision-making structures
- Proactive, adaptive and collaborative strategies (partnerships and multilevel governance) at all levels

- Sustainability-based criteria for planning (formally formulated and implemented to guide decision making)
- Accountability and transparency in governance structures
- Legislative framework
- Public environmental awareness
- Technology and openness to creativity and innovation

The components highlighted above, are mainly principles of good governance that might promote sustainability if implemented within a framework. In an effort to assess the success of an urban sustainability governance framework, Smith and Wiek (2012) identified six evaluative components that include sustainability vision, sustainability targets, governance principles, sustainability actions, sustainable impacts, and organization. That is, apart from the governance principles drawn up above, an urban sustainability governance framework should have sustainability vision, targets, actions, and impacts.

3.2.2 Transformation towards sustainable urban governance

As mentioned above, governance is an important institutional dimension of the sustainable development framework. "Governance can offer both barriers and opportunities to transitioning towards urban sustainability and resilience" (Romero-Lankao et al., 2018). In any discourse on institutional dimension; the pertinent issues such as public participation, capacity building, and disaster preparedness/resilience are brought to fore and they could be considered in implementing a sustainability framework.

A model of governance that lacks these institutional components might not be regarded as being sustainable. They are the overarching components of the sustainable development framework. This framework can be applied at different levels of governance – local, national or global and encapsulates the institutional embeddedness of the balancing elements determining sustainability.

In line with the opinion that simple and cosmetic steps do not lead to good governance, the changes in urban governance could be carried out at three levels to engender transformation; specific episodes "interactions among stakeholders" (roles, strategies and interests), governance processes (networks, coalitions and discourses) and governance cultures (modes of governance and cultural values) (Coaffee and Healey, 2003). Smith and Wiek (2012) suggested that the conventional features of government which include departmentalism, incrementalism and self-reliance must be challenged to foster sustainability. Departmentalism is the traditional way of having different government departments that handle government functions without adequate interdepartmental interaction or collaboration. Incrementalism is the notion of solving problems 'piece by piece' as they arise. Self-reliance is the conventional view that government should solely provide solutions to the urban problem with limited input from stakeholders.

In a treatise that is more relevant to sustainable urban development, McCormick et al. (2013) defined sustainable urban transformation as "structural transformation processes – multi-dimensional and radical change – that can effectively direct urban development towards ambitious sustainability goals". They reported that governance and planning are very important in achieving sustainable urban transformation and a considerable shift in the “development paths” could lead to the transformation. Despite the advocacy to shift away from the traditional government, the political will and influence of such government might help in the transformation towards sustainable governance in some contexts. Moser (2019) argued, with examples from Indonesia, India, Palestine, Kazakhstan and Ecuador, that the “political legitimacy” of leaders can be used to achieve their “utopian urban assemblages”.

3.3 Urban governance and sustainable development in Saudi Arabia

The form of urban governance in Saudi Arabia affects urban management and sustainable urban development because it relates to centralization and the institutional framework for making plans and policies. Urban development in Saudi Arabia has been administered through a centralized framework (Garba, 2004; Mubarak, 2004; Mandeli, 2008; Mandeli, 2016) with limited or no environmental assessment of policies and plans (Alshuwaikhat and Aina, 2004; Alshuwaikhat and Aina, 2005; Rachid and El-Fadel, 2013). Planning of the cities is influenced and approved by a central body, Ministry of Municipal and Rural Affairs (MOMRA), while the five-year national development plan is under the Ministry of Economy and Planning (MOEP). Urban planning documents make limited references to the environment (Alshuwaikhat and Aina, 2004; Alshuwaikhat and Aina, 2005). Apart from the issue of governance or institutional frameworks, there are environmental issues such as high energy and water consumption (sustained by government subsidy), greenhouse gas (GHG) emission, seawater pollution, groundwater depletion and loss of vegetation to consider. The 2012 environmental performance index report indicated that

Saudi Arabia is one of the countries with the worst record in environmental performance (ranked 82 out of 132 countries) (Emerson et al., 2012). In the recent 2018 report, though no longer in the list of worst performers, Saudi Arabia is ranked 86 out of 180 countries with a rank of 158 in air pollution (https://epi.envirocenter.yale.edu).

3.3.1 The case of urban environmental challenges in Riyadh

A case study of Riyadh, the capital city of Saudi Arabia, revealed that the city is already spatially sprawling with leap-frog type, space consuming land development (Al-Hathloul and Mughal, 2004; Mubarak, 2004; Rahman, 2016). A considerable number of the city lots, about one-fifth, is subdivided due to land speculations and the owners keep them undeveloped while waiting for a significant rise in prices (Ahmed, 2013). The ecological footprint of the city is very high relative to other neighbouring cities (Choguill, 2006). Riyadh's footprint is worsened by the fact that it is a landlocked city. For instance, the water provided to its population is sourced from about 400km away from the city. Though the city does not yet feature as a primate city at the national level, it is one of the five cities that have continuously accommodated a large share of Saudi urban population. The share of the population of these cities increased from 27% in 1974 to 45% in 2010. This expansive trend has implications for urban services and infrastructure provision in Riyadh and other cities (Abubakar and Aina, 2016; Gazzeh and Abubakar, 2018). It might also impact on the resilience of these cities to disasters. For instance, the Jeddah flood disaster in 2009 was exacerbated by the location of unplanned settlements along flood paths. The increasing vegetation loss recorded in Riyadh city in the late 1990s might be similarly attributed to spatial expansion – a trend echoed at Tarut Bay (Khan and Al-Homaid, 2003, Al-Shihri, 2016). Negative environmental impacts due to large-scale urban development projects were also noted at Dammam Metropolitan Area by Alhowaish (2015) and Al-Shihri (2016). Moreover, Aina et al. (2014) reported an increase in the concentrations of satellite-derived $PM_{2.5}$ over Riyadh from 12.4 $\mu g/m^3$ in 2002 to 15 $\mu g/m^3$ in 2009. Similarly, Bian et al. (2018) concluded that the concentrations of $PM_{2.5}$ carbonaceous aerosol in Riyadh are comparable to other reported cases in the Middle East. They suggested that the sources of the particulates include cement industries, refineries, and vehicular emissions. Bearing in mind that over 5 million people are exposed to these particulates makes the findings worthy of the attention of the decision makers.

3.3.2 Pressures for change in Saudi urban governance

According to Romero-Lankao et al. (2018), governments are regularly subjected to pressures in form of innovations and experimentations, conflict and contestation, and environmental impacts and triggers that can lead to transformation. Their characterisation of the process of transformation through pressures and drivers might be relevant to the Saudi Arabian context. Recently, due to the political pressure of the Arab Spring events, the imperative of addressing environmental problems and the low oil prices, there has been a remarkable transformation in urban governance in Saudi Arabia. The political upheavals of the Arab Spring, which started in 2011 in Tunisia, influenced the actions of government especially in the social aspect of urban sustainability (Kyriazis et al., 2018). Though Saudi Arabia was not majorly affected, in terms of regime change and protests, by the Arab Spring (Al Tamamy, 2012), notable steps were taken to assuage the populace. The government took actions on improving youth unemployment, providing avenues for public participation at the municipal level, inaugurating social welfare programs and increasing infrastructure spending (Quamar, 2014). Natural disasters such as the Jeddah flood in 2009 and 2011 have also increased the pressure on the government to make far-reaching changes especially in tackling environmental problems. Moreover, the dwindling oil revenues due to low oil prices have added to the pressure on the government to adopt measures that promote sustainability at the national and municipal level.

3.4 Recent changes in Saudi urban sustainability

3.4.1 Changes in urban governance

The recent changes by the Saudi government include changes in the institutional framework of urban governance and far-reaching changes to bring about urban social and environmental sustainability. At the national level, the national development plans have explicitly dealt with issues such as rationalization of subsidies, enhancing productivity and efficiency at municipalities, balanced regional development, quality of life and environmental protection (MOEP, 2005; MOEP, 2010; Al-Jasser, 2013). In terms of urban governance, procedures followed by some of the cities have been altered. The municipalities are granted more autonomy to make planning decisions and may develop their own plans instead of being subjected to centralized planning control by the Ministry of Municipal and Rural Affairs (MOMRA). Also, the private sector is given more opportunities to participate in urban and economic development through public-private partnerships (MOEP, 2005; Abdulaal, 2011). Table 3.1 shows the changes in the structure and characteristics of urban governance in Saudi Arabia. As shown in Table 3.1, members of the public are now elected into the municipal council to participate in local decision making. They can make meaningful input into the plans and policies of the cities.

Table 3.1: Changes in the structure and characteristics of urban governance (Sources: Mubarak, 2004; MOEP, 2005; Mandeli, 2008; Abdulaal, 2012a; Arab News, 2015; Saudi Gazette, 2014; Mandeli, 2016; MOMRA, 2016).

The structure and characteristics of urban governance before 2004	**The structure and characteristics of urban governance after 2004**	**Approved future changes**
• No functional municipal council • Finance from the central government through MOMRA • Full monitoring of municipalities by MOMRA • Establishment of special authority for the development of Riyadh • Limited municipal level coordination of agents of central	• Semi-elected (two-third of the members) municipal council • A Municipality can generate funds from services provided to the public (privatization of some municipal services) • Indirect monitoring by MOMRA (municipal council liaises between municipality and MOMRA) • Establishment of special development authorities	• Municipal councils to approve municipal plans and programs • Inauguration of the law of freedom of information • Inauguration of land use planning guidelines

ministries that provide municipal utilities • Limited private participation • Welfare model of governance	in more cities (e.g. Makkah and Madinah). • Coordination of the agents of central ministries through the municipal council • Women's participation in the municipal council • Establishment of Public-Private partnership • Post-welfare model of governance	

3.4.2 Urban environmental sustainability

In the aspect of urban environmental sustainability, Saudi Arabia has started different projects that focus on providing water and energy through renewable energy sources (Rahman and Khondaker, 2012; Bhutto et al., 2014). They have initiated projects to establish public transportation in big cities to reduce traffic congestion and carbon emission. Prior to this development, there has been insufficient or no public transportation in most Saudi cities. The following three cases: smart city and urban observatory projects, mobility, urban infrastructure and housing, and urban greening are examined to highlight the changes to the real aspects of physical planning and urban sustainability in Saudi Arabia. The cases show that changes have not only occurred in the regulation and procedural aspects of planning, but also in the cityscapes of Saudi cities.

The cases also portray a couple of the changes in urban governance that are driving the new urbanism. For example, the public-private partnership initiatives for developing the smart city projects.

1. Smart city and urban observatory projects

Saudi Arabia has established initiatives and projects to build smart cities (Aina, 2017). Though some of the projects are yet to be completed, a number of achievements are noteworthy. For example, an e-government initiative has been implemented in public agencies which are providing more than 875 e-services (GCF, 2015). At the city level, new or existing cities are planned or being developed as smart cities. The King Abdullah Economic City, one of the new smart cities, is being built to have modern smart infrastructure, e-services and broadband connectivity with a budget of about $100 billion (Moser et al., 2015). The project exemplifies the adoption of a public-private partnership approach in executing projects as the city is managed by a private company with 'entrepreneurship' form of governance. That is the city is an enterprise and the residents are customers to the company that is managing the city (Moser et al., 2015). Moser et al. (2015) have expressed concern about how the new city projects will be able to navigate socio-cultural, governance and bureaucratic challenges of the Kingdom. Moreover, recent smart city studies, Rizzo (2017), Cugurullo (2018) and Yigitcanlar et al. (2018), have argued that smart cities, especially new ones, tend to be located in isolation and unconnected with their context thereby leading to 'fragmented urbanism' that is not human-centred. These concerns might be addressed by the Kingdom's recent political will to resolve the bottlenecks in implementing such projects. Most especially, the announcement of the plan of a bigger unrivalled project of a new city (Neom city) at the north western part of the Kingdom (http://discoverneom.com/) might lead to a new era in implementation. However, the challenge of avoiding fragmentation and technology-centric smart city lacking ‘social intelligence’ (Luca et al., 2017) might remain. The existing cities that are being developed as smart cities include, but are not limited to, Riyadh, Yanbu, Jubail, Jeddah, Makkah, Dammam and Madinah. Some of the cities have implemented smart city systems and applications such as data centre, fibre connectivity, enterprise GIS and digital mapping (Fig. 3.1), traffic control and management (Fig. 3.2), digital signage and address, environmental monitoring and access control (Aina, 2017). As regard environmental monitoring, ArRiyadh Development Authority (ADA) has completed about 32 air quality monitoring stations, which are linked to a common database and published on a website (http://www.arriyadhenv.gov.sa/en/).

Figure 3.1. Yanbu digital map and information kiosk.

Figure 3.2. Riyadh traffic management system (Source: ADA www.ada.gov.sa).

Since the establishment of an urban observatory in Jeddah in 2003 in collaboration with the UN-Habitat and Arab Urban Development Institute (AUDI), other cities in the Kingdom have adopted the concept (Jackson and Simpson, 2012). The aim of the urban observatory is to contribute to the UN's Global Urban Observatory (GUO) and develop a set of urban indicators for monitoring the social, economic and environmental performance of cities. The indicators are standardised to enable comparison between cities (MOMRA, 2016). This is a significant development bearing in mind that as of 2014 the Central Department of Statistics and Information did not have its socioeconomic data on Saudi Arabia in GIS format (MOMRA, 2016). According to MOMRA (2016), about 25 cities are at different stages of implementing urban observatories.

2. Mobility, urban infrastructure, and housing

As mentioned above, Saudi Arabia has embarked on transportation projects, both at the national and city levels, to establish public transit and rail systems. Fast inter- and intra-city metro lines are being constructed to ease traffic congestions. For example, the new Al-Mashaaer Metro that transports pilgrims during the Hajj season has obviated the need for about 12,000 buses since its inauguration (Hazaimeh, 2014). The Haramain rail system has just been completed. The rail line connects the holy cities of Makkah and Madinah (about 400km) via Jeddah and Rabigh (Fig. 3.3). In Riyadh, the public transit being implemented consist of 6 Metro lines (about 176 km) and a network of 22 bus routes (Fig. 3.4). It is proposed that the transit system will reduce the city's fuel consumption by 400,000 litres per day (http://riyadhmetro.sa/en/). Apart from construction, the project team is also engaging in a cultural awareness campaign to prepare the populace for the coming lifestyle change. Choguill (2006) and Nahiduzzaman et al. (2018) have highlighted the need and importance of behavioural change intervention in the drive towards sustainability in Saudi Arabia.

Figure 3.3. Haramain rail network linking Makkah and Madinah.

Figure 3.4. Riyadh Metro line and station under construction.

New urban drainage plans and flood monitoring systems are being implemented to improve the resilience of Saudi cities to flood disasters (Aina, 2017). Urban flooding has been a recurrent issue in cities like Riyadh, Makkah, and Jeddah (Khal, 2013). The General Authority of Metreology and Environmental Protection has also implemented an early warning system to alert citizens of impending severe weather. The government has provided a fund for building houses for the poor to improve the social aspect of sustainability. The Saudi Ministry of Housing allocated more than one hundred thousand housing units in the first quarter of 2018 (Arab News, 2018). However, Kyriazis (2018) has noted that the mega housing project is facing challenges of administrative conflicts, socio-cultural issues, and technical problems. Also, there is a drive towards nationalization of jobs in the private sector (MOEP, 2005; MOEP, 2010), which had hitherto been handled mainly by foreign workers.

3. Urban greening

Aljoufie and Tiwari (2015) have highlighted the lack of green infrastructure in Jeddah, Saudi Arabia’s second-largest city. However, there has been an increase in the number of urban projects being implemented across Saudi cities. In Riyadh, a special environmental project has been implemented to restore and preserve Wadi Hanifah wetlands (120 km green desert valley), which has been polluted by industrial and agricultural activities (Arab News, 2010). In Jeddah, the municipality had initiated a project to maintain and restore about 480 public gardens (Al-Hamid, 2014). In order to avoid the impacts of urban greening on water and energy consumption, a project had been started in Riyadh to use renewable energy in a new international park (Arab News, 2014). Another initiative is the planting of trees along road centreline to improve the greenscape and provide shade for pedestrians. In Yanbu, a 12 km waterfront project with green areas was inaugurated to promote sustainable tourism (Rahman and Khondaker, 2012; Aina 2017). Also, green areas covering about 1.2 million m^2 were developed in the past two decades making the coverage of greenery in the city to be about 40 percent (Fig. 3.5) (RCY, 2016).

Figure 3.5. A park in Yanbu with solar-powered lamp posts.

Recently, in 2016, the government of Saudi Arabia unveiled the Vision 2030 to guide the country to sustainable growth and development. The vision explicitly highlights the importance of environmental sustainability and provides a set of indicators and targets for achieving sustainability (http://vision2030.gov.sa/en). For example, one of the targets of the vision is to have three Saudi cities in the top-ranked 100 cities in the world. This might result in improvement of the social, economic and environmental status of some Saudi cities (Aina, 2017). The Vision and the corresponding National Transformation Program (NTP) 2020 also include targets on improving the level of public participation in the planning process, enhancing the quality of life in the cities and promoting sustainable and balanced urban development (Aina, 2017; Alshuwaikhat and Mohammed, 2017). In terms of governance, the governed by the Council of Ministers which has mandated the Council of Economic and Development Affairs (CEDA) to implement the vision (http://vision2030.gov.sa/en). Government agencies should identify the part of the vision that is relevant to them and strategic roadmaps for achieving it. The government agencies need to be more flexible, accountable and adaptable to challenges (http://vision2030.gov.sa/en). The Vision 2030 is in line with the evaluative framework developed by Smith and Wiek (2012) who emphasized the need for sustainability vision, targets and actions for promoting sustainable urban governance. In the same vein, MOMRA has established a partnership with the UN-Habitat to implement the Future Saudi Cities program (https://www.futuresaudicities.org). The program is going to follow a three-prong approach to achieve sustainable urbanization in Saudi Arabia. The approach has urban planning and design, urban rules and regulation, and municipal finance aspects. While it is too early to assess the impacts of the vision and program on sustainable urban governance in Saudi Arabia, it is expected that they will bring notable changes.

3.5 Examining the transformations in Saudi Arabia using the referenced frameworks

The transformations that have been implemented in Saudi Arabia could have impacts on sustainable urban development in the Kingdom. Using the frameworks by Pierre (1999), Obeng-Odoom (2012), Bulkeley and Betsill (2005), Cash et al. (2006), Coaffee and Healey (2003) and McCormick et al. (2013), it is arguable that the Kingdom is experiencing a shift in urban governance from the traditional welfare mode to the modern post-welfare mode. Since the change affects the structure of urban governance and includes specific sustainability actions, it can be regarded as a sustainable urban transformation. However, some researchers like Alkadry (2015) suggested that the changes towards decentralization are cosmetic and do not necessarily strengthen urban governance since decisions are still made centrally. Mandeli (2016) having acknowledged the changes in the configuration of public management, observed a lack of consolidation of state administrative system and no improvement in organizational effectiveness. Despite the observations by Alkady (2015) and Mandeli (2016), the changes can still be acknowledged as constituting an unprecedented drive towards sustainable urban governance in Saudi Arabia. They could create “awareness about urban planning and development” at the local government level and “promote good governance” (Mandeli, 2008). Moreover, since the shift in the mode of urban governance can be conceptualized as a continuum (Evans et al., 2006), especially from the traditional ‘government’ to the modern ‘governance’ mode, the Saudi experience can be regarded as progress towards sustainability. That is, if indeed the shift to governance is beneficial to sustainable outcomes, then this would seem to be a welcome development. The transformation in urban governance corroborates the view that political power or will could have an influence on sustainable urban governance. Thus, practitioners should explore ways of harnessing the influence of power in their quest towards sustainability.

Assessing the changes in Saudi urban governance

Despite the laudable changes, there are still some issues that need to be addressed. A highlight of the changes that have occurred and the components of sustainable urban governance shows that there are some important areas that are yet to be adequately addressed (Table 3.2). Sustainability-based criteria for planning and legislative framework are yet to be changed or are changed in a limited way. Some other issues relevant to sustainability such as subsidy on water, fuel and electricity tariffs, changing the automobile-dependent lifestyle, undeveloped city lots and pollution of coastal environments might jeopardize the gains of the recent transformations if they are not properly addressed. For instance, the government could not easily find vacant land to allocate new housing projects in the major cities due to leap-frogging development. There are many vacant lots within the city that are owned by speculators. In the case of subsidies for water, fuel and electricity tariffs; the government is still weighing its options since the removal of the subsidies might not be supported by the populace. The issue needs to be resolved in time since local oil consumption is already impacting on available oil for export (Abubakar and Aina, 2016). Also, the case whereby environmental activists have to intervene in Tarut Bay to halt the replacement of rare mangrove vegetation by urban development calls into question sustainability planning in the Kingdom (Arab News, 2013). The incident also raised the issue of valuing ecosystem services since the incentive for developers to acquire land in the area was the low prices. Abdulaal (2011; 2012b) highlighted that the gain of implementing public-private partnership might be jeopardized by the lack of institutional framework and governance legislation for supporting the initiative.

