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MOTORIZED TRANSPORTATION AND THE UHI EFFECT IN DOHA: THE IMPACT OF TRAFFIC ON THE HEAT ISLAND EFFECT

BY

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ABSTRACT

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Doha is a car-oriented city with rapid urban growth and development; one result of this is the replacement of large areas of the local terrain's natural surface with asphalt paving and other building materials. Therefore, as the city and surrounding areas have developed, the local landscape has undergone profound changes. Buildings, roads, and other infrastructure have replaced open land and areas where vegetation once grew. Surfaces that were once permeable and moist have become impermeable and dry. At the same time, Doha has been experiencing rising temperatures associated with the growth of the urban land surface, a change that continues over time as new development occurs. As Doha becomes an increasingly car-oriented city, emissions from cars and asphalt, accompanied by solar radiation, are absorbed by the materials of the local buildings. The net result of all of this is a microclimate that has a negative impact on the environment. Against this background, this study explores the impact of the city's transportation system on its environment. This thesis also explores possible solutions for enhancing the quality of development by reducing the impact of motorized vehicles (most notably cars) on the Urban Heat Island (UHI) effect. The first question that will be addressed -- through an examination of the road network and vehicular movement in Doha in relation to the UHI effect -- can be posed as follows: Does the city's traffic contribute to the UHI phenomenon? Furthermore, the use the Remote sensing (ENVI)[1] program and Geographic Information System (GIS) data permits an examination of the relationship between (a) road surface temperature and its outgoing long wave radiation in Doha and (b) traffic volume. The results of this analysis reveal that automobile traffic is a key contributor to heat formation in Doha, especially in the context of traffic jams. The paved surface materials characteristic of urban roads emit a great deal of heat into the city, in part because they cover such a large fraction of the urban surface. It is also found that part of the UHI effect can be attributed to the dark pavements that are often used on streets and parking lots; these also contribute to the heat and emissions generated by cars and traffic jams, in turn worsening the heat island effect and accompanying pollution. This thesis will conclude with recommendations for achieving sustainable development, with the ultimate goal of improving the quality of life and reducing excessive pressure on the environment in Doha.

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[1] ENVI is a remote sensing program (geospatial software) that processes and analyzes numerous types of imagery and data such as that provided by Landsat, LiDar and SAR.

DEDICATION

This thesis is dedicated to my family, for their endless support and encouragement.

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LIST OF ABBREVIATIONS

UHI	Urban Heat Island
UCI	Urban Cool Island
LST	Land Surface Temperature
GIS	Geographic Information System
MOTC	Ministry of Transport and Communications
QMD	Qatar Meteorology Department
NDVI	Normalized Difference Vegetation Index
TOD	Transit Oriented Development
H: W	Height and Width
SVF	Sky View Factor
DTD	day-to-day
GCC	Gulf Cooperation Council
MMUP	Ministry of Municipality and Urban Planning
LULC	Land Use / Land Cover

CHAPTER 1: INTRODUCTION

1.1 The Role of Urban Development in Increasing the UHI

At least 60 to 70 percent of the world's population lives in cities. As urbanization spreads, growth in energy-intensive activities such as those related to transportation and electrical generation has followed. The environment has been adversely affected by the large amount of heat created as a result. In other words, the world's rapid urbanization and urban growth has led to the emergence of "urban heat islands" (UHIs or UHI) that affect microclimatic conditions. In condensed and tightly-clustered urban developments, the prevalence of UHIs is high; such regions have characteristics that are distinct from those typical of more general regional and global climatic patterns.

The effects of urbanization and urban expansion play a particularly major role in tropical desert regions, where effects of intensive urbanization have an especially acute effect on local climate variations. The ability to sustain a good quality of life in arid cities that support growing populations will be determined, to a significant extent, by the understanding of the climatic changes caused by urbanization (Pearlmutter et. al., 2007).

The urban areas of the Arab Gulf states offer an ideal living laboratory for the study of the influence that urban population growth has on UHIs, and of the increasingly visible effects of global climate change (Guyot, 2008). They are densely populated areas located in hot and arid regions, similar to many areas around the world that are currently dealing with rapid urbanization in the face of limited water supplies.