Moreover, since some of the changes are still at the proposal stage, they might be jeopardized by policy implementation failure. Howes et al. (2017) argued that the gap between governments' commitments to sustainability and the actual achievement of building sustainable societies by states has been due to policy implementation failure. Some of the Saudi urban development projects such as the King Abdullah Economic City and King Abdullah Financial District have not been completed due to implementation problems (Aina, 2017). Also, the drainage plan to combat urban flooding has not been fully implemented as recent cases of devastating urban flooding were reported in districts of Jeddah (Arab News, 2017). Though the devastation was relatively minimal due to the broadcast of the weather forecast through social media to discourage people from going out unnecessarily, the incomplete drainage system contributed to the flooding (Arab News, 2017).

Table 3.2: Highlight of components of sustainable urban governance and recent changes.

Components of sustainable urban governance	**Recent changes in urban governance**
Public participation	• Public sittings that showcase future plans • Debates on social media about future plans • Election of municipal council members • Yet to have a formalised public participation procedure

Decentralized decision making	• Municipalities have greater autonomy • Big cities such as Makkah, Riyadh Madinah have special development authorities • The decentralization is yet to be completed since most decisions are still made centrally • Municipalities still depend on the central government for funds
Proactive, adaptive and collaborative strategies (multilevel governance)	• Public-private partnership • Establishment of the national committee on GIS spatial data infrastructure • Partnership with UN-Habitat on the Future Saudi Cities program • Need for an institutional framework to support public-private partnership
Sustainability-based criteria for planning	• Use of sustainability criteria (indicators and targets) in Saudi Vision 2030 document
Accountability and transparency	• Establishment of the national anti-corruption body (The National Anti-Corruption Commission) to promote corporate governance • Estalishment of a body for measuring and monitoring the performance

	government agencies
Legislative framework	• Yet to be changed
Public environmental awareness	• Increasing coverage of environmental issues by the press • Establishment of the Non-governmental environmental body (Saudi Environmental Society). • Environmental activism (the case of experts who are campaigning for the declaration of Tarut Bay as a conservation area) • The level of participation of Non-govermental body is still low.
Technology and openness to creativity and innovation	• Use of renewable energy • Smart city projects • Adoption of advanced geospatial techniques and the creation of urban observatories by municipalities • Need to develop local talents

3.5.1 Comparison with international practices

The United States, Canada, United Kingdom, European Union and Australia have implemented the practice of integrating sustainability principles through strategic environmental assessment (SEA) into their planning processes. A notable difference between urban governance in these countries and urban governance in Saudi Arabia is the finance of the local government. The municipalities in Saudi Arabia get their financial allocation mainly from the central government and their dependence on the government limits their autonomy and incentive to promote efficiency. Despite the reforms, Saudi municipalities still depend on the central government, to a large extent, for their finances. This is similar to what was reported in other developing countries where governance is characterized by low tax levels and lack of autonomy due to over-centralization of decision making (Garba and Al-Mubaiyedh, 1999). In the aforementioned countries, local governments generate their funds through taxation and they are consequently accountable to the taxpayers. This is part of the challenges highlighted by Crot (2013), in the study of Masdar City, which might be inimical to urban sustainability.

In Canada, the municipalities have autonomy on how they plan and implement sustainability strategies; and there are documented guidelines on consultation with the community and integration of sustainability principles in their plans (Stuart et al., 2014). Each municipality is encouraged to make an Integrated Community Sustainability Plan (ICSP), but without regulatory authority or formal procedure (Stuart et al., 2014). In the UK, sustainability governance is guided by the EU SEA Directive (2003) that requires the implementation of the Strategic Environmental Assessment (SEA) in planning and policy-making (Atkinson and Klausen, 2011). The planning procedure can be described as hierarchical, technocratic, sectoral with low public awareness (Atkinson and Klausen, 2011). In Sweden, spatial planning is mainly carried out by the local governments without any central control (Persson, 2013). It was reported by Persson (2013) that the planners have already adopted the principles of sustainable development and they make their plans sustainable ‘by default’. It can be concluded from this comparison that the implementation of sustainability in planning varies even within the same country. However, there are some themes that are common to the reviewed cases. Autonomy of the local planning authorities (decentralization), sustainability planning guidelines and public participation are the themes that are prevalent in all the cases.

3.5.2 Towards SEA-based sustainable urban development framework in Saudi Arabia

The implementation of SEA-based planning framework has been acknowledged as a means of promoting sustainable urban development (Alshuwaikhat and Aina, 2004; Alshuwaikhat and Aina, 2005). However, as discussed in the previous sections, Saudi Arabia has not implemented an SEA-based framework for sustainable urban development. This shortcoming has been noted by several studies such as Alsuwaikhat and Aina (2004), Alshuwaikhat and Aina (2005), Rachid and El-Fadel (2013) and MOMRA (2016). These studies noted that there is no SEA legislation or guidelines (except environmental impact assessment (EIA) of plans), limited public participation and no influence of the SEA on decision making. A framework can be implemented by the Presidency of Meteorology and Environment (PME) and the Council of Ministers as suggested by Alshuwaikhat and Aina (2004), since the hierarchy of decision making has not changed much except the enhancement of the municipal council. Policy SEA should be implemented at the top decision-making level such as Council of Ministers while plan and program SEA should be implemented at the ministries involved in planning and detailed plan and program SEA should be done at the municipal level (Alshuwaikhat and Aina, 2004). The municipal council should be empowered to coordinate the agents of the different ministries at the municipal level especially where their duties and services overlap. It is expected that the forthcoming land use planning guide (MOMRA, 2016) might address the prevailing shortcomings. In addition, there is a need to review the General Environment Code which is the main legal document for EIA. The code has been inaugurated since 2001 and it has not been revised since then.

3.6 Conclusion

This article has explored the urban governance and sustainable urban development debate that a top-down approach to governance could influence urban sustainability in a positive way using the framework of sustainable urban governance. In the case of Saudi Arabia, there have been notable positive changes in urban governance and the governance for sustainable development. Due to the imperative of addressing pressing environmental issues, low oil prices and the pressure from Arab Spring, the government has implemented notable projects and policies to reduce Saudi environmental footprint.

These transformations strengthen the point that a top-down approach initiated by those in the top echelon of a society can have a great influence on the move towards sustainability. The top-down approach provides the needed leadership and political will to “make things happen”. For example, the new Vision 2030 that provides a vision of urban sustainability and set of goals to be achieved which were previously non-existent was established by the central government and had been adopted by all agencies and the private sector. The new Saudi Vision 2030 and partnership with UN-Habitat on the Future Saudi Cities program might lead to an improvement in sustainable urban governance. The partnership with UN-Habitat can provide an opportunity for sharing experiences and technical skills. Also, the smart city projects, such as the new Neom city, are envisioned and supported by the government. The adoption and implementation of these projects by all the levels of government had been facilitated by the centralized form of governance. This could be relevant in other contexts as noted by Moser (2019). The adoption of the top-down approach does not preclude the need for bottom-up interactions through citizen and stakeholder participation. As argued by Patterson et al. (2017), there might be a need for both “top-down steering and bottom-up self-organization” to achieve a successful transformation to sustainable urban governance. The development of public-private partnership projects is an aspect of the bottom-up approach that could be further explored.

It should be noted that some important aspects of sustainability have not be affected by the changes in Saudi urban governance. The legislative framework and the administrative procedures for sustainable urban development are still mainly in business as usual mode. There is a need to implement a framework of legislation and administrative procedures to ensure proper sustainable institutionalized urban governance. Also, the drive towards decentralization has not been far-reaching. The municipalities still depend on the central government for their finance. The adopted public-partnership has faced the challenges of lack of operational framework and legislation. These limitations need to be addressed to improve on the recent transformation.

Acknowledgements

The authors wish to acknowledge the support of the University of the Witwatersrand, South Africa, Yanbu Industrial College, Saudi Arabia and King Fahd University of Petroleum & Minerals, Saudi Arabia. The comments of Prof. Ali Modarres and Prof. Ronan Paddison on the initial draft of the manuscript are highly appreciated. The authors are also grateful to the anonymous reviewers for their valuable comments.

CHAPTER FOUR

Using multisource data and the V-I-S model in assessing the urban expansion of Riyadh city, Saudi Arabia from 1972 to 2014

This chapter is based on:

Aina, Y.A., Adam, E., Ahmed, F., Wafer, A. and Alshuwaikhat, H.M., 2019. Using multisource data and the VIS model in assessing the urban expansion of Riyadh city, Saudi Arabia. *European Journal of Remote Sensing*, 52(1), pp.557-571.

Abstract

The paper examines the application of remote sensing techniques, based on Vegetation-Impervious surface-Soil (V-I-S) model and spatial metrics, in an urban analysis for promoting urban sustainability and understanding urban growth theory. In order to improve the accuracy of land cover classification and minimize uncertainty, spectral angle mapping (SAM), spectral mixture analysis (SMA) and band ratioing were applied on multi-date and multisource data for land cover classification and comparison of the discrimination efficiency of these techniques. For the spectral mixture analysis, subsets of the Landsat (2, 3, 4, 5 and 7) and ASTER (1, 2 and 3N) images were selected. The PURITY module of IDRISI was used to purify the end members by using the typicality of each training pixel. Thereafter, the Bayesian probability of each component is computed and used for the spectral unmixing. The classified images of different years were compared to analyze the changes in land use and spatial pattern using V-I-S, a form of percentage of landscape (PLAND) and annualized urban sprawl index (AUSI). The result indicates that band ratioing, with suitable thresholds, can be applied to discriminate land features. However, the performance of band ratioing (69% accuracy) is not as good as that of SAM (75%) and SMA (86%) in discriminating between vegetation and agricultural land. The land use analysis results denote that urban growth management strategies in Riyadh have not been completely successful and the growth pattern substantiates the urban theory of diffusion and coalescence.

Keywords: land use/cover change; urban expansion; urban growth boundary; spatial metrics; V-I-S model; Riyadh

4.1 Introduction

The city of Riyadh is one of the fastest growing cities in the Middle East. The population of the city is currently about 6.5 million and the annual population growth rate of Riyadh, although already declining, currently stands at around 4% (http://www.arriyadh.com/Eng/ab-arriyad/index.aspx/?1=1&menuId=4701). However, the size of growth is a major influencing factor that threatens the sustainability of the city. The resultant spatial footprint has been extensive and the city's population density is declining in a typical sprawl format. The spatial extent of Riyadh is currently about 1000 km^2 and the population density has decreased from 38000 people per square km in 1950 to 6825 in 1999 (Al-Sahhaf, 2000). The ecological footprint coefficient of the city (4.5) is higher than the coefficients of most cities in the neighbouring countries (Choguill, 2006). The sustainability of the city is threatened by the increasing demand for water and infrastructure, traffic pollution and encroachment on natural vegetation (High Commission for the Development of Riyadh [HCDR], 2003). Currently, urban infrastructure such as electricity, telephone, water and sewage is being overstretched and the percentage of population provided with public utilities is reducing (Abubakar and Aina, 2016).

Urban growth management strategies (urban growth boundaries – UGB) have been adopted by the Riyadh Development Authority (ADA) to reduce spatial growth and foster sustainable urban development (HCDR, 2003). This is in congruence with the Saudi national spatial strategy of promoting a decentralized and spatially balanced urban system (Alkhedheiri, 2002). However, there are indications that the strategies have not been totally successful (Al-Hathloul and Mughal, 2004; Mubarak, 2004). Urban land has extended beyond the urban growth boundaries and natural habitats and vegetation are being changed and encroached upon. The prevailing urban growth needs to be monitored to ensure sustainable urban development.

The Vegetation-Impervious surface-Soil (V-I-S) model was presented by Ridd (1995) as a useful means of examining the environmental impact of urbanization and thereby assisting urban environmental management and sustainability. The model can be applied in deriving the biophysical composition of the urban environment and thereby in analyzing urban environmental change. The application of the V-I-S model might be driven by data derived from remote sensing since different approaches have been developed to extract the biophysical composition of urban areas from satellite images (Ridd, 1995). The post-classification comparison technique has been widely used for land use change detection and analysis (Jensen, 2015). The method could be applicable in estimating the V-I-S composition in an urban area for spatial and temporal analysis. The post-classification method requires accurate classification of the satellite images prior to change analysis. Moreover, the model can be applied at different scales from the sub-pixel level to an entire city. The focus of this study is on the city scale.

Band ratioing is one of the existing change detection and land use mapping techniques (Lu et al., 2004a). Band ratioing is also called image division (Mather and Koch, 2010), since it involves dividing the corresponding pixel values of two images by each other. For example, the division of Near-infrared Band by Red band results in values that depict vegetation abundance. It is a simple method that can be quickly computed but the image bands and thresholds must be identified to achieve desired results and accuracy. Moreover, band ratioing can reduce the effect of illumination variation resulting from environmental factors such as topography (Mather and Koch, 2010). Al-Saud (2005), in a study of Al-Hasa in Saudi Arabia, applied a set of band ratios to discriminate land features in an arid environment. In the same vein, Alqurashi and Kumar (2016) used a set of indices based on ratioing to classify land covers in some Saudi cities. The set of band ratios by Al-Saud (2005), which has not been rigourously tested, could be applied in a similar environment (Al-Saud, 2005).

The spectral angle mapping (SAM) technique is one of the recent classification methods developed to improve classification accuracy. The SAM algorithm computes the similarity between a known (reference) spectrum and an unknown (target) spectrum and a group of similar spectra is classified into a specific class (Jensen, 2015). The spectra (both known and unknown) are considered as vectors and the angles between the vectors are computed to evaluate their similarity. The angles usually vary from 0^0 to 90^0 and 0^0 indicates high similarity while 90^0 indicates dissimilarity. Similarly, spectral mixture analysis (SMA) is based on spectral analysis. It is used to extract features from an image by computing the fraction of each feature in a pixel (sub-pixel analysis). Samples of spectra of the features being classified are used in computing the fractions of the features in a pixel. The spectra samples, which are called endmembers, should be pure and distinct from one another. Spectral mixture analysis can be used to generate urban impervious surfaces and land covers without elaborate training data if the endmembers are adequately defined (Voorde et al., 2011). MacLachlan et al. (2017) asserted that SMA is increasingly used for representing urban land cover using the V-I-S framework due to the capability of extracting fractions of urban materials at sub pixel level. However, the endmembers might not adequately represent the complex spectral heterogeneity of urban areas (MacLachlan et al., 2017). Thus, the selection of appropriate endmember for each feature is critical in spectral mixture analysis because endmembers are used as reference to determine the spectral components of the pixels. This study uses image subset and typicality threshold to select endmembers for spectral mixture analysis and compares the discrimination efficiency of the SMA with that of the other techniques (SAM and Band ratioing) to ascertain the best method to use with the V-I-S model. The SAM and the SMA methods were selected because the SMA is widely used for extracting impervious surfaces and suitable for the V-I-S model while the SAM is based on the same concept of analyzing spectra.

Urban and remote sensing researchers have asserted that the analysis of land use change and urban spatial expansion need to be linked with urban form and processes for it to lead to effective urban intervention and planning (Longley and Mesev, 2001; Dietzel et al., 2005; Dahal et al., 2016). Dietzel et al. (2005) and Dahal et al. (2016) applied spatial metrics to show, by presenting empirical results for some North American cities, that the spatial evolution of urban areas oscillates between two phases - diffusion and coalescence (theory of urban growth). The question still remains whether other cities, especially in the developing countries, will follow the same pattern. This study explores the application of band ratioing and spectral mapping techniques for land use change and urban growth analysis and how the results of urban growth analysis are linked with urban growth theory. The objectives of the study are to: (1) examine the spatial and temporal change in land use and urban growth in Riyadh using the V-I-S model at the city scale; (2) compare the efficiency of band ratioing and spectral mapping methods in discriminating and mapping urban land cover in an arid environment; (3) link land use change and urban growth analysis in Riyadh with urban growth theory using a spatial metric; and (4) assess the effectiveness of the urban growth boundaries implemented in Riyadh.

4.2 Background

4.2.1 V-I-S model

There is a growing interest in adopting the V-I-S model as a simple means of analyzing changes in biophysical composition of urban areas. Ward et al. (2000) applied the V-I-S model in southeast Queensland, Australia to examine the changes in land cover types and urban growth between 1988 and 1995 and noted the need for further work on developing methods for evaluating urban composition and comparing V-I-S model results from different cities. Setiawan et al. (2006) demonstrated the use of the model in developing countries and asserted that the model can be applied in comparing land cover changes in an urban area over a period of time or comparing different urban areas. They noted that the model is meant for characterizing urban land cover, but can also be used for land use study because there is a relationship between V-I-S components and land use. Despite the successful implementations of V-I-S model in different studies, the problem of accurate extraction of urban components has not been resolved. The practical application of the V-I-S model, especially in urban planning, is still restricted due to unsatisfactory levels of accuracy in discriminating and quantifying V-I-S components in urban areas and the mixed pixel problem (Weng, 2012; Guo et al., 2014). Though the level of accuracy has been improving, the mixed pixel problem is still a concern in using medium spatial resolution images (Weng, 2012).

4.2.2 Improving the accuracy of image classification

In order to improve the accuracy of extracting urban composition from satellite images and also to resolve the mixed pixel problem, some studies (Weng, 2010; Kwarteng and Small, 2010; Jacobson, 2014; Fan et al., 2015) had used spectral mixture analysis for image classification. The mixed pixel problem, which is resolution dependent, arises from the basic assumption of pixel-based classification techniques that the pixel is homogenous. In reality, each pixel comprises two or more components that are found in spatially varying fractions of the pixels in an image. So, a pixel might be classified as a feature while it comprises two or more features having equal fractions. The mixture analysis method is effective in handling mixed pixel problems and providing spatially continuous biophysical variables (Weng, 2010; Feizizadeh et al., 2013; Fan et al., 2015; Wetherley et al., 2017) if appropriate endmembers are selected.

Mather and Koch (2010) had suggested spectral angle mapping as an alternative to mixture analysis to avoid the critical step of selecting endmembers in the mixture analysis method since they are both based on the analysis of spectra. Dennison et al. (2004) showed, using a spectral library (compilation of spectral signatures of surface materials), that multiple endmember SMA and SAM produced similar results. Though the results were similar, the outcome may have been different if the endmembers were taken from an image and not from a spectral library. Yonezawa (2007) demonstrated the capability of SAM by using a SAM algorithm to complement the traditional maximum likelihood method in order to improve the classification accuracy. The study asserted that the overall accuracy of the land cover classification was improved by the SAM algorithm.

Band ratioing is another technique that has been used to provide urban composition data for the V-I-S model. Setiawan et al. (2006) applied the hierarchical classification scheme (H-VIS) in mapping urban land use in Indonesia. The classification scheme was conducted by applying thresholds to the Normalized Difference Vegetation Index (NDVI). The study demonstrated the applicability of band ratioing for land use classification. Shrestha and Conway (2011) also successfully delineated ex-urban development by using band ratioing (NDVI) and binary recoding.

4.2.3 Analysis of urban landscape

The combination of spatial metrics with urban analysis tools, such as remote sensing, can provide new information about urban dynamics and spatial structure (Herold et al., 2005). One of the spatial metrics applied by Dietzel et al. (2005), Weng et al. (2007) and Aina et al. (2008) in analyzing urban spatial growth is the percentage of landscape (PLAND). PLAND is a metric that shows the percentage of the landscape occupied by each land cover class per unit area. Though PLAND is a simple metric, as a measure of landscape composition and dominance, it can capture the characteristics of urban landscape as shown in the studies by Kong et al. (2012), Chen et al. (2014b) and Sertel et al. (2018). A multi-date computation of the metric depicts the dynamics of landscape composition. A drawback of the metric is the lack of spatial explicitness (Liu et al., 2010). That is, the metric does not depict urban spatial pattern or changes in spatial structure in a location specific manner. Liu et al. (2010) suggested a new spatially explicit index called the land expansion index (LEI). The index can explicitly indicate if spatial expansion is due to infilling, edge-expansion or outlying growth. It is computed by creating a buffer around a newly grown urban patch and determining if the patch is infilling, edge-expansion or outlying growth based on the percentage of intersection between old and new patches. The value ranges between 0 and 100. The computation of the index is more complex than that of PLAND and it is also sensitive to buffer distance. A different method of calculating PLAND is explored in this study to make the metric more amenable to depicting changes in urban spatial structure. An annualized urban sprawl index (Hepinstall-Cymerman et al., 2013) is also explored in studying land use change.

Recent studies have focused on urban growth in Riyadh due to the rapid urbanization and spatial growth occurring in the city. Mashee and Malthus (2010) examined the urban expansion in Riyadh from 1994 to 2007 by using an object-oriented technique. Al-Ahmadi et al. (2009a, 2009b, 2009c) and Alqurashi et al. (2016a) focused on developing, calibrating and validating predictive urban growth models of Riyadh city. Although the studies presented some of the changes in land use and spatial structure, the focus was on modeling and predicting urban spatial growth by 2020.

4.3 Data and methodology

4.3.1 Study area

The study area covers 1488 km^2 of the Riyadh city area. Figure 4.1 shows location of Riyadh, the capital city of Saudi Arabia. Riyadh plays a major role in the Saudi urban system as an administrative, legislative and commercial centre. It is bounded in the north and east by the Ad-Dhana sand dune landscape, in the west by the Arabian shield and in the south by the Rub Al-Khali desert (empty quarters). The city is located in a desert landscape about 400km from the east coast (Gulf) and 1000km from the west coast (Red Sea) of Saudi Arabia. Riyadh has experienced rapid urbanization especially during the oil boom period in the 1970s and 1980s. Rapid spatial expansion of the city has been driven by the oil economy and automobile dependency. In order to manage rapid urban growth, two phases of urban growth boundary had been implemented. That is, the boundary beyond which new urban development is not officially supported with infrastructure and facilities. Fgure 4.2 shows the urban growth boundary (UGB) for Phase I (632 km^2), which was delineated for 1995 while the boundary for Phase II (1,149 km^2) was delineated for 2005 and Phase III (2,130 km^2) was delineated for 2021. There is an additional boundary regarded as the development environs. It is about 3,120 km^2 in extent and it can be allocated to cater for future growth. The boundary might become Phase IV of the UGB series. The main objectives of the growth boundaries are to make the footprint of the city more compact, protect agricultural land and natural areas and reduce pressures on the provision of additional infrastructure to new haphazard settlements (Alkhedheiri, 2002).