The expansion of urban areas replaces the natural landscape with paved surfaces and other artificial building materials. Buildings, roads and other infrastructure replace open land and areas supporting vegetation ("green areas"). Land that was once permeable and moist becomes impermeable, dry and reflective, the last of which is indicated by high albedo values. This leads to climatic warming which in turn creates stress on the local habitat. In particular, urban areas tend to experience higher temperatures than surrounding suburban and rural areas, creating an "island" phenomenon. This "Urban Heat Island" effect has important effects on human health and energy consumption.

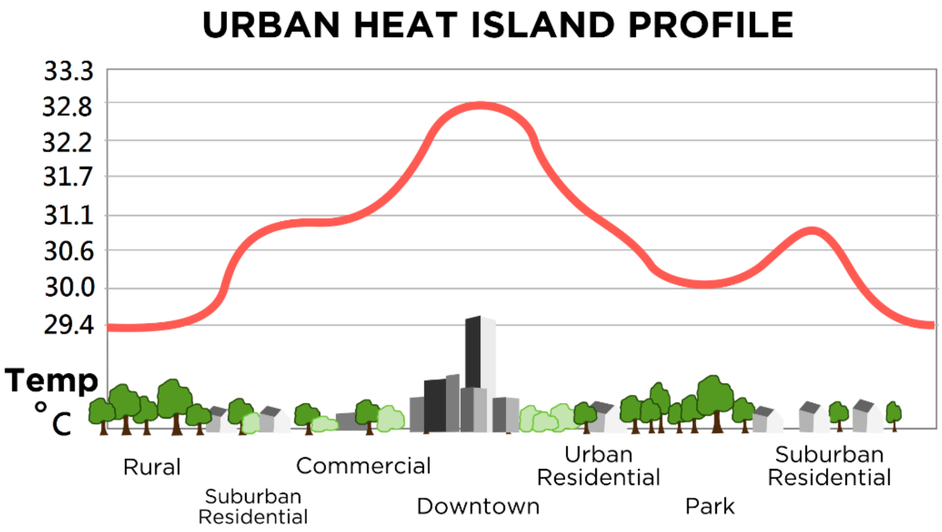


Figure 1. UHI Profile (Source: https://commons.wikimedia.org).

The rapid urbanization of the Gulf region has often been interpreted as a negative phenomenon with unpleasant consequences such as poor housing conditions and street life, environmental degradation, and an excessive use of automobiles with a corresponding lack of pedestrian traffic. Nonetheless, despite the problems that can come from uncontrolled urban development, cities are vital from a national perspective, since they are a key source of economic growth (Johansson et. al., 2006). It should also be noted that at the regional, international and global levels, the rise of cities and urban spaces has led to important changes in the ways in which policy makers approach urban problems. For instance, the development of UHIs influences microclimates, thermal conditions and quality of life, as can be seen in the increased energy demand for cooling buildings, in elevated greenhouse gas emissions, and in compromised human comfort (Radhi, 2013). In this ongoing process of urbanization, changes in city landscapes in the GCC region are especially rapid and profound (Wiedmann et. al., 2012). Research on the impacts of urbanization on local temperature has shown that the centers of large cities in areas with hot climates similar to that of the GCC are typically elevated by two to four degrees Celsius, relative to their rural surroundings (Radhi, 2013).

Many factors influence the environmental aspects of urban areas. Growth and development in such areas act as climate modifiers, and these effects can be considered with respect to a number of different climate-related variables. Such variables include air temperature, radiant temperature, air velocity, and humidity; all of these are affected by the urban fabric of the city. If urban planning and development take place with a lack of consideration (or lack of knowledge) of urban climate issues, the typical result is an urban area that is uncomfortable for those living and working there.