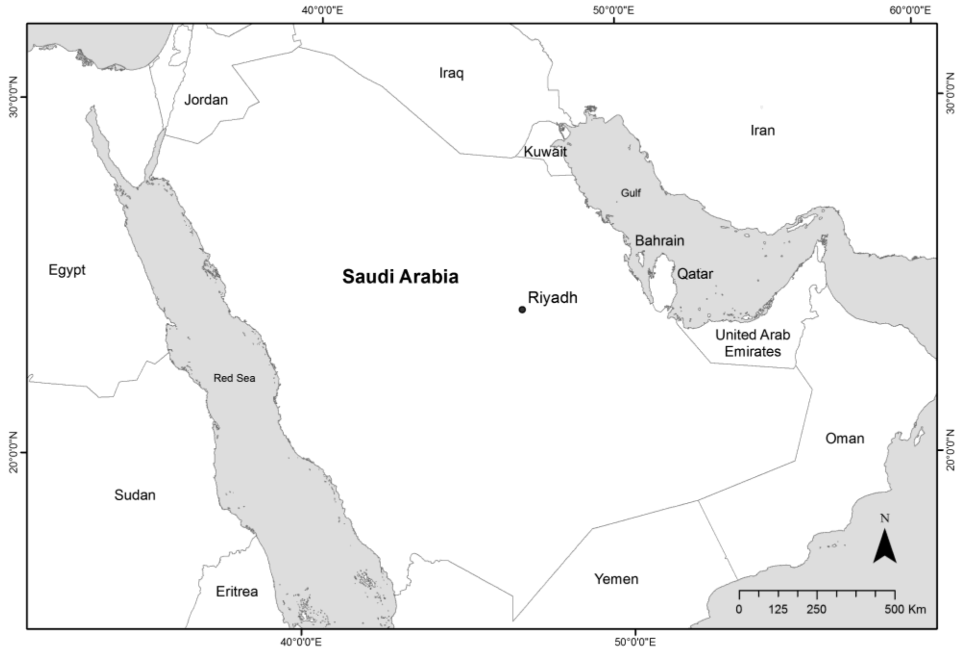

Figure 4.1. Location of Riyadh, Saudi Arabia.

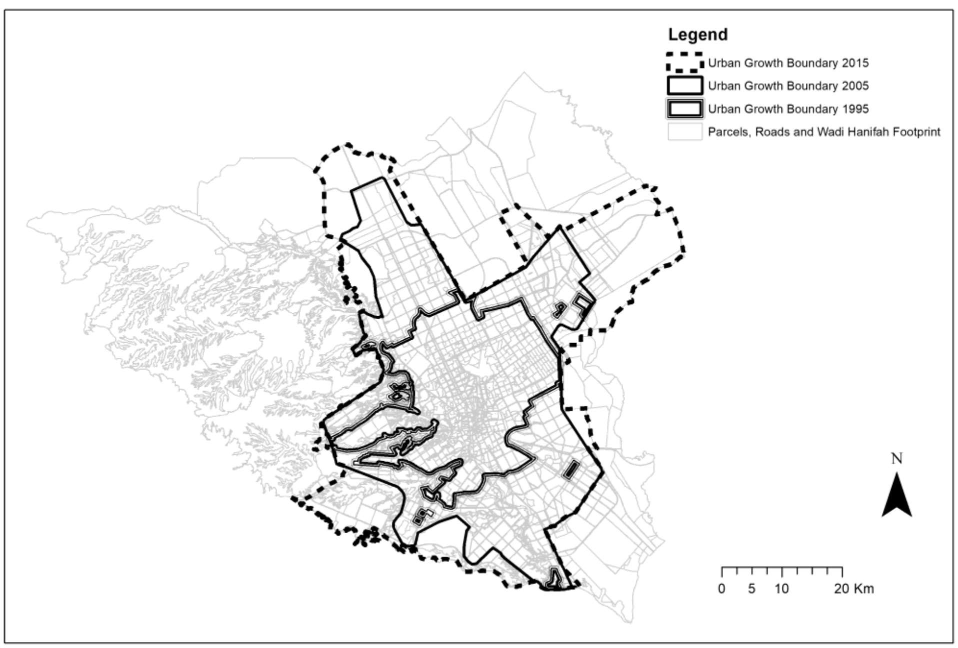

Figure 4.2. Riyadh City and the Urban Growth Boundaries (UGB) (1995, 2005 and 2021).

4.3.2 Data and image preprocessing

The data sources for the analysis include multi-date and multisource satellite images from 1972 to 2014. Vector data (shapefile format) for the two phases of UGB and land use were also acquired for the study from Riyadh Development Authority. The land use shapefile contained the land use data of Riyadh and it was used for classification accuracy assessment (complemented by Google Earth™ images of the area). Figure 4.3 shows the satellite images that include Landsat MSS (1972), Landsat TM (1985 and 1995), ASTER (2005) and Landsat OLI (2014) images. ASTER image was used because of the SLC-off problem of Landsat data acquired after May 31, 2003 that have resulted in data gaps in Landsat images. Anniversary date images were chosen to reduce errors due to seasonal changes (see table 4.1). The satellite images were all geo-referenced to root mean square error of less than 0.25 pixel and projected to UTM (Universal Transverse Mercator) Zone 38 North. The images were resampled to 30m using a nearest neighbour method. The 1972 image has a coarser resolution of 60m. The satellite images coverages for 1985 and 1995 comprised two scenes each, since the study area was not fully covered by single scenes. The images were atmospherically corrected by using the dark object subtraction method. Image mosaic and subset operations of IDRISI™ Selva 17.2 were carried out on images with two scenes to extract the development area of Riyadh for the study. The location of the testing samples (275) for accuracy assessment are shown in figure 4.4. The training samples, which are the endmembers, are separate from the testing samples.

Table 4.1: Description of satellite images.

Image type	Acquisition date	Path/Row	Spatial resolution
Landsat MSS	1 August 1972	178/43	60m
Landsat TM	31 July 1985/27 November 1987	166/43 165/43	30m
Landsat TM	4 July 1995/13 September 1995	165/43 166/43	30m
ASTER	24 August 2005	Not Available	15m
Landsat 8 OLI	16 August 2014/25 August 2014	166/43 165/43	30m

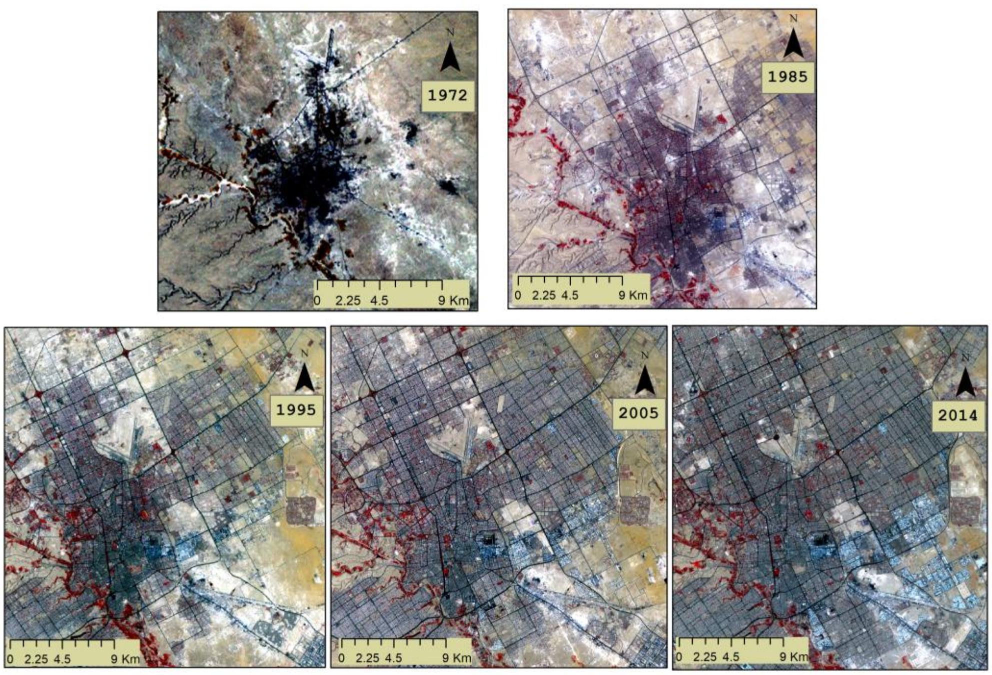

Figure 4.3. Multi-temporal images of Riyadh.

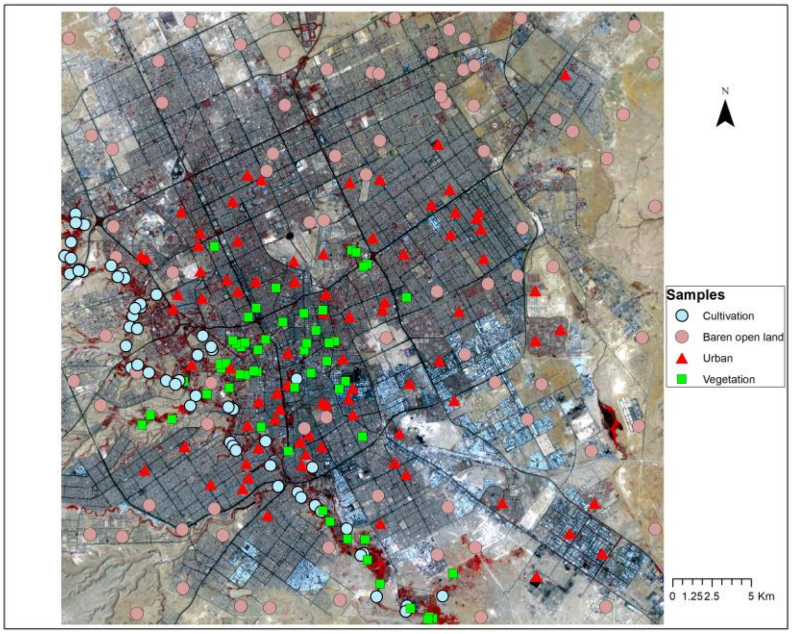

Figure 4.4. Sample points for accuracy assessment.

4.3.3 Image classification and analysis

A post-classification technique for land use change detection and analysis was adopted in this study. Prior to the post-classification analysis, three different classification techniques - spectral angle mapping, spectral mixture analysis and band ratioing - were applied for the classification. ILWIS 3.7.2 software package was used for spectral angle mapping and band ratioing classification. ILWIS has a built-in spectral angle mapping classification algorithm. The SAM algorithm was used to classify the images into four different land use types: urban, natural vegetation, cultivated agricultural land and barren open land. Due to the low spatial resolution, the 1972 image was classified into three land cover types: urban, vegetation cover and barren open land. Therefore, the comparison of land cover change between 1972 and 1985 was done based on three classes – urban, vegetation and barren open land. In line with the V-I-S model; urban land use represents impervious surface, barren open land represents bare soil and two classes (natural vegetation and cultivated agricultural land) represent vegetation.

The ratios presented by Al-Saud (2005) were used to classify the images into four classes. The ratios were based on Landsat TM imagery, but they can be used to classify images with similar bands. However, in this study, the ratios were assessed on classification of Landsat imagery only. The ratios are 2/3, 4/5, 5/6, and 5/7. The ratio 2/3 is very good for discriminating natural vegetation while ratio 4/5 is good for extracting barren land. Band ratios 5/6 and 5/7 are good for discriminating urban area and natural vegetation, respectively. After the ratios had been computed, different thresholds were applied to the results to get the most suitable threshold (based on trial and error and visual assessment) for each feature.

The IDRISI™ Selva 17.2 was used in performing the sub-pixel classification. The most important aspect of spectral mixture analysis is the selection of endmembers. Authors such as Small (2006), Lu et al. (2004b) and Weng (2010) reported that applying principal component analysis (PCA) or minimum noise fraction (MNF) or using a subset of Landsat images can reduce the correlation between images. This study used subsets (2, 3, 4, 5, and 7) of the Landsat images and subset (1, 2, and 3N) of the ASTER image. Endmembers were selected from the images and the parametric option of the PURIFY module (Eastman, 2012) of IDRISI™ was applied to the selection to improve the purity of the endmembers. The module calculates the typicality of each training pixel by computing the distance between the pixel and the mean of its class. Pixels with low typicality are dropped from the sample and pixels with high typicality are included in the training sample based on a threshold chosen by the user (0.7 was chosen for this study). The pixels with lower typicality might not be pure enough for the study and choosing higher typicality would result in rejecting most of the pixels.

After the purification of the endmembers, the UNMIX module (Eastman, 2012; Warner and Campagna, 2013) was used to generate the fractions of land cover types in the study area. The module uses the Linear Spectral Unmixing (LSU) method to compute the fractions. The method assumes a linear combination of the pure training samples (endmembers). The mathematical equation of LSU can be written as

$$R = \sum_{i=1}^{N} f_i \ r_i + e \qquad (1)$$

Where **R** is the spectral reflectance of a mixed pixel in the spectral bands, **N** is the number of endmembers, $\boldsymbol{f_i}$ is the fraction of ith endmember, $\boldsymbol{r_i}$ is the reflectance of ith endmember, $\boldsymbol{e}$ is the error term. The approach is most effective if the endmembers are few and distinct (Eastman, 2012). This study applied the probability guided unmixing method. In this method, the Bayesian probability of each component is computed prior to mixture analysis and the user can also select the number of components to consider in each pixel (Song, 2005; Eastman, 2012). The Bayesian probability method uses the endmember signature probability distribution rather than the constant signature used by a typical LSU analysis (Song, 2005). Thereafter, the HARDEN module (Eastman, 2012; Warner and Campagna, 2013) was used to assign the fractions to classes. The HARDEN module assigns a pixel to the class with the maximum fraction. After the classification, a majority filter (3x3) was applied on the classified images to remove isolated pixels. The flowchart of the classification process is presented below (see figure 4.5). The accuracies of the classification results were assessed by using 275 sample points that were selected by stratified random sampling. The land cover types were verified by using high resolution images from Google Earth and the "show historical imagery" feature.

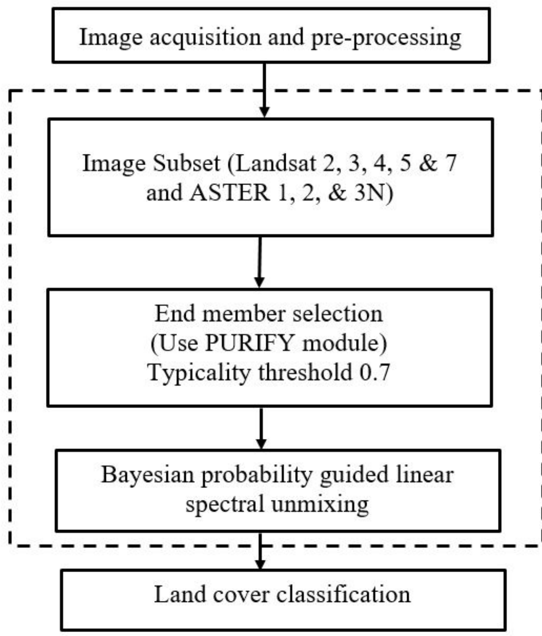

Figure 4.5. Classification flow chart.

The results of the image classifications of different years were compared to depict the changes in land use and spatial pattern of urban growth. The changes were analyzed by computing the PLAND, the sprawl index and percentages of land cover types. Classification accuracies were also computed for the different techniques to ascertain the most appropriate method for land cover classification in the study area. The SMA method was chosen for the analysis due to the level of accuracy and being suitable for extracting the urban materials for the V-I-S model. The urban growth boundary shapefiles were used to assess, in spatial context, the effectiveness of the urban growth boundary policy. A metric (PLAND) (Dietzel et al., 2005) was computed for urban extent in each classified image in order to examine the linkage between urban growth and spatial processes (changes in spatial structure of a city). PLAND is the percentage of landscape, or the sum of areas of a land cover type divided by the total area.

Traditionally, the total area is computed from the administrative boundary of the area and is thereby constant. This study explored a varying total area by computing the urban field area for each year. It is the area of a circle that bounds the extent of the study area (Longley and Mesev, 2001). The "Urban Field" PLAND (UFPLAND) could depict the process of urban spatial growth as diffusing or coalescing. If the growth is diffusing, it is expected that there will be scattered "seeds" of centers of growth over the landscape and the UFPLAND value will be low. On the other hand, if the process is in a state of coalescence, the urban extent will be more compact and UFPLAND value will be high. The UFPLAND might not be sensitive to spatial pattern and processes within the urban field especially when it is low. Thus, in a typical urban setting, the PLAND will increase with time showing mere urban expansion. On the other hand, UFPLAND has a varying total landscape area. If the total landscape area is expanding over a period of time, it means more area outside the spatial extent has been developed – diffusion. If the total land area is fixed over a period of time, it means development is mainly taking place within the spatial extent – coalescence. Though the metric will not indicate differences in the pattern of change within the spatial extent, it will indicate the overall pattern.

An annualized urban sprawl index (AUSI) was also computed for the study area to capture the changes in urban land consumption throughout the study period. AUSI was computed by dividing an annualized change in urban extent (in km^2) by an annualized change in population size for the same period (Hepinstall-Cymerman et al., 2013). Changes in urban land cover within and outside the urban growth boundaries were analyzed by calculating the amount in km^2 of new urban land cover within and outside the urban growth boundaries.

4.4 Results and discussion

4.4.1 Accuracy assessment

The classification result shows that the band ratioing method can be applied to discriminate land cover types especially if an appropriate threshold is used. But, the performance is not as effective as the SAM and SMA methods in discriminating between vegetation and agricultural land. Tables 4.2, 4.3 and 4.4 shows the performance of all the three methods in classifying 1985 image, which is used for the accuracy assessment. The performance of the methods is poorer in discriminating between agricultural land and vegetation than mapping other features. The overall accuracy for band ratioing is 69% while the overall accuracy for SAM is 75%. The overall accuracy for spectral mixture analysis ranged from 83% to 86% for the different years. The highest kappa statistics for SMA was 81%. It should be noted that urban extent tends to be slightly overestimated by the SAM algorithm in 2005 while the band ratio method slightly underestimates the urban extent (upon visual assessment) (see figure 4.6). The urban extent in 2005 according to the SAM technique was 638 km^2 while the SMA urban extent for the same year was 622 km^2.

The band ratio method outperforms the SAM in depicting the gaps (undeveloped lands) within the urban area. It is also more suitable for extracting the road network if the appropriate threshold is applied. Despite having lower accuracy than the SMA, the SAM technique produced similar results (see figure 4.6). In their study of five Saudi cities, Alqurashi et al. (2016a) obtained an accuracy of 87.5% for a 1985 image and 92.8% for a 2014 image by using the object-oriented image analysis (OBIA) method. Since 85% is widely used as sufficient accuracy (Foody 2006) and the use of urban fractions in the V-I-S model, LSU analysis might be preferred. The study by Lu and Weng (2006) yielded 83.78% as the overall accuracy. A recent study by Guo et al. (2014) achieved the overall accuracy of 96.69% using support vector machine (SVM). However, the classes are different from the ones used in this study. The classes are high albedo, low albedo, vegetation and soil.

Table 4.2: Error matrix of band ratioing method.

	Classified land cover (1985)					
Reference	Cultivation	Barren open land	Urban	Vegetation	Total	Producer accuracy
Cultivation	42	2	7	4	55	76.4
Barren open land	0	83	0	0	83	100
Urban	0	25	57	0	82	69.5
Vegetation	20	6	22	7	55	12.7
Total	64	116	84	11	275	
User accuracy	65.6	71.6	67.9	63.6		

Table 4.3: Error matrix of spectral angle mapping method.

	Classified land cover (1985)					
Reference	Cultivation	Barren open land	Urban	Vegetation	Total	Producer accuracy
Cultivation	43	0	0	12	55	78.2
Barren open land	0	69	14	0	83	83.1
Urban	2	7	73	0	82	89
Vegetation	16	4	14	21	55	38.2
Total	61	80	101	33	275	
User accuracy	70.5	86.3	72.3	63.6		

Table 4.4: Error matrix of spectral mixture analysis method.