1.1.2 Rapid Urban Development in Doha and its Impact on the UHI

Over the past few decades, Qatar has witnessed rapid urban growth that has transformed its capital, Doha, from a small port town into a sprawling metropolitan city. Urban development in the wake of a hydrocarbon-driven economic boom, as well as changes in demographic composition, have caused a drastic reduction in the amount of open space in the city of Doha, from 76.81% in 1997 to 25.3% in 2010 (Balakrishnan, 2014). During this time, Qatar has also undertaken a number of large “mega-projects” in order to attract global firms, professionals and tourists; these developments have played a crucial role in Qatar’s modernization experience and its nation building process. The hosting of “mega-events” in Qatar has also played a significant role in Doha’s development and expansion, as such events require a variety of new infrastructure and other large-scale modifications of the urban space.

The government has focused on a number of key themes as its foundation for future development of the country. These include the establishment of state-owned and semi-privatized institutions, and in many cases policymakers in Qatar have utilized public-private partnerships. This has led to government investments in new infrastructure to address increasing demand; such projects include new airports, highways, ports, stadiums and hotels.

The intensive urbanization process that Qatar has experienced since the mid-1970s has transformed the country’s urban landscape. In a relatively short time, an economy that had been based largely on fishing and pearl diving has changed into one that is much more multi-faceted (Jaidah et. al., 2009). Figure 2 illustrates this urbanization process, which has resulted in a rapid increase of the urban population. This rapid urban development in Doha has tended to result in rushed and low-quality housing construction, poor street conditions, dependency on automobiles with a corresponding lack of consideration of pedestrian traffic, and an overarching disregard for environmental concerns. Doha’s car-centered development is reflected in its urban planning, with many widened roads providing access to the city. As noted earlier, despite the problems brought about by urbanization, an urban area is also an essential source of economic growth; Qatar’s rising financial industries, banking sector, and health and sports facilities are located primarily in its urban areas.

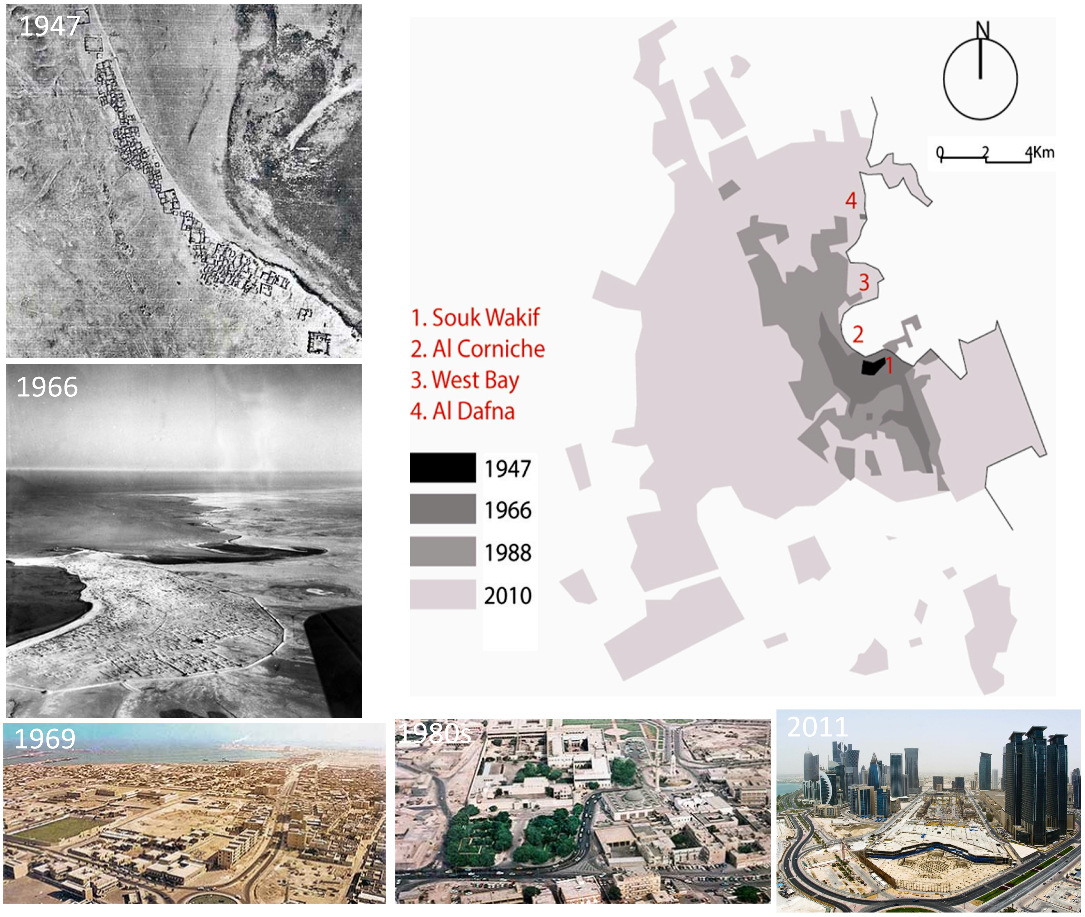


Figure 2. Urban development in Doha (Source: Rizzo, 2014).

In Qatar, fossil fuels are used in power plants to generate electricity, although alternative sources of energy have recently been utilized to an increasing extent. Nevertheless, the role and capacity of renewable energy sources have been relatively minor in the country to date. What is particularly concerning is that more than 60% of the country’s electricity is used for air conditioning. During the summer, increased energy demand to cool buildings results in increased air pollution due to fossil fuel burning; this in turn means that more heat is generated and air pollution is aggravated. This entrapped heat results in a warming of ambient air temperatures that in turn creates further electrical energy demand (El Morjani, 2013).

Health risks associated with pollution and the UHI effect are alarming, especially for children, the elderly, and people with heart disease, asthma and other diseases. During heat waves and spikes, the increased temperatures and the polluted environment bring additional hazards to the vulnerable population. Urbanization and air pollution are the main anthropogenic factors that influence the effects of heat waves.

Overall, urban planners should aim to create a city which is sustainable and which provides a livable environment. However, the current forms that urban spaces tend to take, as well as the ways in which they are developed and regulated, do not generally take this aim into account. Therefore, the ways in which cities are planned and constructed require major revisions that acknowledge the importance of climatic considerations.

In order to build more sustainable, livable and effective urban environments, it is important to understand that many factors influence microclimatic conditions; these include urban form, topography, water bodies and vegetation. Microclimate conditions can therefore be improved through a careful use of appropriate building materials, cool island elements, connectivity, and shaded pedestrian areas. Buildings and street canyon geometry greatly influence UHI effects at a microclimate scale, in addition to their other effects on the atmosphere and human activity. Lessons can also be learned from how cities have traditionally been developed, resulting in better designs with a favorable microclimate – one that improves environmental comfort and climate maintenance in the urban context of Doha.

In recent decades, the government of Qatar has implemented several mega-projects that have provided modern urban facilities and increased tourism. Urban expansion and development in Doha, driven by economic and population growth, have been especially rapid and remarkable since around 2003. Major developments during that time include the new Hamad Airport as well as mega-projects like the Pearl and Lusail City in the North of Doha, the Qatar National Convention Center, Souq Al Wakra, and numerous large-scale shopping malls.

Not surprisingly, these developments have created extensive traffic congestion and localized environmental impacts, affordable housing shortages, and a general increase in land values. To confront these issues, the Ministry of Municipality and Urban Planning (MMUP) has been working since 2005 on a new Qatar National Development Framework (QNDF) which attempts to manage growth by implementing sustainable urban development (Rizzo, 2014). Furthermore, the Qatari government has been attempting to address a variety of needs related to population growth, health, economic activity, transportation, and other public services. Government-initiated, policy-related strategies to enhance the quality of urban planning and promote sustainability include the following:

- Qatar National Vision 2030: This plan considers four main aspects of development -- specifically human development, social development, economic development and environmental development (General Secretariat for Development Planning, 2016), with appropriate strategies and programs for each.

A key goal is “creating a role model for sustainable development of the Gulf’s most livable towns and cities.” Sustainability is therefore one of the most crucial pillars of the Qatar national development strategy. Sustainable urban development requires consideration of issues related to energy consumption, pollution, and the extraction and use of natural resources. Given that urban areas tend to have a substantial negative impact on the environment, these policy issues need to be understood and addressed at the urban level in a comprehensive way.