	Classified land cover (1985)					
Reference	Cultivation	Barren open land	Urban	Vegetation	Total	Producer accuracy
Cultivation	47	0	0	8	55	85.5
Barren open land	0	73	10	0	83	88
Urban	1	2	79	0	82	96.3
Vegetation	16	2	8	29	55	52.7
Total	64	77	97	37	275	
User accuracy	73.4	94.8	81.4	78.3		

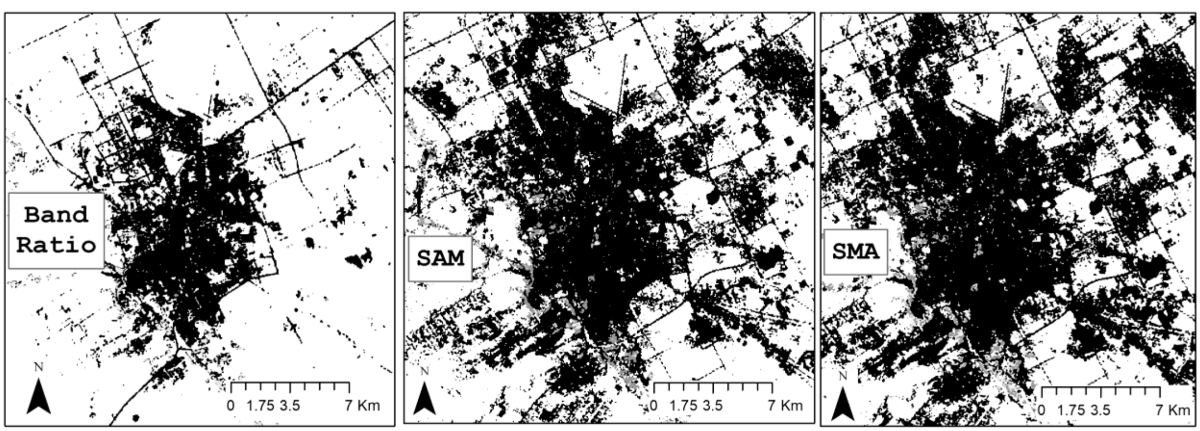

Figure 4.6. Image Classification (1985) – Band Ratio, SAM and SMA Methods.

4.4.2 Change analysis

As mentioned above, the Spectral Mixture Analysis technique was used in the change analysis. Table 4.5 shows how the urban extent in Riyadh increased from about 43 km^2 in 1972 to 780.6 km^2 in 2014. The period between 1972 and 1985 had the highest spatial expansion of 353 km^2 from 43 km^2 to 396 km^2. The growth rate of urban extent which had started tapering as shown by the urban land expansion from 1995 to 2005 picked up again from 2005 to 2014. The lowest rate of expansion was recorded in 2005. Figure 4.7 shows the spatial expansion of Riyadh from 1972 to 2014. The urban spatial extent compiled from the satellite images is actually less than the 1000 km^2 reported by Riyadh Authority (HCDR, 2003), but it is consistent with findings of Mashee and Malthus (2010). This might be due to leap-frog development outside the city fringe. Some land areas of the city are just subdivided without being developed immediately and they remain vacant for many years.

Table 4.5: Land use/land cover change in Riyadh, 1972 – 2014.

<table>
<tr><th>Land use/land cover type</th><th>1972 (km^2)</th><th>1985 (km^2)</th><th>1995 (km^2)</th><th>2005 (km^2)</th><th>2014 (km^2)</th><th>1972 to 1985 (km^2)</th><th>1985 to 1995 (km^2)</th><th>1995 to 2005 (km^2)</th><th>2005 to 2014 (km^2)</th><th>1972 to 2014 (km^2)</th></tr>
<tr><td>Barren open land</td><td>1432.2 (96.2%)</td><td>1069.8 (71.9%)</td><td>932.2 (62.6%)</td><td>836.4 (56.2%)</td><td>673.2 (45.3%)</td><td>-362.4 (-25.3%)</td><td>-137.6 (-12.9%)</td><td>-95.8 (-10.3%)</td><td>-163.2 (-19.5%)</td><td>759 (-53%)</td></tr>
<tr><td>Urban</td><td>42.7 (2.9%)</td><td>396 (26.6%)</td><td>516.5 (34.7%)</td><td>622.1 (41.8%)</td><td>780.6 (52.4%)</td><td>353.3 (827.4%)</td><td>120.5 (30.4%)</td><td>105.6 (20.4%)</td><td>158.5 (25.5%)</td><td>737.9 (1728.1%)</td></tr>
<tr><td>Cultivation</td><td rowspan="2">13.4 (0.9%)</td><td>12.7 (0.9%)</td><td>16.9 (1.1%)</td><td>10.9 (0.7%)</td><td>15.6 (1.0%)</td><td rowspan="2">9.1 (67.9%)</td><td>4.2 (33.1%)</td><td>-6.0 (-35.5%)</td><td>4.7 (43.1%)</td><td rowspan="2">21.1 (157.5%)</td></tr>
<tr><td>Vegetation</td><td>9.8 (0.7%)</td><td>22.7 (1.5%)</td><td>18.9 (1.3%)</td><td>18.9 (1.3%)</td><td>12.9 (131.6%)</td><td>-3.8 (16.7%)</td><td>0.0 (0%)</td></tr>
</table>

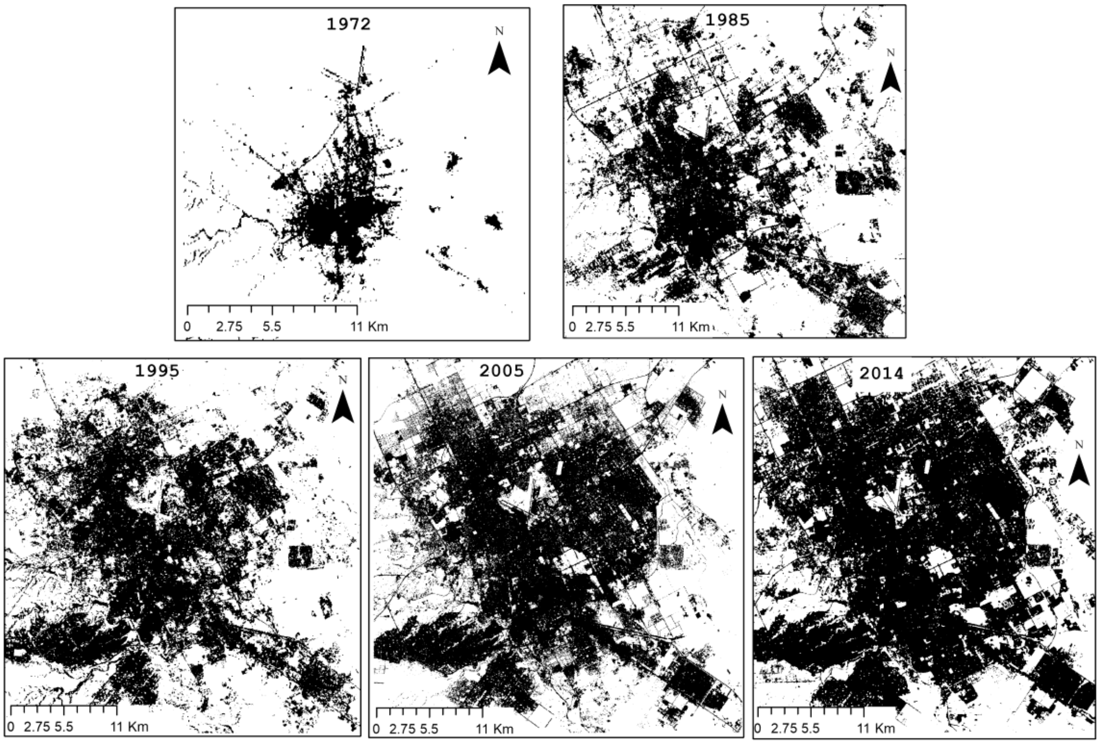

Figure 4.7. Urban Spatial Expansion in Riyadh (1972 – 2014).

The vegetation cover had a different trend from the urban area. Vegetation cover increased from 13.4 km^2 in 1972 to 39.6 km^2 in 1995, but later reduced to 29.8 km^2 in 2005. The decrease in vegetation cover indicates encroachment of built-up area on vegetation and agricultural land. It was only in 2005 that the land area gained by urban land use (105.6 km^2) exceeded the land area lost by barren open land (-95.8 km^2). The findings corroborate the earlier works by Al-Sahhaf (2000), Al-Ahmadi et al. (2009a, 2009b, 2009c) and Mashee and Malthus (2010) that highlighted the rapid urbanization in Riyadh. The changes in vegetation cover have implications on the environment in the Riyadh area. The increase in vegetation cover might have implications on water consumption and underground water usage while the decrease might reduce the mitigating effect of vegetation on the microclimate as suggested by Stabler et al. (2005). The trend of vegetation cover had changed by 2014 with the area covered by vegetation increasing from 29.8 km^2 in 2005 to 34.5 km^2. The fractions of impervious surface and vegetation also highlight the changes discussed above. The mean fractions changed with increase or decrease in the spatial extent of the urban components (see table 4.6). The annualized sprawl index indicates a decreasing trend in land consumption from 1972 to 2014 (see table 4.7). There is indication that the urban growth boundary implemented by the Riyadh Authority has not been completely successful. Urban development had occurred outside the 1995 and 2005 boundaries in 1995 already (see figure 4.8 and table 4.8). The urban field area had increased to 2300 km^2 by 1985, but it remained constant till 2014. Despite the shortcomings, the policy has helped to curb haphazard and outlying (leapfrog) spatial growth in the city by achieving a constant urban field since 1985 and limiting urban development to this area. However, with the new trend (2014) (see table 4.8) of increase in land development outside the growth boundaries (even the 2021 boundary), the Riyadh Authority might need to increase efforts in curbing sprawl. The new spate of land development might be attributed to the commencement of the third phase of UGB and increasing population pressure (see table 4.7).

Table 4.6: Change in impervious surface and vegetation fraction in Riyadh, 1972 – 2014.

Year	Impervious surface fraction		Vegetation fraction	
	Mean	Mode	Mean	Mode
1972	0.35	0.05	0.14	0.05
1985	0.50	0.95	0.14	0.05
1995	0.54	0.95	0.16	0.05
2005	0.61	0.95	0.15	0.05
2014	0.63	1.00	0.14	0.05

Table 4.7: Annualized sprawl index of Riyadh, 1985 – 2014.

Year	Population (000)	Population change	Δ pop/year	Urban extent (km^2)	Change in urban extent	Δ km^2/year	Annualized urban sprawl index
1972	666.8 (1974)			42.7			
1985	1500	833.2	64.1	396	353.3	27.2	0.42
1995	2777.1 (1992)	1277.1	127.7	516.5	120.5	12.1	0.09
2005	4087.2 (2004)	1310.1	131	622.1	105.6	10.6	0.08
2014	5676.6 (2013)	1589.4	176.6	780.6	158.5	17.6	0.10

Note: Population data obtained from Central Department of Statistics & Information http://www.cdsi.gov.sa/

Table 4.8: Change in urban extent inside and outside urban growth boundaries, 1985 – 2014.

Year		1995 urban growth boundary	2005 urban growth boundary	2021 urban growth boundary
1985	Inside (km^2)	241	325	334
	Outside (km^2)	112	28	19
	Total (km^2)	353	353	353
	% Outside	32	8	5
1995	Inside (km^2)	104	116	120
	Outside (km^2)	17	5	1
	Total (km^2)	121	121	121
	% Outside	14	4	1
20005	Inside (km^2)	60	98	99
	Outside (km^2)	46	8	7
	Total (km^2)	106	106	106
	% Outside	43	8	7
2014	Inside (km^2)	78	140	138
	Outside (km^2)	81	19	17
	Total (km^2)	159	159	159
	% Outside	51	12	11

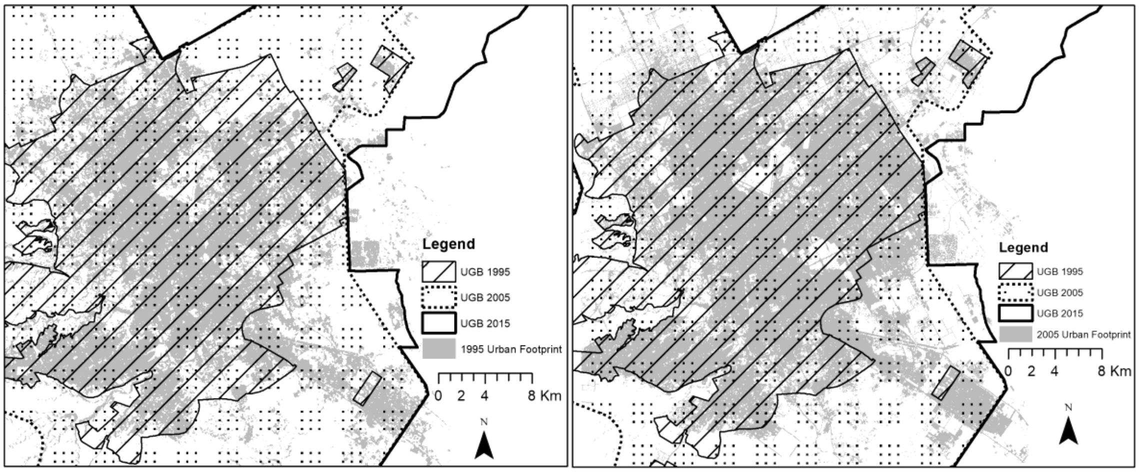

Figure 4.8. Urban expansion outside the Urban Growth Boundaries (UGB) in Riyadh.

The result of the spatial metric computation indicates that the urban growth process in Riyadh followed the urban theory of diffusion and coalescence highlighted by Dietzel et al. in 2005 and Dahal et al. in 2016 and 2017. Liu et al. (2010) and Dahal et al. (2017) mentioned three types of growth during the diffusion-coalescence phases of urban growth; in-filling, edge-expansion and outlying growth. Outlying growth occurs mainly at the diffusion phase while in-filling and edge-expansion occur mainly at the coalescence phase. The studies (Dietzel et al., 2005; Dahal et al., 2016 and 2017; Liu et al., 2010) did not use LSU, but adopted spatial metrics in monitoring urban expansion. The growth of Riyadh started within the city walls in the 1950s. Thereafter, the city expanded outward in a gradual manner. In the 1970s, due to unprecedented increase in government spending the spate of development increased, which led to the leap-frog growth witnessed later. The growth between 1972 and 1985 constituted the diffusion phase whereby expansion was mainly through outlying growth. After 1985, the spatial expansion of the city started tapering as new development was largely due to edge-expansion and “in-filling” rather than isolated and outlying growth at the edge of the city. This was the coalescence phase.

The lowest PLAND figure is 3% for 1972 and thereafter, the figure increases to 42% in 2005 and 52% in 2014. This indicates the rapid change of land cover from barren open land to impervious surface due to urbanization. The change in PLAND value for vegetation depicts a low percentage of coverage by green area in Riyadh. Unlike the PLAND values, the UFPLAND depicts the phases of the changes occurring in the land use and land cover of the study area. The highest UFPLAND figure was 32% for 1972, which indicates coalescence. Thereafter, the figure declined to 17% in 1985 (diffusion) and picks up again in 1995 and 2014 to reach 34% (coalescence) (see figure 4.9). The increases in UFPLAND values from 1985 to 2014 are due to the fact that the urban field area is constant (2300 km^2) while urban land cover area was increasing. It should be noted that the PLAND and UFPLAND of 1972 might have been affected by the differences in sensor resolution. The application of the V-I-S model to Riyadh also depicts the same process. The land cover composition in 1972 was desert according to V-I-S ternary. It changed to low-density residential in 1985 and medium to high density in 1995, 2005 and 2014 as the impervious surface increased. This is corroborated by the fractions of the impervious surface. The mean increased from 0.35 in 1972 to 0.63 in 2014 indicating increasing imperviousness. The mode of the fraction of the impervious surface also increased from 0.05 to 1 indicating coalescence. The percentages of barren open land and urban area were 63% and 35%, respectively, in 1995 and 56% and 42%, respectively, in 2005. This indicates that Riyadh became a medium-density residential area from 1995 to 2005 and it is progressing towards high density.

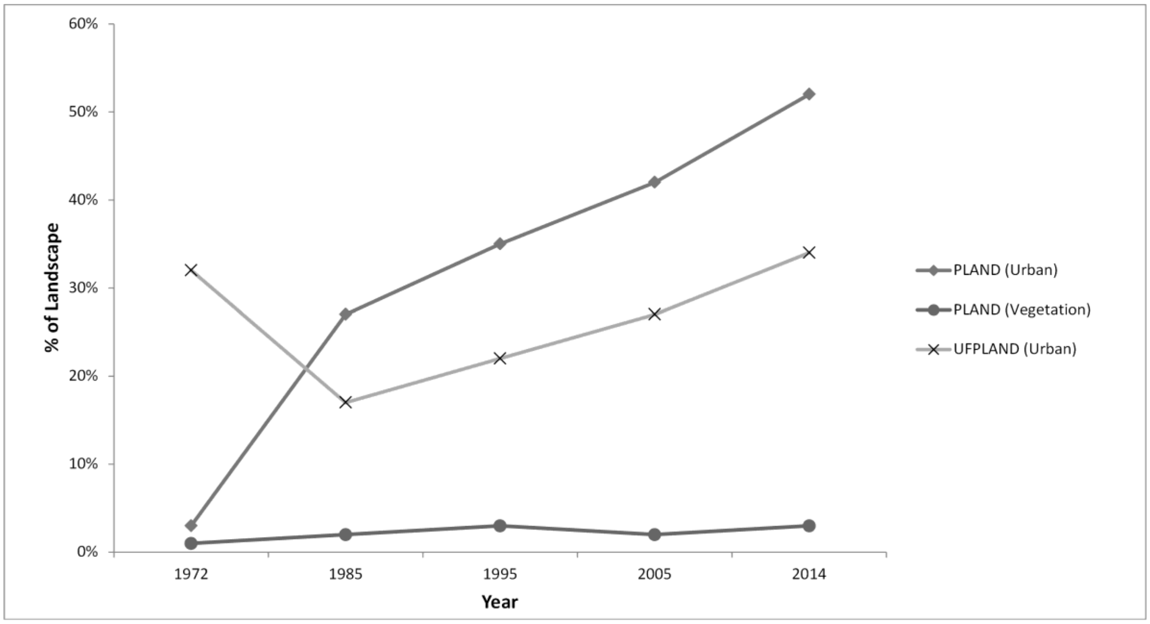

Figure 4.9. Percentage of Landscape (PLAND) and (UFPLAND) for the Process of Diffusion or Coalescence.

4.5 Conclusion

This paper presents issues and techniques that are related to urban growth management and applies them to the fast-growing city of Riyadh. A form of a spatial metric (percentage of landscape) has been presented by this study. This metric highlights the changes in urban spatial pattern in a better way than the traditional version. It depicts the changes in the diffusion and coalescence phases of urban spatial growth. Other indicators/metrics like the V-I-S model and AUSI were also applied in highlighting changes in land cover and effectiveness of UGBs in Riyadh.

In regard to Riyadh, this study has shown the spatial impact of urban expansion especially on vegetation loss. There had been an increase in vegetation cover in Riyadh since the 1950s until around 1995 when encroachment on vegetation cover became apparent. Though the vegetation loss has been reversed in 2014, the task at hand is to develop a means of adequately forestalling increases in vegetation loss. On the other hand, the metrics of urban expansion is improving as indicated by the reduction in the rate of spatial expansion and increase in the urban area's percentage of landscape.

The analysis has therefore, shown that despite a few failures, the urban growth boundary strategy in Riyadh has been working to some extent. The hitherto rapid spatial expansion has slowed down and the 'gaps' and brownfields within the city are being developed. There is a caveat. How can it be confirmed that the changes are due to planning intervention and not the normal processes of urbanization, suburbanization and re-urbanization or oscillatory diffusion and coalescence? Having used these techniques to understand spatial processes of the city, how do planners know when and where to intervene? Arriyadh Authority had made some efforts through the initiation of the Urban Growth Strategy for Riyadh and this could be a starting point towards better urban growth management.

This work could still be extended further by looking into other spatial metrics that were used in testing the hypothesis of diffusion and coalescence. Such a study will help in confirming the universality of the theory of diffusion and coalescence. The possibility of using the urban fractions derived from spectral unmixing as an indicator of urban sprawl can also be examined. The result can be compared with the result of a known sprawl estimator such as Shannon’s entropy method that had been applied successfully in studying sprawl (Bhatta et al., 2010). The accuracy achieved by the study by using the LSU is sufficient and similar to what has been achieved by other studies. The accuracy needs to be improved to achieve the accuracy of object-oriented image analysis (OBIA).

Acknowledgements

The authors are grateful to the anonymous reviewers for their useful comments. The authors would like to acknowledge the assistance of the following institutions in the acquisition of the necessary data for this work – King Abdul Aziz City for Science and Technology (KACST), Riyadh Development Authority (ADA), King Fahd University of Petroleum and Minerals, United States Geological Survey (USGS) and Global Land Cover Facility of University of Maryland.