- Qatar National Master Plan (QNMP): This plan covers the general guidelines and framework of development and urban planning in all sectors through 2032.
- The Comprehensive Transportation Plan for Qatar: This plan deals with the development and growth of population and economic activity and the need to provide infrastructure that enhances mobility and accessibility, taking into account multiple modes of transportation needed by the public. Furthermore, this plan takes into consideration anticipated future transportation demand and its potential impact on the environment.

1.1.3 The UHI Effect in Doha

The extent of the UHI effect can be difficult to determine precisely, especially in desert areas, because the sand that surrounds urban areas can absorb heat from sunlight and thus be characterized by high surface temperatures. This problem can be exacerbated by the presence of salt flats (*sabkha*) with high surface temperatures. In the dry lands and desert environments typical of Qatar, the UHI effect is somewhat more pronounced, as sand in the Qatari desert has a higher albedo that reflects a greater amount of sunlight, and consequently tends to lose heat faster, than is the case with the country’s urban centers that are closer to the seacoast.

As mentioned earlier, recent years have seen a reduction in open spaces in Doha, from 76.81% in 1997 to 25.3% in 2010, due to urban development, a bigger population, and economic growth impacting on residential, commercial and recreational needs (Hashem, 2014). Urban expansion leads to changes in land use/cover which in turn affect the city’s climate; the urban thermal environment changes because of replacement of natural surfaces with building materials (Polydoros, 2015). The many challenges arising from urbanization and growth, both in the medium and long term, affect several aspects of development; relevant indicators are those related to social, physical and environmental factors and the use of arable land for residential or industrial purposes.

For instance, the State of Qatar has recently begun to implement a number of mega-projects such as those in the West Bay area, where many company head offices, government ministries, and hotels are located. While such developments help make many activities and facilities more accessible, it is also true that this amount of development and activity in the city is likely to lead to further increases in ambient heat levels. In addition, it is also quite likely that the presence of high-rise buildings in urban areas on the coast has reduced the moderating effect that sea breezes would otherwise have on high temperatures, particularly in the summer.

The UHI phenomenon plays a critical role in energy consumption, and must therefore be correctly studied and analyzed. UHI effects are higher in the central part of the city, as this is the most active and densely developed region. The heated areas and the areas surrounding affluent neighborhoods directly and indirectly affect microclimate dynamics, which may also increase the temperature of urban areas. Furthermore, there are many elements of human activity that increase heat, such as energy consumption by vehicles, street surfaces, and the energy consumed in the cooling of buildings. Increased heat and emissions contribute to pollution, which in turn leads to health problems.

Main roads and public activities are both associated with moderately increased temperatures throughout the year (Wong, 2016). Many factors affect microclimatic conditions in cities; these include streets, urban geometry, surface materials, open spaces and green areas (Shafaghat, 2016). These elements therefore affect human comfort levels in urban areas.

Doha’s outdoor environment is generally considered most comfortable between November and April. During the warmer period between May and October, the air is often uncomfortably hot and humid. Figure 3 illustrates the typical changes in outdoor temperature during the year in Doha.