CHAPTER FIVE

Examining the spatio-temporal dynamics of $PM_{2.5}$ in Saudi Arabia using satellite-derived data: A cluster study

This chapter is based on:

Aina, Y., Adam, E. and Ahmed, F., 2016. Examining the Spatio-temporal Dynamics of PM2. 5 in Saudi Arabia Using Satellite-derived Data: A Cluster Study. *The First Saudi Conference on the Environment*, 7 - 9 March, 2016, King Khalid University, Saudi Arabia. *Preprints, (doi: 10.20944/preprints201612.0011.v1).*

Abstract

The study of the concentrations and effects of fine particulate matter in urban areas has been of great interest to researchers in recent times. This is due to the acknowledgment of the far-reaching impacts of fine particulate matter on public health. Remote sensing data have been used to monitor the trend of concentrations of particulate matter by deriving aerosol optical depth (AOD) from satellite images. The Center for International Earth Science Information Network (CIESIN) has released the second version of its global $PM_{2.5}$ data with improvement in spatial resolution. This paper revisits the study of spatial and temporal variations in particulate matter in Saudi Arabia by employing cluster analysis of the new data. Cluster analysis of the $PM_{2.5}$ values of Saudi cities is performed by using Anselin local Moran's I statistic. The analysis is carried out at the regional level by using self-organizing map (SOM). The results show an increasing trend in the concentrations of particulate matter in Saudi Arabia, especially in some selected urban areas. The eastern and south-western parts of the Kingdom have significantly clustering high values. Some of the $PM_{2.5}$ values have passed the threshold indicated by the World Health Organization (WHO) standard and targets posing health risks to the Saudi urban populations.

Keywords: satellite data; fine particulate matter; air pollution; geographic information system; health risks; spatial analysis; Saudi Arabia

5.1 Introduction

Fine particulate matter is one of the important air quality parameters. Recently, fine particulate matter is receiving a lot of attention due to the health, environmental and social implications of increasing particulate matter concentrations. The International Agency for Research on Cancer (IARC) has confirmed the carcinogenicity of $PM_{2.5}$ (Loomis et al., 2013). A positive relationship between exposure to $PM_{2.5}$ and incidences of lung cancer has been found in areas with annual average levels of $PM_{2.5}$ ranging from 10 to 30 μg/m^3 (Loomis et al., 2013; Hoek & Raaschou-Nielsen, 2014). Even in areas where the concentrations of $PM_{2.5}$ are less than 10 μg/m^3, there are risks of lung cancer (Loomis et al., 2013). The study by Franck et al. (2014), in Santiago de Chile, indicated that exposure to $PM_{2.5}$ was highly correlated with cardiovascular hospital admissions. Nasser et al. (2015) concluded that particulate matter constitutes a risk factor for cardiovascular diseases in the Middle East countries that include Iran, Saudi Arabia, the United Arab Emirates and Qatar. These findings underscore the need to monitor particulate matter concentrations in order to establish means of controlling the concentrations.

Several authors have reported the monitoring of particulate matter at the global and local levels. Brauer (2016) reported about 20% increase in the global exposure to particulate matter and about 2.9 million deaths in 2013 attributed to exposure to fine particulate matter. Farahat (2016) examined the variations, causes and effects of the concentrations of pollutants (especially aerosols) over the Arabian Peninsula. In Saudi Arabia, Al-Jeelani, 2009, Aburas et al., 2011, Munir et al., 2013, Rushdi et al., 2013, Shaltout et al., 2013, and Habeebullah, 2013 identified particulate matter concentrations and compositions in the major cities of the Kingdom such as Riyadh, Jeddah and Makkah. El-Mubarak et al. (2014) identified polycyclic aromatic hydrocarbons (PAHs) in the particulate matter over the city of Riyadh. They found high PAHs and particulate matter concentrations that could be attributed to traffic emissions (El-Mubarak et al., 2014). Also, organic tracers, that could pose toxicity risks, were found in the particulate matter over Dhahran city, Saudi Arabia (Rushdi et al., 2014).

Data derived from satellite images are used to supplement ground measurements in monitoring particulate matter concentrations. Sinha et al. (2015) used satellite data (Moderate Resolution Imaging Spectroradiometer [MODIS]) and ground-based observations to estimate $PM_{2.5}$ values over Hyderabad in India. Similarly, Farahat et al. (2015) used multisensor satellite data (including MODIS) and ground observations from AErosol RObotic NETwork (AERONET) to monitor aerosols' dynamics over Saudi Arabia. Recently, efforts have been made to produce satellite-derived global data sets of particulate matter concentrations (Battelle Memorial Institute and Center for International Earth Science Information Network [CIESIN], 2013; de Sherbinin et al., 2014; van Donkelaar et al., 2010, 2015a, 2015b). The first set of the global data (Battelle Memorial Institute and CIESIN, 2013; de Sherbinin et al., 2014) has a spatial resolution of about 50 km while the second set has a resolution of about 10 km. Aina et al. (2014) explored the first set of data in monitoring the changes in $PM_{2.5}$ concentrations of Saudi Arabia especially variations among Saudi cities. The second set of data is finer in resolution and might give different results. Thus, the aim of this study is to reexamine the spatial and temporal variations in $PM_{2.5}$ over Saudi Arabia using the new global data set.

5.2 Materials and methods

5.2.1 Study area

The location of the study is Saudi Arabia. The country covers an area of about 2 million km^2 making it the largest country in the Arabian Peninsula. According to the Kingdom's General Authority of Statistics, the 2014 estimate of Saudi Arabia's population was ~31 million (http://www.stats.gov.sa/en). More than 80% of the population lives in urban areas. The major cities in Saudi Arabia include Riyadh, Jeddah, Dammam, Makkah and Madinah and the two industrial cities of Jubail and Yanbu (Figure 5.1). About half of the Saudi population resides in these cities. Though there are other cities with higher populations than the industrial cities, the share of the Kingdom's economic activities from these two cities brings them to prominence.

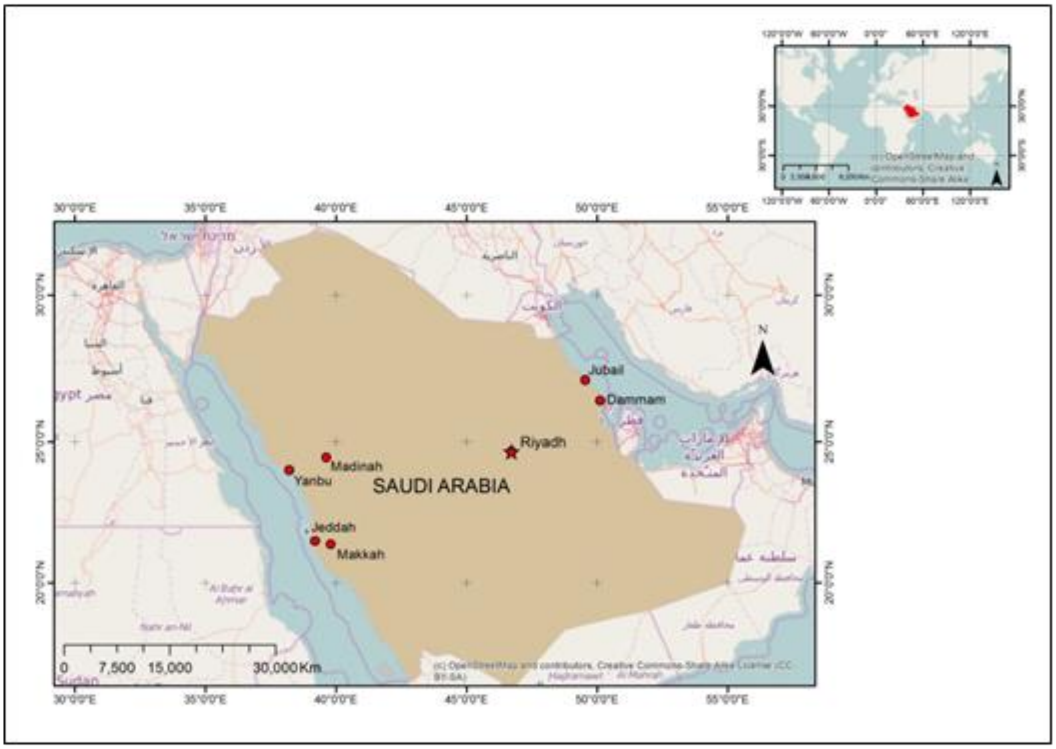

Figure 5.1. Location of Saudi Arabia and selected major cities.

5.2.2 Data acquisition

The $PM_{2.5}$ data was downloaded from Socioeconomic Data and Applications Center (SEDAC) website hosted by CIESIN (http://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-avg-pm2-5-modis-misr-seawifs-aod-1998-2012). The data provides a satellite-derived (MODIS, MISR and SeaWiFS) global multiyear (1998-2012) continuous surface of PM2.5 concentrations in a series of three-year average grids (1998-2000, 1999-2001, 2000-2002 and so on) with a spatial resolution of about 10 km (van Donkelaar et al., 2015a). This study sampled the central years (1999 for 1998-2000, 2000 for 1999-2001 and so on). The population data was derived from the 2010 population census document provided by the Central Department of Statistics and Information, Saudi Arabia (http://www.cdsi.gov.sa/english/index.php). The document contains a list of Saudi cities with populations of at least 5000 people. The cities with at least 10,000 inhabitants (about 80% of the Saudi Arabian population in 2010) were selected for this study. The locations of the cities was derived from Saudi Geological Survey publication (SGS, 2003) and Google Earth as reported in Aina et al. (2014).

GIS Analysis

The analysis was carried out by using ArcGIS 10.2. The global datasets were clipped and constrained to the national boundary of Saudi Arabia. Thereafter, the subsets that were produced from this manipulation were used to map the concentrations of particulate matter over each city. Since the data has a higher resolution than the previous version analyzed by Aina et al. (2014), the number of raster cells covering each city has increased. For example, only two cells covered Riyadh at the 50 km resolution data while about twelve cells covered the city at the 10 km resolution data. However, the two-cell resolution from the previous study (Aina et al., 2014) was adopted to allow comparison of the two data sets. Cluster analysis was carried out at the city level by implementing Anselin local Moran's I statistic (Anselin, 1995) using the Cluster Analysis tool provided in ArcGIS 10.2. For the regional analysis, a shapefile of the administrative regions of Saudi Arabia was used to extract the $PM_{2.5}$ values and ClusterPy (Duque et al., 2011) was used to carry out the cluster analysis (all the data are included from 1999-2011) by executing self-organizing map (SOM) algorithm.

5.3 Results and discussion

The new global data has some gaps (missing data) over Saudi Arabia (Figure 5.2). The $PM_{2.5}$ values of some of the cities had to be estimated by using the neighboring value by adopting a standard gap-filling method. The previous version of the data at the 50 km resolution did not have any gaps over Saudi Arabia. The results of the visualization of the global data show that there was an increase in the $PM_{2.5}$ concentrations over Saudi Arabia from 1999 to 2011 (Figures 5.3 and 5.4). The maps were produced by classifying the based on the $PM_{2.5}$ values 10, 15, 20, 25, 35, and more than 45. In 2011, a large part of Saudi Arabia (~1169300 km^2) had concentrations above the WHO target of 35 μg/m^3 than in 1999 (~261700 km^2) (Figures 5.3 and 5.4).

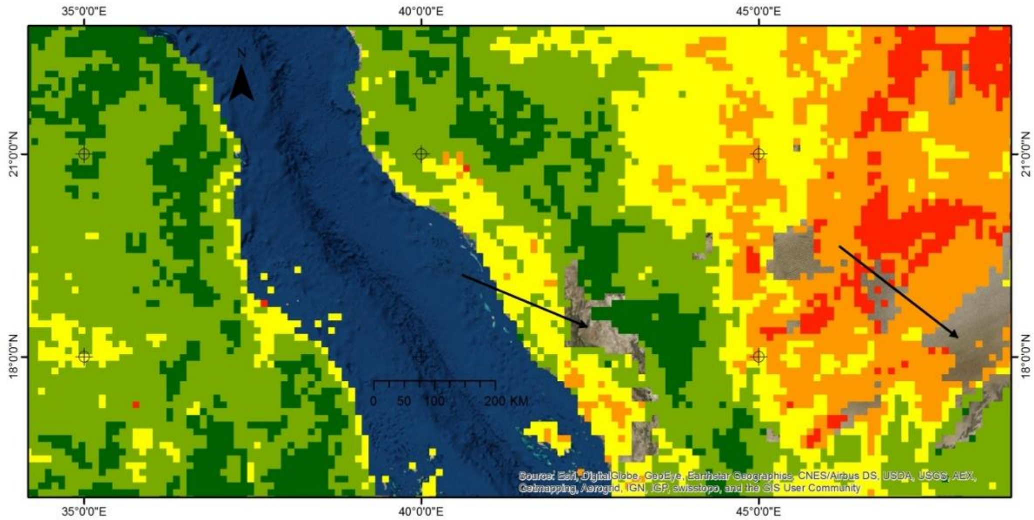

Figure 5.2. Gaps in the global data (1998 – 2011).

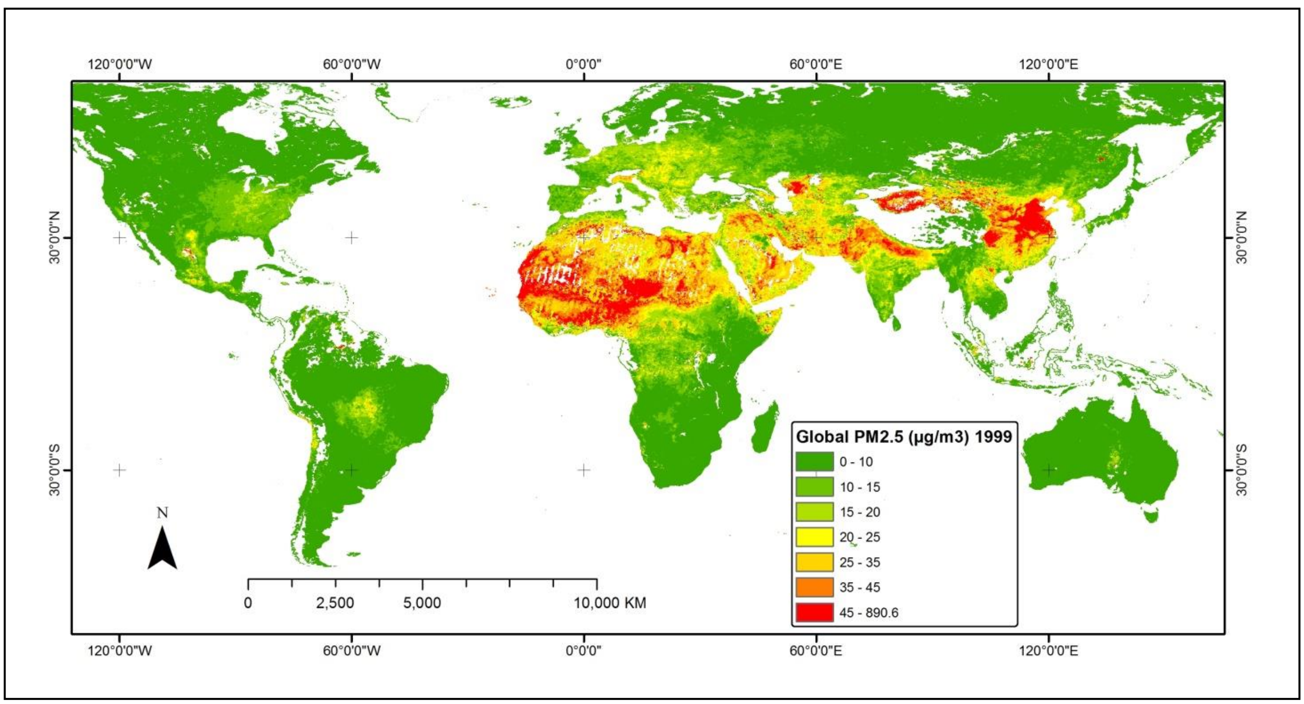

Figure 5.3. Global $PM_{2.5}$ concentrations -1999.

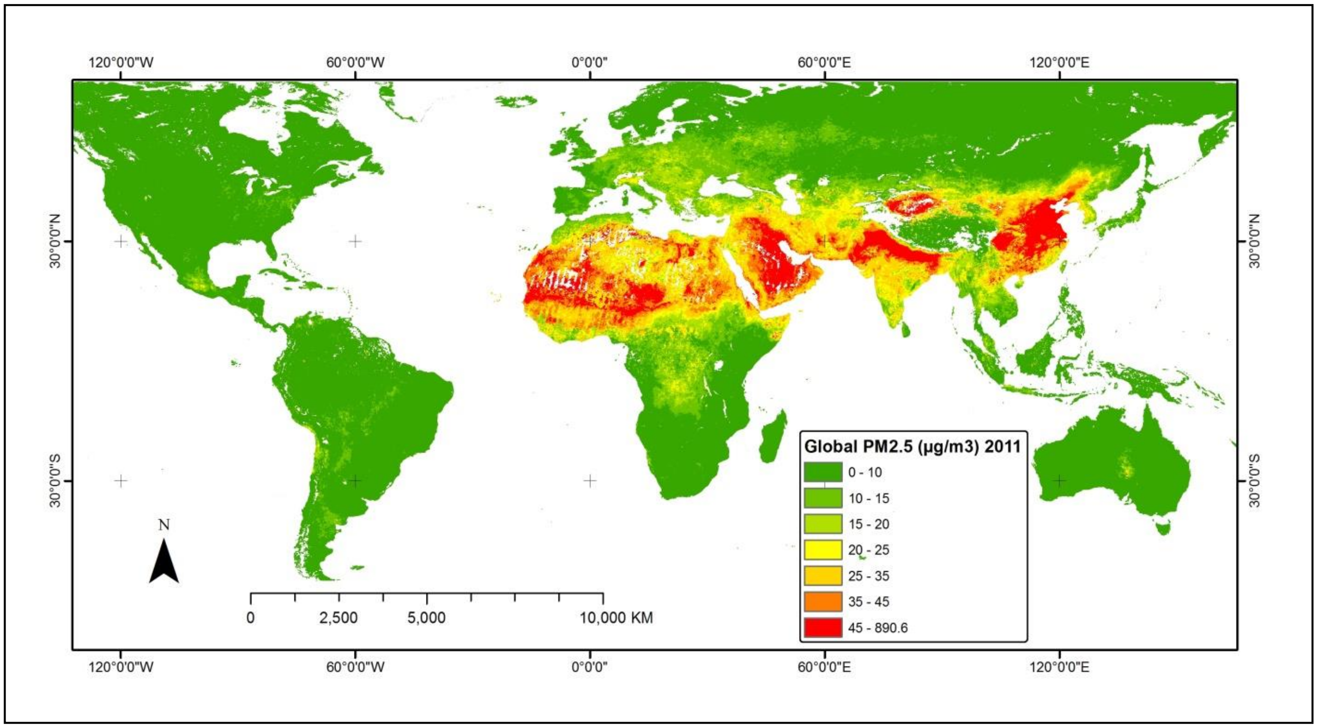

Figure 5.4. Global $PM_{2.5}$ concentrations – 2011.

Table 5.1 and 5.2 show $PM_{2.5}$ values of some selected cities from 1999 to 2011. Though the results depict a trend of increasing particulate matter concentrations over Saudi Arabia like the 50 km resolution data (Figure 5.5), the $PM_{2.5}$ values are higher than that of the previous data. For instance, the lowest $PM_{2.5}$ value derived from the previous data was 10.1 μg/m^3 and the highest was 40.4 μg/m^3 (Aina et al., 2014) while the lowest and the highest values for the new data are 16.5 and 62.6 μg/m^3. Also, some cities that have low values according to the previous data (Makkah, Madinah and Jubail) have got high $PM_{2.5}$ concentrations for the new data. Figures 5.6 and 5.7 show that there is only one cluster of high values in the 1999 data while in the 2011 data there are many clusters. The clusters occur in the eastern part of Saudi Arabia where considerable oil production activities take place. In the 2011 data, clusters of low values occur in the western part of the Kingdom.

Table 5.1: $PM_{2.5}$ concentrations (in µg/m^3) in selected Saudi cities (1999-2005).

Cities	Population 2010	1999	2000	2001	2002	2003	2004	2005
Riyadh	5,188,286	30.65	37.30	39.30	40.55	39.60	40.20	40.20
Jeddah	3,430,697	27.35	27.80	27.75	27.75	34.20	35.65	33.85
Makkah	1,534,731	17.20	22.0	25.70	25.70	30.40	30.50	30.50
Madinah	1,100,093	15.60	22.10	25.30	25.30	25.30	25.00	24.50
Dammam	903,312	48.20	37.40	30.50	30.50	31.10	31.10	31.10
Jubail	142,825	35.20	38.40	40.00	40.00	41.60	52.20	44.90
Yanbu	73,000	16.50	19.50	21.10	25.70	28.60	25.70	16.50

Table 5.2: $PM_{2.5}$ concentrations (in µg/m^3) in selected Saudi cities (2006-2011).

Cities	Population 2010	2006	2007	2008	2009	2010	2011
Riyadh	5,188,286	42.50	44.90	53.35	53.35	52.50	52.10
Jeddah	3,430,697	33.20	33.20	33.40	39.60	36.80	39.35
Makkah	1,534,731	31.60	31.90	36.50	36.50	36.00	36.00
Madinah	1,100,093	25.00	25.00	28.40	29.90	29.90	32.20
Dammam	903,312	31.70	34.30	39.70	39.70	40.50	41.00
Jubail	142,825	48.90	48.90	58.10	58.50	58.50	62.60
Yanbu	73,000	25.40	25.40	24.00	30.00	25.10	28.80

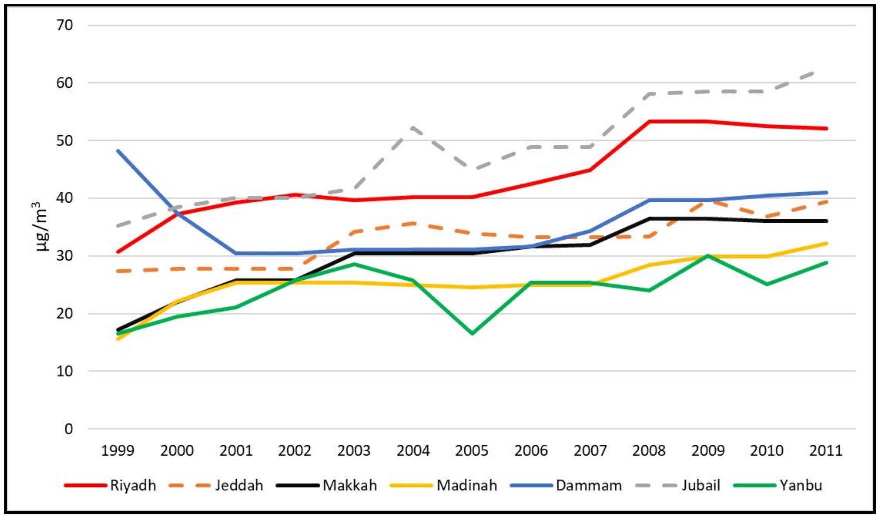

Figure 5.5. $PM_{2.5}$ concentrations (in µg/m^3) in selected Saudi cities (1999-2011).

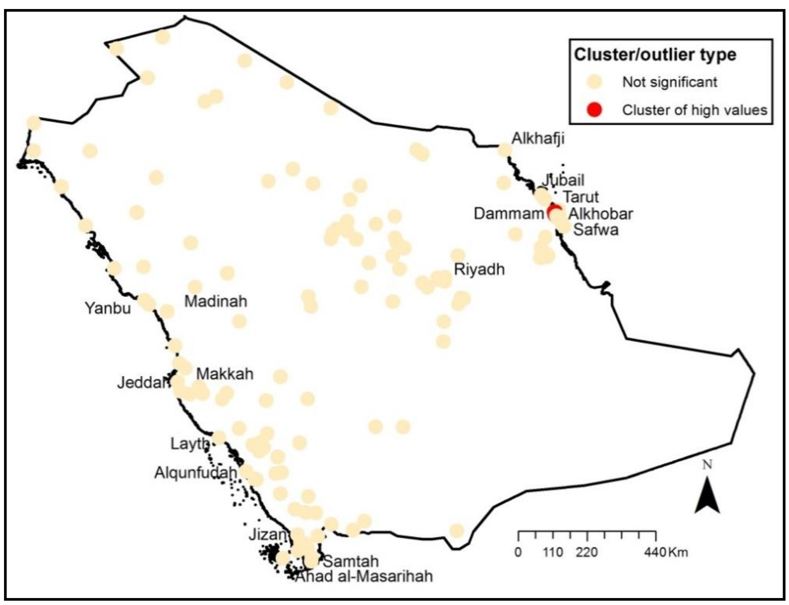

Figure 5.6. Clusters of $PM_{2.5}$ values over Saudi Arabia – 1999.

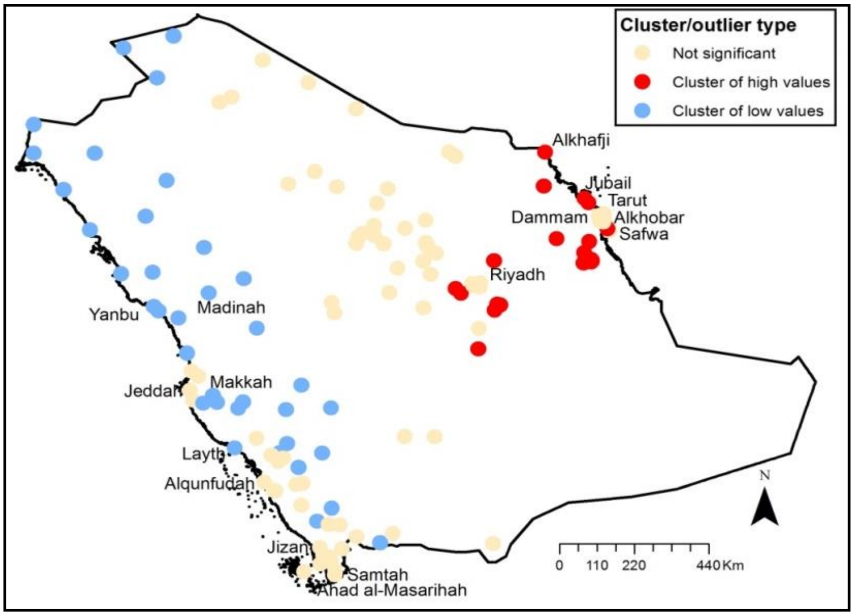

Figure 5.7. Clusters of $PM_{2.5}$ values over Saudi Arabia – 2011.

The results of SOM analysis show four clusters (Figure 8). The clusters of high values are in the eastern and the south-western part of the country. The clusters of low values are highlighted in the western and north-western parts of the Kingdom. Some of the high concentrations of particulate matter might be due to natural factors such as loading of sandstorms. As shown in Figure 5.8, the "empty quarters" of the uninhabited part of the Rub'al Khali desert are included in the cluster of high values.

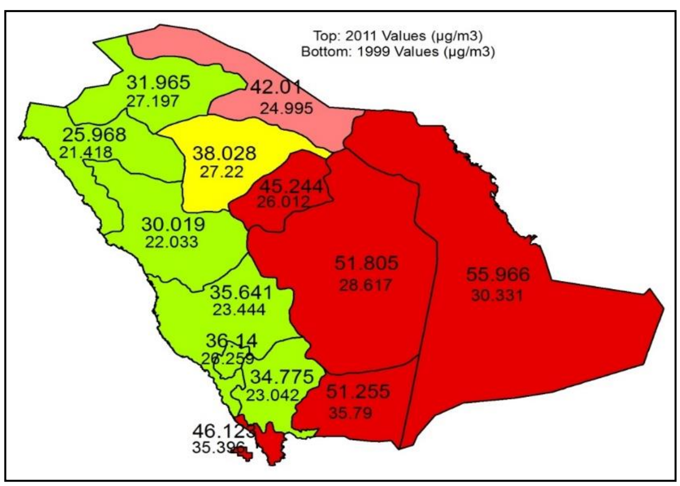

Figure 5.8. Regional clusters of PM2.5 values over Saudi Arabia (1999-2011).

5.4 Conclusion

The study reexamines the $PM_{2.5}$ concentrations over Saudi Arabia using the new global satellite-derived data. It highlights the differences between the previous version of the data and the new version. Though the new version has some data gaps, it is capable of depicting the particulate matter concentrations of the Kingdom. It is more accurate than the previous version due to the higher values derived for Saudi cities. Aina et al. (2014) reported that the earlier version might have underestimated particulate matter concentrations. Regarding the concentrations over Saudi Arabia, an increasing trend was observed in all the cities and regions. Further research can be carried out to validate and improve the accuracy of the values derived for Saudi Arabia. Other satellite data, such as nighttime data, can be combined with particulate matter data to ascertain the effects of economic activities and urban expansion on particulate matter concentrations.

Acknowledgements

The authors are grateful to the Batelle Memorial Institute and the Center for International Earth Science Information Network (CIESIN), Columbia University for providing the global $PM_{2.5}$ data used in this study.

CHAPTER SIX

Impact of urbanization on urban heat island effects: Geographical random forest analysis with urban density, traffic, and social media data

This chapter is based on:

Aina, Y. A., Adam, E. M. and Ahmed, F. 2017. Spatiotemporal variations in the impacts of urban land use types on urban heat island effects: the case of Riyadh, Saudi Arabia. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-3/W2, pp. 9-14.

Aina, Y. A., Adam, E. and Wafer, A. (under major revision). Impact of urbanization on urban heat island effects: Geographical random forest analysis with urban density, traffic, and social media data. *Remote Sensing*.

Abstract

The recent literature on land surface temperature (LST) and urban heat island (UHI) highlights the need for more studies on the relationship between LST/UHI and biophysical/socioeconomic factors, especially in the arid environments. This study examines the spatio-temporal variations of LST/UHI induced by biophysical and socioeconomic factors in Riyadh, Saudi Arabia. The LSTs of the study area for four years between 1985 and 2015 in June/July were derived from multi-date Landsat images. The UHI index of the different land-use/land-cover types (high-density residential, medium-density residential, low-density residential, industrial, vegetation, and desert) was computed from the LST data to analyse their relationships. Thereafter, geographical random forest analysis was used to determine the influence of biophysical and socioeconomic factors on LST/UHI. The findings show a trend of rising minimum temperatures from 1995 in all the land-use types. The industrial area has the highest temperatures while the temperatures of the vegetation area are the lowest. However, the means of the normalised LST values depict a decreasing trend. The geographical random forest analysis indicates that land use/land cover (65%) has the highest influence on LST/UHI followed by nighttime light (20%), traffic (16%), tweet density (15%), population (14%) and built-up area (4%).

Keywords: Land Surface Temperature; Land Use/Land Cover; Night-time Light Data; Tweet Density; Urban Expansion; Urban Heat Island

6.1 Introduction

The increasing rate of urban spatial expansion, especially in developing countries, has been unprecedented. Globally, the rate of increase of urban spatial extent is higher than the growth rate of the urban population (Seto et al., 2011). The global urban extent has increased by 58,000 km^2 from 1970 to 2000 (Seto et al., 2011), reaching about 800,000 km^2 in 2018 (Huang et al., 2021) and is expected to increase by, at least, 400,000 km^2 in 2030 (Seto et al., 2011). The fastest increases globally, between 2001 and 2018, occurred in Asia and Africa (Huang et al., 2021). Asia's percentage in the global urban spatial extent increased from 31% to 38% while that of Africa increased from 5% to 6% (Huang et al., 2021). The rapid expansion might continue as the world population is expected to reach at least 9.6 billion in 2100 (Mora et al., 2020). A recent study by Zheng et al. (2021) reported that 83% of urban land changes are due to land-use intensification by the factory and high-rise development. Similarly, Jiao et al. (2021) found that about 65% of the assessed 112 cities had more sprawling urban growth from 2000 to 2014 than between 1990 and 2000. The land-use change, intensification and expansion have implications on the environment. The rapid spatial growth has an influence on climate (Seto and Shepherd, 2009; Mishra et al., 2015; Sobrino and Irakulis, 2020), flood risk (Muis et al., 2015), biodiversity (Grimm et al., 2008), carbon emissions (Houghton et al., 2012; Gurney et al., 2021), health (Patz et al., 2005; Sobrino and Irakulis, 2020) and energy use (Santamouris et al., 2015; Güneralp et al., 2017). Li et al. (2017a) reported that about 115000 km^2 of farmland and 20000 km^2 of forest were lost to urban encroachment between 2000 and 2010. The impacts of urban spatial expansion undermine the ability of most Saudi cities to achieve sustainable development goals (SDGs) and urban environmental sustainability.

It evident that most of the cities have not been able to meet the challenges of rapid urban expansion as impacts like urban heat islands and others are frequently occurring (Shaw, 2021). Urban heat island (UHI), as one of the impacts of urban spatial growth, is attracting growing attention due to its implications for climate change and urban sustainability. It is a phenomenon whereby an urban zone has a higher temperature than its surrounding non-urban areas, indicating the effects of anthropogenic features and activities in urban zones (Voogt and Oke, 2003; Zhou et al., 2019; Roshan et al., 2021). Urban natural surfaces are changed to impervious surfaces that include buildings and road networks during urbanization and spatial expansion. The spatial morphology, land use and surface materials of urban areas influence local temperatures by making them warmer than the surrounding non-urbanized or rural areas. The urban heat island phenomenon poses challenges to urban sustainability by affecting energy demand, health and pollution (Santamouris, 2020). Thus, it is necessary to monitor urban heat islands and their relationships with environmental and socio-economic factors in order to enhance the formulation of strategies that can be used to mitigate their adverse effects. However, the traditional method of monitoring through ground measurements that are mainly obtained from airports and weather stations is constrained by limited spatial coverage. Also, the weather stations might be located in the outskirts of cities, thereby posing challenges to the acquisition of representative temperatures for urban areas. Moreover, it might be challenging to get data with optimum spatial coverage through ground measurements due to the required sampling (Li et al., 2013) as there are few weather stations. Thermal remote sensing has provided alternative and reliable means of acquiring data at different spatial resolutions and coverages.

Thermal remote sensing data have been used to investigate UHI parameters and the relationship between UHI and biophysical components of the urban environment (Voogt and Oke, 2003; Weng, 2009; Ngie et al., 2014). Yue et al. (2007), Zhang et al. (2009) and Arshad et al. (2021) examined the relationship between satellite-derived land surface temperature (LST) and the normalized difference vegetation index (NDVI) which is an indicator of vegetation health and abundance. The studies by Zhou et al. (2011), Lu et al. (2015), Gage and Cooper (2017), Odindi et al. (2017) and Berger et al. (2017) investigated the association between LST and land-use/land-cover types. Other studies by Soydan (2020), Kowe et al. (2021), Ma et al. (2021), Shukla and Jain (2021) and Mahato and Pal (2021), investigated the influence of landscape patterns and configurations on LST. The findings indicated correlations between landscape metrics and surface temperature (Ma et al., 2021; Kowe et al., 2021). Also, Kowe et al. (2021) detected a strong relationship between surface temperature and patch cohesion. Gage and Cooper (2017) and Berger et al. (2017) included vertical structure (3D) in their analysis of the effect of the height of high rise buildings on surface temperature. Jiang and Weng (2017) highlighted the importance of surface roughness in determining soil moisture and its relationship with LST. Bechtel (2012) estimated UHI parameters used for UHI modeling such as the mean and amplitude of the annual brightness temperature cycle. The above-mentioned studies focused mainly on the relationship between LST and biophysical factors.

Weng (2009) highlighted the need for more studies on the estimation of UHI parameters and the relationship between socio-economic factors and LST by arguing that most of the studies of LST and land use/land cover (LULC) were descriptive and simple correlation studies. The studies on the relationship between LST and LULC continue to attract the attention of researchers seeking better understanding of the factors influencing the UHI. Some studies have used time series, statistical analysis and modelling to improve the knowledge about the influence of the characteristics of urban surfaces on UHI (Fu and Weng, 2016; Li et al., 2017b; Tran et al., 2017; Tian et al., 2021). Recently, some researchers have focused on the non-biophysical variables (Li et al., 2020; Chen et al., 2021; Liu et al., 2021). Li et al. (2020) examined the socio-economic drivers of UHI and concluded that factors like economy, population and industrial structure have effects on UHI. Chen et al. (2021) used night-time light data as a proxy for economic activities in studying the factors influencing the UHI. Other possible proxies are social media geotagged data. Similarly, the effects of driving factors including gross domestic product (GDP), nighttime light index and population density on LST in the Pearl River Delta, China were shown to be significant (Liu et al., 2021). Chen et al. (2021) argued that the influence of socioeconomic variables, including proxies, has not been fully understood. In addition, Santamouris (2020) argued for more studies that holistically consider the biophysical and socioeconomic factors affecting UHI and their impacts on the urban environment.

Furthermore, most of the UHI studies have focused on the vegetated regions of the world. In their review of the literature on UHI, Rasul et al. (2017a) suggested the need for more studies on UHI in the arid and semi-arid areas. In the same vein, Zhou et al. (2019)

observed geographical biases in the literature on UHI and reported that more studies should focus on the understudied regions including Africa, South America and Asia. Moreover, the studies on UHI usually compare multi-date to detect changes, but this is challenging due to temporal and spatial variations in climatic/environmental conditions. Researchers have tried to reduce the effects of these variations by using the mean, standard deviation and normalisation (Rasul et al., 2017b). To improve the method based on normalisation, Rasul et al. (2017b) presented a normalised ratio scale technique for analysing changes in LST or UHI over different periods. The technique is yet to be rigorously tested by other studies.

In Saudi Arabia, particularly Riyadh the capital city, there has been a lack of in-depth studies on UHI despite the rapid growth of urban spatial extent in major cities (Aina et al., 2008; Rahman, 2016; Alqurashi et al., 2016a;2016b) and some reported environmental impacts (Aina et al., 2014; Alqurashi and Kumar, 2016). The studies by Hereher (2016), Rahman et al. (2017), Aina et al. (2021) and Parvez et al. (2021) were based on Dammam, Makkah area, Jeddah and Yanbu. The studies on Riyadh did not consider the land cover types within the city (Alghamdi and Moore, 2015; Lazzarini et al., 2015; Salman et al., 2021; Abulibdeh, 2021). Rahman (2018) examined the effect of population density on LST. The study considered the effects of mainly biophysical factors. Thus, this study aims at examining the impacts of urbanization on the urban heat island effects in Riyadh by considering the influence of urban density, traffic, land-use/land-cover types and social media data using a geographical random forest algorithm. It will also examine the application of normalisation techniques in comparing temporal and spatial changes in land surface temperatures.

6.2 Materials and methods

6.2.1 Study area

Riyadh is a global city (Short, 2017) and the largest city in the Gulf Cooperation Council (GCC). It is the most populous city in Saudi Arabia with a population of about 6.5 million in 2016 and a population growth rate of about 4% (http://www.arriyadh.com/Eng). The number of housing units in Riyadh is 1.2 million (http://www.arriyadh.com/Eng). The urban density of the built-up area in Riyadh is about 71 persons per hectare (MOMRA, 2019). It is located in the central region of Saudi Arabia (Longitude 46.68° E and Latitude 24.71° N) at about 600 metres above sea level, away from the two coasts in the west and east of the country. Figure 6.1 shows the location of Riyadh city in Saudi Arabia. Riyadh's climate is hot and dry with a temperature regime that varies from 11 degrees Celsius in winter to 42 degrees Celsius in summer (http://www.arriyadh.com/Eng). The highest rainfall occurs between November and March and the highest average monthly rainfall is about 44 mm. There is virtually little or no rainfall from April to October. Though recent efforts have been made to develop a mass transit in Riyadh by establishing the Riyadh Metro, the city's transportation is automobile-dependent. The major roads in Riyadh are wide with about 6 or more lanes. The roads are always congested during most of the day, especially at peak hours. It was suggested that more than 92% of the journey in Riyadh is made by automobile and it is expected that the roads will reach 90% congestion by the end of 2021 (Youssef et al., 2021). This has implications for greenhouse gas emissions and urban climate. Saudi's carbon dioxide emissions per capita, about 19 metric tonnes in 2015, are higher than the global average and the per capita emissions in the United States, European Union, and the Arab World (MOMRA, 2019).

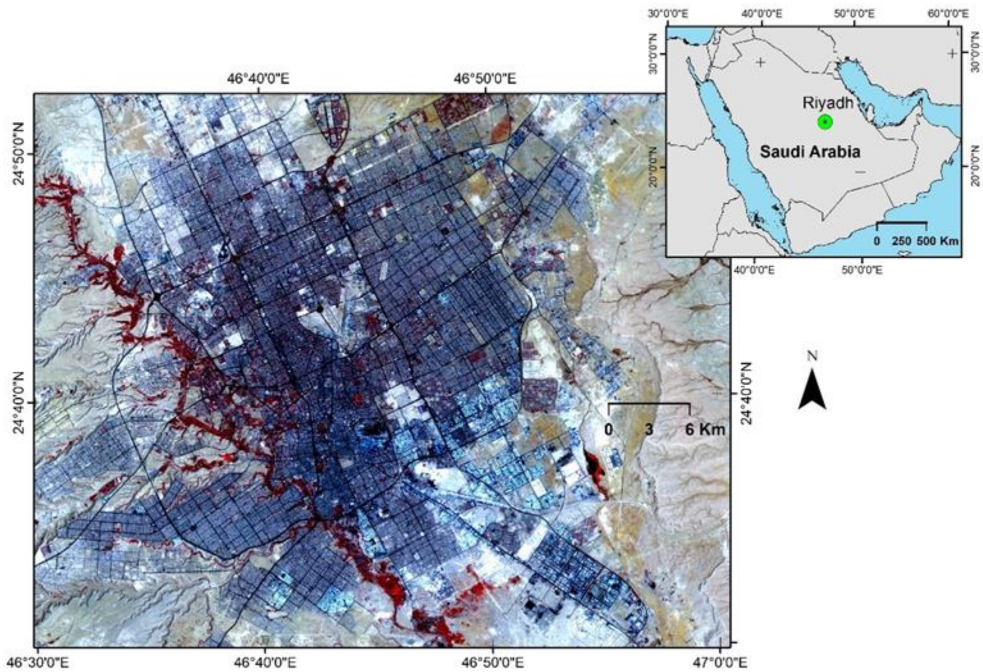

Figure 6.1. Location of Riyadh city in Saudi Arabia

6.2.2 Landsat images, tweets, urban density and traffic data acquisition

The study used multi-temporal Landsat data downloaded from the USGS website (https://earthexplorer.usgs.gov). The study covered the period between 1985 and 2015 and it focused on the summer season (June/July) to reduce the effect of seasonal changes. The image of the year 2015 was the latest image acquired for the study to ensure compatibility with other data. For example, the readily available tweet data is for 2014. Table 6.1 shows the identity details and acquisition dates of the images acquired from

USGS. Two images were downloaded for each year to provide footprint coverage of the study area.

Table 6.1: Details of the satellite images.

Sensor	Path/Row	Date
TM	165/043 166/043	22 June/31 July 1985
	165/043 166/043	4 July/13 Sept. 1995
ETM+	165/043 166/043	31 July/6 July 2002
TIRS	165/043 166/043	27 July/18 July 2015

An urban density map of Riyadh was extracted from an official document (ADA, 2003b) and Google Earth was used to confirm the density of the identified residential density areas (High, Medium and Low). The confirmation was carried out by checking the closeness/compactness and height of the buildings. The assumption is that high-density areas will have high buildings that are close to one another while low-density areas will have low buildings that have spacious surroundings. Other land-use/land-cover types such as industrial, vegetation and desert were identified by using Google Earth only. Samples (50 points per land use/land cover type) were taken to analyse the effect of land use/land cover on UHI (a total of 300 points).

In addition, tweet data of Saudi Arabia was extracted from the 2014 data harvested by Jiang et al. (2016). The kernel density function in ArcGIS was used to convert the point data to densities (Figure 6.2). The function computes the density around each point feature using a kernel function and search radius (ESRI, 2020). Thereafter, the Jenks natural break was applied to classify the densities into five classes (Figure 6.2). High tweet densities are located in the city centres while the low densities are at the outskirts (Figure 6.2). Jiang et al. (2016) stated that tweet density can be a proxy of population density. The population, built-up area and traffic (distance to major roads), night-time light datasets were downloaded from the WorldPop website (www.worldpop.org). Figure 6.3 shows the night-time light intensity of Riyadh ranging from 0 to 1600. Similar to the tweet density, the high light intensity pixels are found in the centre of the city.

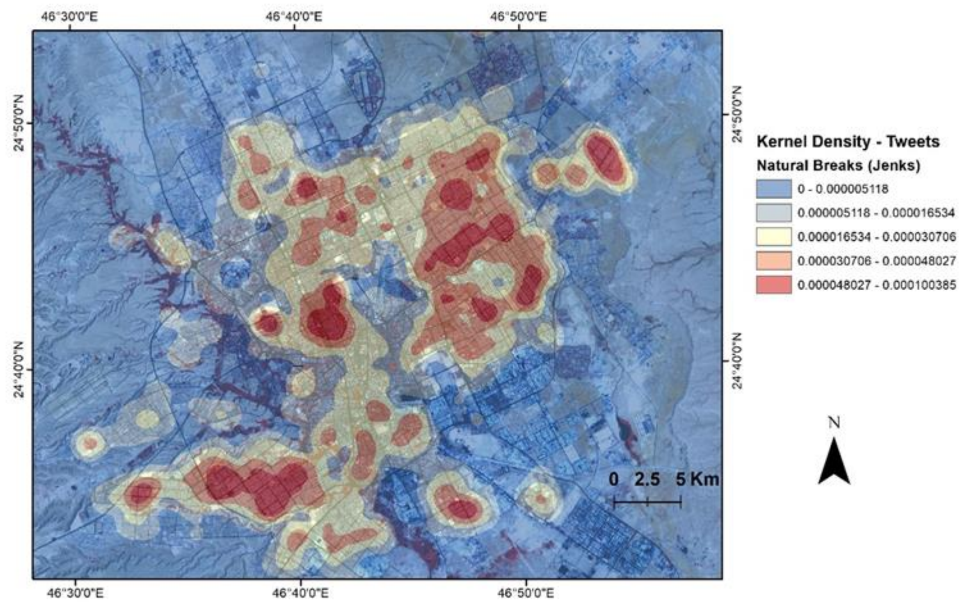

Figure 6.2. Tweet density of Riyadh.

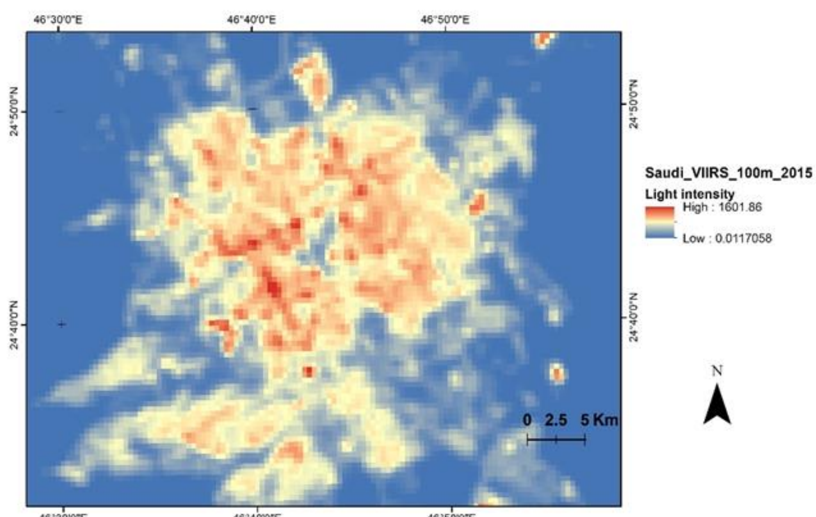

Figure 6.3. Night-time light intensity of Riyadh.

The road and population data are visually depicted in Figures 6.4 and 6.5. The road data has a pixel size of 100 m and it shows the distances to the roads in Riyadh. The city has a dense road network. The pixel size of the population data is also 100 m. The data indicates the number of people per pixel in Riyadh. The number ranges from 0 to 25. Unlike the road data whereby the dense network is in Riyadh centre, some pixels with high population are located at the fringes of the city (Figure 6.5). This might be due to the algorithm used in allocating population to the pixels. Alahmadi et al. (2021) found a correlation coefficient of 0.73 between simulated Riyadh 2010 population and the WorldPop data.

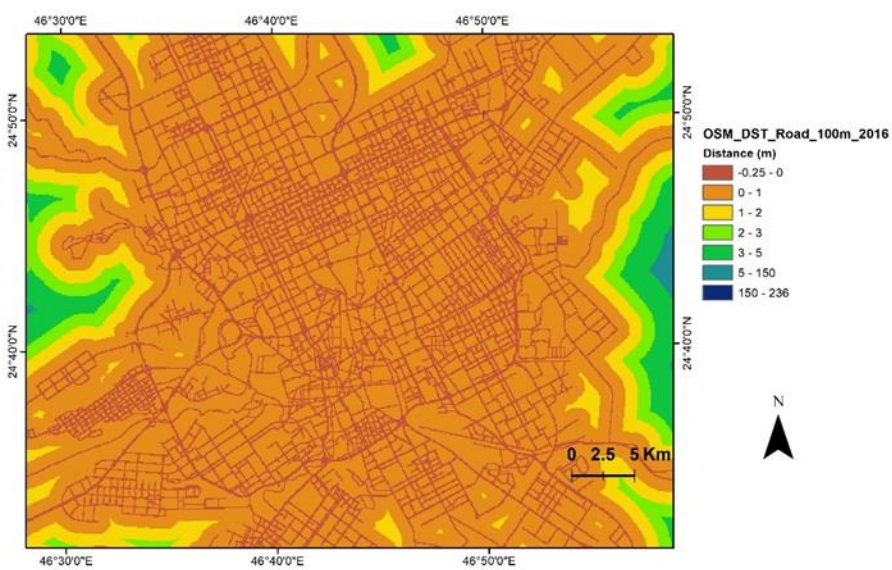

Figure 6.4. Distances to major roads in Riyadh.

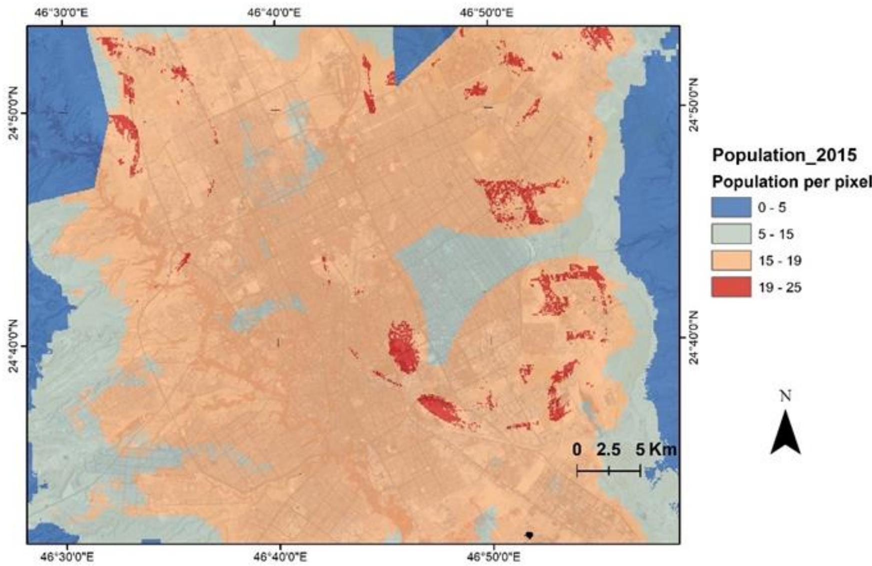

Figure 6.5. Population data of Riyadh shown by 100m pixel.

6.2.3. LST extraction, normalisation and analysis

To estimate LST from the thermal image, the pixel values of the dataset were converted to at-sensor spectral radiance (Lλ) by using Eq. 1.

$$L\lambda = Gain * DN + Bias \qquad (1)$$

where Lλ = at-sensor radiance

Gain = slope of the radiance (Table 6.2)

Bias = intercept of the radiance (Table 6.2)

DN = digital number (pixel values)

Table 6.2: Conversion coefficients for digital numbers (Source: Chander et al., 2009).

Sensor	**Band**	**Gain**	**Bias**
TM	6L	0.055158	1.2378
ETM+	6L	0.0	17.04
TIRS	10	0.000334	0.10000

The second step is to compute the LST by using inverse Planck function in Eq. 2.

$$LST = K2/\ln(K1/L\lambda + 1) \qquad (2)$$

where LST= LST at-satellite brightness (Ye et al., 2017)

K1 = calibration constants (Table 6.3)

K2 = calibration constants (Table 6.3)

$L\lambda$ = at-sensor radiance from Eq. 1

Table 6.3. Calibration constants for thermal bands (Source: Chander et al., 2009).

Sensor	**K_1 (W m−2 sr−1 µm−1)**	**K_2 (K)**
TM	607.76	1260.56
ETM+	666.09	1282.71
TIRS	774.8853	1321.0789

The ‘LST’ calculated in Eq. 2 is the brightness temperature or at-satellite brightness. The result from the equation can still be processed further to get higher accuracy by using LST derivation algorithms and atmospheric data. Nevertheless, at-satellite brightness can be used to represent LST if there are no atmospheric data or the focus is on long-term trends, as Ye et al. (2017) reported. Thus, LST is represented in this study by at-satellite brightness as suggested by Ye et al. (2017).

After the derivation of the LST, the LST data was normalised using three different methods - normalisation, scaling to 1985 values and normalised ratio scale (NRS) by Rasul et al. (2017b). The normalisation was done to facilitate comparison of the multi-year values of LST and evaluate the normalisation methods. Thereafter, the sample points (300) were used to extract the LST values for the different land-use/land-cover types. The statistics (mean and standard deviation) of the values were computed for the different land-use/land-cover types and urban densities. One-way analysis of variance (ANOVA) was performed to determine if the differences observed in the LST values were statistically significant.

In addition, the global Moran’s I statistic was computed for the LST values of the different periods to assess the spatial autocorrelation of the values and the cluster pattern. The value of the Moran’s I index ranges from -1 to 1. Moran’s I index value of -1 means nearby values are highly dissimilar (dispersal) while the index value of 1 indicates that nearby values are highly similar (clustering). Moran’s I index value of 0 means a random spatial distribution. The Moran’s I index was computed using the ‘raster’ package in R version 4.1.3. The package has spatial autocorrelation functions for calculating global and local Moran’s I statistics. The p-values were calculated for the Moran’s I index values to determine the statistical significance of observed indexes. A UHI index was calculated for the different land use/land cover using SUHI – Surface Urban Heat Island, as shown in Eq. 3 (Voogt and Oke, 2003; Lazzarini et al., 2015). UHI index was also calculated for each of the LST layer of each year.

$$SUHI = LST(URB) - LST(SUB) \quad (3)$$

where LST(URB) = LST of urban area (Land use types)

LST(SUB) = LST of suburban area (Desert)

The ancillary data were used in regression analysis to determine the influence of the different socioeconomic activities on the LST and UHI index. The geographical random forest algorithm in the R 'SpatialML' package (Georganos et al., 2021) was used, as an exploratory tool, to model the relationships. The tool is a spatial analysis local model of the Random Forest algorithm (Georganos et al., 2021).

6.3 Results and Discussion

6.3.1 Satellite-derived and normalised LST

The results of the LST from 1985 to 2015 (Figure 6.6) show no prominent trend of increasing maximum temperature. However, the minimum temperature starts its increasing trend from 1995 to 2015. The highest minimum temperature shown is 32°C in 2015 while the lowest temperature was 15°C in 1995.

High-temperature values were observed along the transportation network. The 2015 image (Figure 6.6) shows the most prominent high temperatures along transport corridors. This is most likely due to the increasing number of vehicles on the city's roads. The results of the LST normalisation (Table 6.4) depict decreasing values of mean LST except the normalized ratio scale (NRS) method, which shows an increase of 0.27 from 1986 to 2015. During the computation of the NRS, the final percentage could not be successfully computed using the equation provided by Rasul et al. (2017b) as the mean NRS was the same as the mean LST. So, a constant (2000) was used to compute the final NRS to change it to values similar to the LST values and not the same.

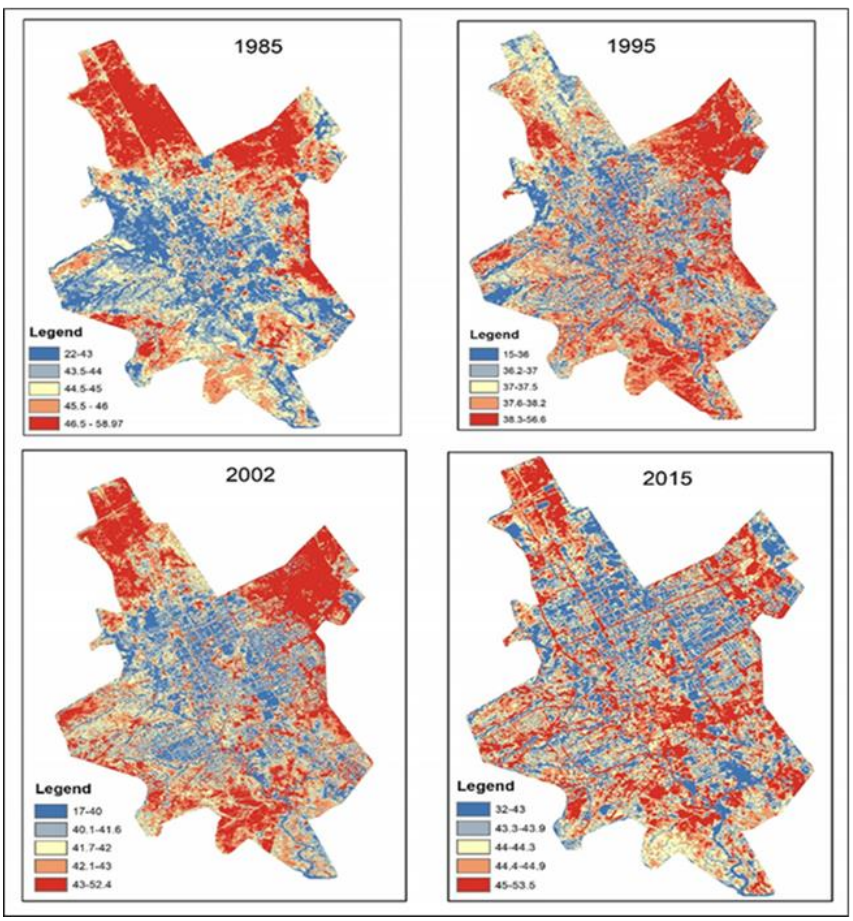

Figure 6.6. Changes in LST in Riyadh from 1985 to 2015.

Table 6.4: Mean and standard deviation of LST and normalized LSTs.

	Mean 1985	SD 1985	Mean 1995	SD 1995	Mean 2002	SD 2002	Mean 2015	SD 2015	ΔLST 85-95	ΔLST 95-02	ΔLST 02-15	ΔLST 85-95
LST	44.10	2.94	37.07	1.61	42.84	2.02	44.44	1.24	-7.03	5.77	1.6	0.34
NLST	74.16	4.98	64.45	2.78	49.34	3.26	38.16	3.50	-9.71	-15.11	-11.18	-36
SLST	44.10	2.94	38.07	1.63	28.84	2.00	22.04	2.12	-6.03	-9.23	-6.8	-22.06
NRS	47.05	6.10	43.89	3.50	45.65	4.19	47.32	2.61	-3.16	1.76	1.67	0.27

NLST – normalised LST, SLST – LST scaled to 1985 minimum and maximum, NRS – normalised ratio scale LST

6.3.2 LST and land use types

The results of the statistical analysis are shown in Tables 6.5 and 6.6. They show that the desert is generally warmer than the other land-use/land-cover types. This supports the findings of the previous studies by Alghamdi and Moore (2015) on Riyadh and Parvez et al. (2021) on Yanbu. The LST means in 1995 are lower than the means of other years. This might probably due to an increase in the vegetation cover from 1985 to 1995. Aina et al. (2019) and Alghamdi and Moore (2015) highlighted that the vegetation cover in Riyadh increased from 1985 to 1998 and started to decrease thereafter. However, changes in the vegetation cover of the built-up area might not account for the decrease in desert temperatures in 1995. The results indicate a trend of increasing temperatures in all the land-use/land-cover types from 1995 to 2015. The ANOVA indicates significant differences in the LST of the land-use land-cover types at 0.01 level.

Table 6.5: LST values by land-use types and Moran I in 1985 and 1995.

Land-use type	1985		1995	
	Mean	Standard Deviation	Mean	Standard Deviation
Desert	45.58	3.28	37.84	1.23
High density	42.34	0.73	37.36	1.18
Medium density	45.63	1.83	37.62	1.07
Low density	43.62	1.07	37.64	1.03
Industrial	40.47	3.78	36.13	3.48
Vegetation	43.33	4.54	35.25	3.08
ANOVA (p value)	2.20E-16		1.30E-10	
Moran's I index	0.95		0.80	
Moran's I index (p value)	0.00		0.00	

Table 6.6: LST values by land-use types and Moran I in 2002 and 2015.

Land-use type	2002		2015	
	Mean	Standard Deviation	Mean	Standard Deviation
Desert	44.15	1.78	45.22	1.25
High density	42.05	0.95	44.39	0.51
Medium density	42.97	1.76	43.46	0.67
Low density	40.82	1.19	43.60	0.86
Industrial	40.98	3.73	45.14	1.97
Vegetation	40.19	4.53	40.30	2.90
ANOVA (p value)	2.18E-13		2.20E-16	
Moran's I index	0.93		0.94	
Moran's I index (p value)	0.00		0.00	

The values of Moran's I index in Tables 6.5 and 6.6 indicate that the spatial distribution of LST values in Riyadh were highly clustered from 1985 to 2015. That is, LST values were highly influenced by nearby values. The index reduced from 0.95 in 1985 to 0.80 in 1995 and increased thereafter from 0.93 in 2002 to 0.94 in 2015. This indicates that the spatial clustering of LST values was more stable between 2002 and 2015 than the other period.

6.3.3 SUHI analysis

The findings of the SUHI analysis are shown in Table 6.7. Also, the urban heat island index (UHII) and the changes in the UHII in Riyadh are shown in Table 6.7 and Figure 6.7. The SUHI analysis shows that the desert is warmer than the other land-use/land-cover types (Table 6.7). The urban heat island index (UHII) and the changes in the UHII in Riyadh are shown in Table 6.7 and Figure 6.7. Almost all the SUHI results are negative except the SUHI for the medium density areas in 1985 (Table 6.7). The results are in agreement with the findings by Alghamdi and Moore (2015), but disagree with the findings by Lazzarini et al. (2015) and Sobrino and Irakulis (2020). Lazzarini et al. (2015) observed that the built-up area of Riyadh has positive SUHI compared with the suburbs (the desert area). The SUHI values of high-density, low-density, and industrial areas show an increasing trend from 1985 to 2015 to indicate that their values are nearing the desert values (Table 6.7). On the other hand, the SUHI values of vegetation and medium density areas show a reducing trend (Table 6.7).

Table 6.7: SUHI values of different land-use types (1985 – 2015).

	SUHI 1985	UHII 1985	SUHI 1995	UHII 1995	SUHI 2002	UHII 2002	SUHI 2015	UHII 2015
High density	-3.25	-0.07	-0.48	-0.01	-2.10	-0.05	-0.82	-0.02
Medium density	0.05	0.00	-0.22	-0.01	-1.18	-0.03	-1.76	-0.04
Low density	-1.96	-0.04	-0.20	-0.01	-3.34	-0.08	-1.61	-0.04
Industrial	-5.11	-0.11	-1.71	-0.05	-3.18	-0.07	-0.08	0.00
Vegetation	-2.25	-0.05	-2.59	-0.07	-3.97	-0.09	-4.92	-0.11

The trend of the UHII is similar to the trend of SUHI from 1985 to 2015. According to figure 6.7, in 1985 and 1995, the areas with UHII that exceed the mean and two standard deviations are many. However, in 2002 and 2015, the areas in this category had increased occurrences of heat islands despite the indication by the normalised LST values that the mean LST was decreasing. Also, the results for 2015 indicate that the influence of traffic on the heat island was increasing as the high UHI index occurred around traffic corridors. The dark and wide asphalt roads tend to absorb heat and become potential sources of the heat island.

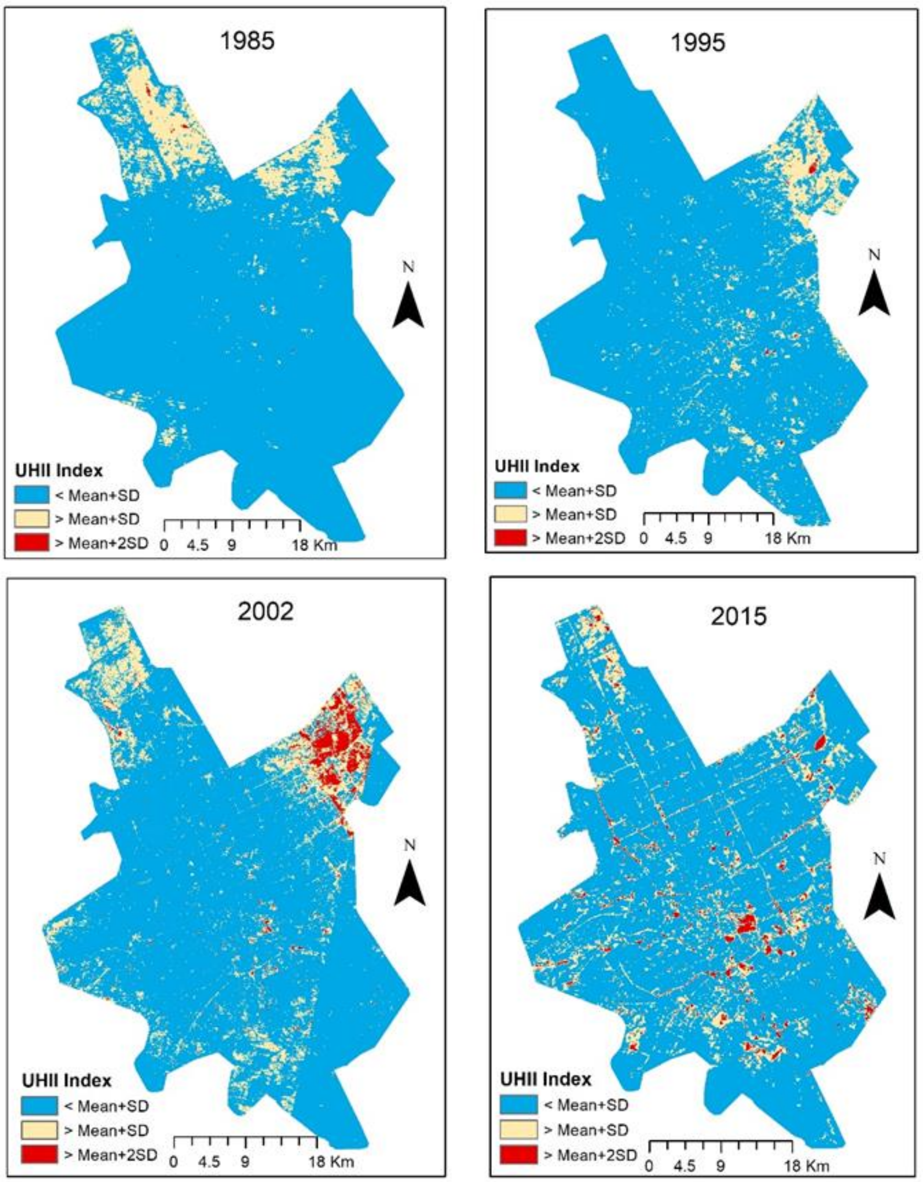

Figure 6.7. Changes in the urban heat island index in Riyadh from 1985 to 2015.

6.3.4 Geographical random forest analysis

The geographical random forest analysis indicates that about 71% of the dependent variables (LST and UHII) can be explained by the independent variables (land-use/land-cover types, tweet density, traffic, nighttime light, population and built-up area) (Table 6.8). The built-up area is a zero and with one layer indicating impervious surfaces in Riyadh. The percentage increase in Mean Squared Error when an independent variable is permuted (%IncMSE) and the decrease in node impurities (IncNodePurity) are the two measures of importance (Georganos et al., 2021; Quinones et al. (2021)). The findings of the random forest analysis for the two dependent variables (LST and UHII) are very similar, hence, the results that were obtained from the use of LST as a dependent variable are presented as representative outputs (Table 6.8).

Table 6.8: Importance of independent variables with LST as the dependent variable.

<table>
<tr><th>Variables</th><th>%IncMSE</th><th>IncNodePurity</th><th>R^2 (%)</th><th>%Variable explained</th></tr>
<tr><td>Land-use/land-cover type</td><td>65.14</td><td>810.13</td><td rowspan="6">90.8</td><td rowspan="6">70.72</td></tr>
<tr><td>Nighttime light</td><td>20.07</td><td>272.27</td></tr>
<tr><td>Traffic</td><td>16.42</td><td>170.97</td></tr>
<tr><td>Tweet density</td><td>15.35</td><td>50.51</td></tr>
<tr><td>Population</td><td>13.70</td><td>196.94</td></tr>
<tr><td>Built-up area</td><td>3.64</td><td>17.92</td></tr>
</table>

The findings show that the land-use/land-cover class has the highest importance or influence (by %IncMSE) which was about 65%. The second highest importance is by nighttime light which was about 20%. Population, tweet density and traffic had about 15% each while the built-up area had about 4%. Figure 6.8 shows the mean of the local %IncMSE, which indicates that the major influencing variable among the land-use types is vegetation followed by industrial and desert land-use land-cover types.

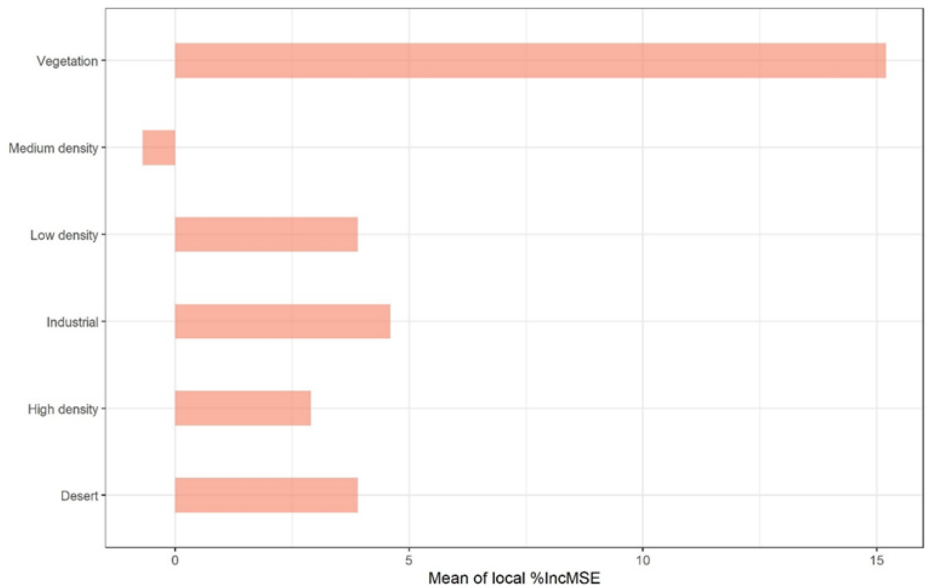

Figure 6.8. Local importance of land-use types.

6.4 Discussion

The results show increases in the minimum temperatures of Riyadh over the years from 1985 to 2015. As regards the relationship with land use, the desert and the industrial areas have the highest temperatures while the vegetated areas have the lowest. Conversely, the means of normalised LSTs show decreasing values over the years except the NRS, which show increasing values from 1995 to 2015. These results are in disagreement with findings from the study of the semi-arid city of Erbil in Iraq, which indicated a decreasing trend in NRS from 1992 to 2013 (Rasul et al., 2017b). The difference might be due to the difference in the development of the two cities. The area studies in Erbil witnessed rapid urban development from 2003 to 2013 turning most barren land into green areas (Rasul et al., 2017b). Also, since the increase from 1985 to 2015 is very low, 0.27, it might not indicate a major change. Moreover, the increase between 2002 and 2015 (1.67) is lower than the increase between 1995 and 2002 (1.76). This indicates that the change in LST values is reducing over the years. Jiao et al. (2021) highlighted that the urban expansion in Riyadh showed more compactness between 2000 and 2014 than the period between 1995 and 2000. Also, Khan et al. (2018) found out that vegetation cover increased in Riyadh by about 42% from 2006 to 2014 while urban coverage increased by 13%. This indicates that more vegetation cover was added to the landscape of Riyadh during this period and it could have influenced the urban heat island effects.

As regards the UHI, the desert/barren area which is the non-urbanized zone of Riyadh has higher temperatures than the urbanized areas. Therefore, the urbanized areas can be regarded as "cool islands" as they have negative SUHIs. However, the results of the industrial area show a temperature regime similar to the desert. The UHII results also depict a similar pattern whereby the urbanized areas are cooler than the surrounding desert. The results contrast with the findings of Lazzarini et al. (2015) and Sobrino and Irakulis (2020) that indicated that Riyadh had a positive SUHI, that is, heat island. This might be due to the lower resolution of the imagery used by Sobrino and Irakulis (2020) or/and the differences in defining the suburban area for calculating the SUHI. Also, the study by Lazzarini et al. (2015) used MODIS diurnal images to depict the UHI variations. However, other studies such as Alghamdi and Moore (2015) and Rahman (2018), found that the city centre is cooler than the suburb.

The geographical random forest analysis indicates that both biophysical and socioeconomic factors influence the LST/UHI in Riyadh with land-use type emerging as the major influencing factor. This is expected since the industrial and vegetation land-use types have been shown to have remarkable relationships with LST and UHI. This supports the findings of Rahman (2018) that population density, NDVI, normalised difference Built Index (NDBI) and neighbourhood area had significant effects on LST. While the multiple regression model by Rahman (2018) could explain about 77% of the variations in the LST, the model by this study can explain 71%. The difference might be due to the differences in the variables because this study used more socioeconomic variables than the previous study. Similarly, in the Yangtze River Delta, Chen et al. (2021) highlighted the influence of the Enhanced Vegetation Index (EVI), NDBI, population density, night-time light, water index, Gross Domestic Product (GDP) and precipitation have impacts on UHI. Moreover, Shafizadeh-Moghadam et al. (2020) found out that NDVI, land use/land cover, altitude and traffic influenced LST in Tehran. However, they found lower LST values long the major roads in contrast to the result of this study. The difference was due to the vegetation planted along major roads in Tehran. It implies that the current efforts of urban greening in Riyadh and other Saudi cities might effectively reduce the impacts of UHI (Aina et al., 2021). It has been suggested that Riyadh needs an addition of about 80% of the current green spaces to fulfill the international green space requirement (Addas and Maghrabi, 2021). This study and the assessment of spatial heterogeneity by Quinones et al. (2021) have shown that the geographical random forest algorithm can be used for exploratory analysis. A limitation of this study is that the proxy data might not adequately represent the situation on the ground. For example, the population data acquired from the WorldPop do not adequately model the population distribution of Riyadh. Population is allocated to some areas without population and some areas with high population are given low population. The highest population count per 100 m^2 in Riyadh should be higher than 25.

6.5 Conclusions

The study of UHI effects is relevant to the UN Sustainable Development Goal (SDG) 11, which promotes the achievement of sustainable cities (Abubakar and Aina, 2019). In line with the target of SDG 11 to reduce the adverse environmental impacts of urban areas, this study has shown the changes in the LST values of the different land-use types in Riyadh. The trends of some of the indices require attention. The analysis of the influence of physical and socio-economic factors shows that land-use/land-cover type has a high influence on the temperature regime in Riyadh city. There is a need for further studies to explore the influence of more variables since the variables analysed could only explain 70% of the dependent variable. Also, population data of the study area can be used to analyse the exposure of the population to high temperatures.

Different mitigation measures should be introduced to abate the negative trends. The recent initiative to design road centrelines with greenery might be useful in reducing UHI effects in Riyadh. Future studies can explore further the use of NRS in normalising LST for temporal analysis especially in comparing cities. Also, additional bio-physical and socio-economic factors can be considered to increase the percentage of the variations in LST that can be explained by the model.

Acknowledgements

The authors would like to acknowledge the assistance of the following institutions in the acquisition of the necessary data for this work – King Abdul Aziz City for Science and Technology (KACST), ArRiyadh Development Authority (ADA), WorldPop, and United States Geological Survey (USGS).

CHAPTER SEVEN

Remote sensing for urban growth and sustainable city development: A synthesis

Abstract

This chapter provides a summary of all the issues, analyses, and results discussed in the previous chapters. It presents a synthesis of the thesis by highlighting three-prong approach adopted by this study. It discusses the technical, analytical and policy preview aspect of the thesis. It depicts what was achieved by using the DSR framework, an indicator-base framework, in assessing the environmental sustainability of Riyadh. The chapter concludes by providing guidance on future research.

Keywords: urban sustainability, DSR framework, urban governance and policies, sustainability indicators, sustainability assessment, geospatial techniques

7.1 Introduction

To contribute to the literature on urban sustainability assessment, this study adopted the DSR framework, which offered the latitude to explore the indicator based aspects in assessing urban sustainability by using remotely-sensed data. The research adopted a three-pronged approach that consisted of technical, analytical and policy research aspects as shown in Figure 7.1. The technical aspect involved the detection and mapping of changes in urban growth over a period of time by using remote sensing data, PLAND spatial metric and V-I-S model. The environmental impacts (vegetation change, particulate matter concentrations and changes in thermal regime) of the changes in urban growth were evaluated as part of the analytical aspect. The policy research aspect involved the review of urban growth policies and urban governance and the recommendation of a better framework for sustainable urban development.

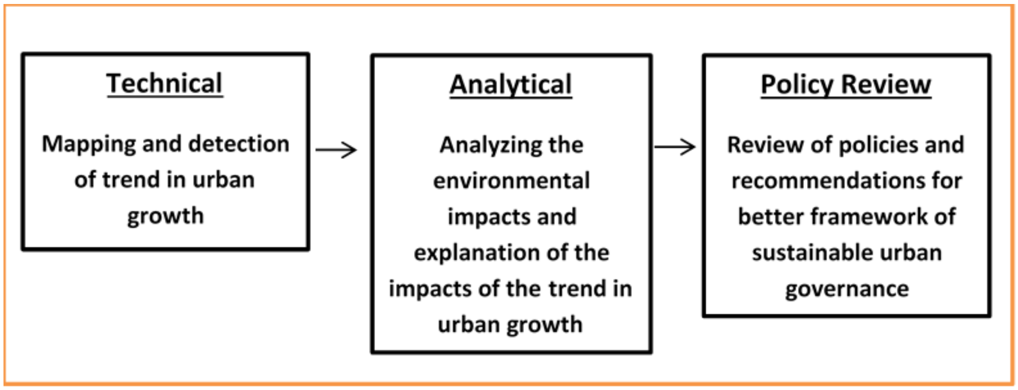

Figure 7.1. The three-prong approach.

7.2 DSR framework, urban sustainability, and spatiotemporal analysis

This study explored the DSR framework of indicators in assessing urban sustainability. It highlighted the potentials of the DSR framework in promoting urban sustainability. The framework needs adequate data to compute the indicators. This study used three important indicators that could be derived from satellite data – land-use change, LST and particulate matter. The framework requires multitemporal analysis to monitor the changes in the values of the indicators and the responses through urban governance. Indices such as UHI and normalisation were used to enable spatial and temporal comparison. Zhou et al. (2021) highlighted the importance of the analysis of spatial heterogeneity and temporal trend in their study of the sustainability of urban agglomeration in China. Zhu et al. (2019) reported that urban spatial heterogeneity is an important issue to consider in using remote sensing for urban sustainability assessment.

7.3 Changes in urban governance and policies in Saudi Arabia

Recent studies have shown that the inclusion of policy analysis in the framework of urban sustainability assessment enhances the assessment and provides more insights on how the interaction between human and environmental systems influence urbanization and the environment (Allen et al., 2018; Zhou et al., 2021). This study examined the changes in urban governance and policies in Saudi Arabia in order to better understand how government interventions influence urban growth and spatial expansion in Riyadh. Government documents and relevant literature were reviewed to identify the changes in urban governance in Saudi Arabia and compare the Saudi context with the best practices found in the literature.

7.4 Land use change and urban expansion in Riyadh

Reba and Seto (2020) reported that there is a gap in the coverage of land-use change studies. They found that most of the studies were on the United States and China. This study explored three different algorithms in classifying Landsat images of Riyadh. The classified images were used to compute the indicators (PLAND, UFPLAND and annualised urban sprawl index) for the analysis of land-use change in Riyadh. The changes in the impervious surface and vegetation fractions were computed and used as inputs into the V-I-S model. The metrics (PLAND and UFPLAND) were used to examine how the urban expansion had followed the urban theory of diffusion and coalescence. In Riyadh, diffusion occurred between 1972 and 1985 while coalescence occurred from

1985 to 2014. Riyadh's extent had expanded by about 740 km^2 from 1972 to 2014. The urban growth boundary has not been totally successful in curbing sprawl.

7.5 Environmental impacts of urbanization in Riyadh

The environmental impacts of urban growth and expansion in Riyadh were assessed using particulate matter ($PM_{2.5}$) and LST. Due to the resolution of the $PM_{2.5}$ data (10 km), the analysis was carried out at the city level. Cluster and hotspot analysis, Moran I for city level and SOM for the regional level, was implemented to identify the cities and regions with relatively high concentrations of $PM_{2.5}$. Thereafter, seven Saudi cities were selected for trend and comparative analysis. As for the LST, the UHI index was computed for land use types in Riyadh city. ANOVA was computed to identify the linkage between land use types and LST. In addition, the influence of socioeconomic factors (urban density, population, social media usage) on LST was analysed using a geographical random forest algorithm.

7.6 Conclusion, contribution to science, recommendations and future research

This study used the DSR framework with satellite-derived data to examine the environmental impact of urbanization in Riyadh and thereby the environmental sustainability of the city. The study contributes to remote sensing and sustainability assessment by providing a case study of the use of the DSR framework based on remote sensing data to assess urban sustainability in a region that has limited coverage in the literature. As regards methodology, the study contributes to image classification by comparing three classification algorithms (Band Ratioing, Spectral Angle Mapping and Spectral Mixture Analysis). Also, the study compared normalization methods and identified the linkages between UFPLAND and the urban expansion theory of diffusion and coalescence. The study contributes to the machine learning algorithm by testing the application of a geographical random forest algorithm in identifying the influence of socioeconomic factors on LST and UHI. It contributes to the study of Riyadh by highlighting the changes in land use and the environmental effects of the changes including the influence of socioeconomic effects. In terms of policy, the study highlights the policies that have driven urban growth in Riyadh and the recent transformation in urban governance and policies that might improve Riyadh’s achievement of sustainability.

The main conclusions of this study, according to the findings from the objectives, are highlighted below:

1. The DSR framework is suitable for assessing the urban sustainability of a city and remote sensing data can be integrated with the framework. However, there are challenges of data uncertainty, linkage with the SDGs and standardisation of the indicators.
2. The urban governance and policies of urban growth and spatial expansion in Riyadh had been oil-driven. However, with the low oil prices and increasing environmental impacts, the policies are changing to promote more sustainable urban development. The vision 2030, for the first time in the kingdom, has the objective of promoting environmental sustainability. The changes include the

implementation of Riyadh Metro and public transport, Riyadh greening and smart city project.

3. The land-use change analysis indicates that the Spectral Mixture Analysis classification method is the most accurate of the three algorithms (Spectral Angle Mapping, Band Ratioing and Spectral Mixture Analysis) and it is the most suitable the V-I-S model. The UFPLAND reflects the urban expansion theory of diffusion and coalescence. The urban area in Riyadh expanded by 1728% from 1972 to 2014. There was vegetation loss in Riyadh between 1995 and 2005 (16.7%) but by 2014, the loss had reduced to zero. The UFPLAND analysis indicates that the urban expansion in Riyadh was mainly “diffusion’’ between 1972 and 1985 and then changed to coalescence between 1985 and 2014. The V-I-S model analysis indicates that the city had changed from low-density development in the 80s to medium to high-density in the 90s up till 2014. This shows the Urban Growth Boundary policy had worked to some extent.

4. The indicator analysis showed that $PM_{2.5}$ concentration had been increasing in major Saudi cities including Riyadh. The hotspot is around the Eastern Province due to oil production activities. The LST analysis, indicated that a new normalisation method could not be computed successfully. The LST values, especially minimum and maximum, increased from 1985 to 2015. There is a significant difference in the LST values of the different land-use types. However, the normalised mean LST showed a decreasing trend. The geographical random forest analysis indicated that land use types have a major influence on LST values.

This study focused mainly on the environmental aspect of sustainability. To improve the understanding of the use of DSR framework for sustainability assessment in urban areas, indicators from the other dimensions of sustainability should be added to the framework in future research. Also, future research projects should look into the development of more remote sensing-based indicators. Moreover, future studies should consider more socioeconomic factors while examining the factors that influence LST in urban areas. The changes in urban policies and the smart sustainable city projects in Riyadh are new and just being implemented. Future studies can examine whether these policies have resulted in a more sustainable city.

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