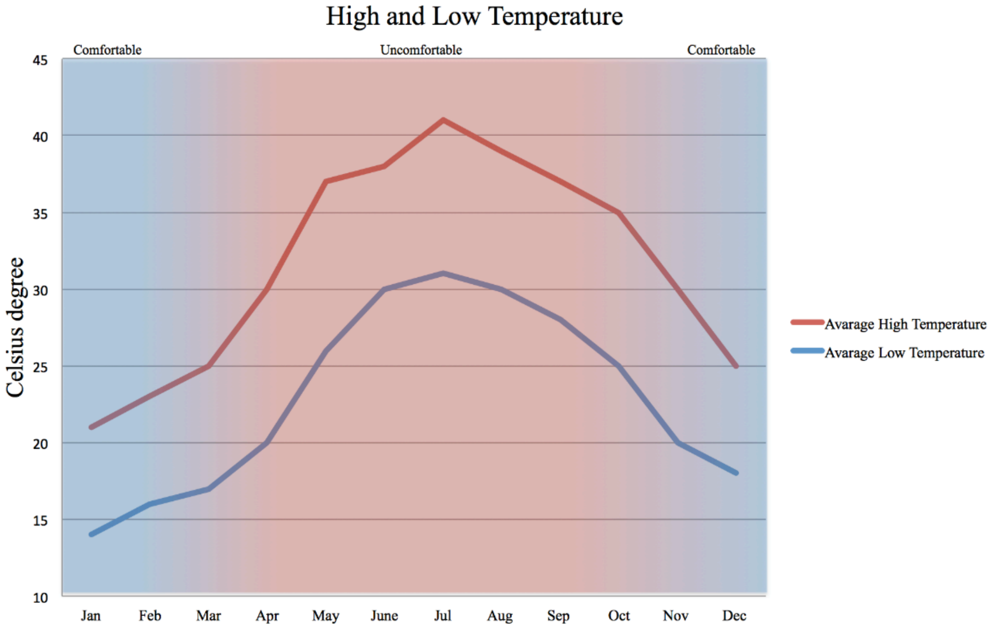


Figure 3. Periods of human comfort (Source: QMD).

During hot summer days, high temperatures force most people to use their cars, and there is increased energy demand for cooling buildings; the result is more burning of fossil fuels, leading to greater air pollution. This in turn results in more generated heat in the outdoor environment, adversely affecting human comfort.

Transportation systems are obviously an important aspect of any urban development. Private transportation is typically the main transport component considered in the context of urban planning in Doha, as this city is very car-oriented. Infrastructure development along these lines has been extensive, especially in the last 10 years, as the local need for mobility and accessibility is great. Moreover, this trend appears likely to continue to an even higher degree in the immediate future. Thus, the city’s future development in terms of transport and mobility patterns is poised to have an even greater impact on the local environment.

When urban development lacks a suitable design origin, as when clusters of buildings are built that are made of materials absorbing solar radiation, this has a significant impact on the city's microclimatic conditions. At the same time, air pollution and greenhouse gas emissions have brought further pressure on the urban landscape, adding to human discomfort. Rossi (2016) proposed new strategies for energy conservation, such as the use of innovations such as cooler construction materials. Others have suggested substituting the use of fossil fuels with energy sources having a low environmental impact and requiring fewer alterations in land use (Rossi et. al., 2016). The interplay between air temperatures and wind speeds also affects human comfort within a given microclimatic context (Dimoudi, 2013).

Compact urban areas in which all residential needs can be met within easy walking distance can reduce commuting and the need for cars, and enhance the quality of life in cities that as a result are healthier while still offering opportunities for economic investment. Building management, infrastructure, and resources are three major factors which must be considered when attempting to create such "eco-districts." It is also important to control and reduce negative impacts on the environment by managing waste distribution and the use of energy and natural resources.

Study of the UHI phenomenon is increasingly recognized as being of great importance in the Arabian Gulf region, especially in the past 10 years; such research now informs policymakers about many aspects of development in the region, such as in development programs that are being carried out at the national level in Qatar. Planning for pedestrians, walkability and convenient transportation is fundamental to smart growth, as is reducing car dependence in higher-density areas. One example of this is the designing of shaded walking and jogging paths to encourage people to travel on foot, thereby decreasing cars' impact on the environment and limiting urban sprawl. Wey and Hsu (2014) distinguish two perspectives in the literature, namely "New Urbanism" and "Smart Growth." They argue that while the former focuses on architectural methods of improving the environment, the latter comes more from a land use planning perspective (Wey and Hsu, 2014).

There have been a number of studies exploring the UHI phenomenon in West Bay, a business district in Doha. Relevant contributors to UHI there include distances between buildings and the nature of the open spaces in the studied area; one study also discussed UHI in the context of heat waves in Qatar. Contributors to UHI-related heat include climate control inside buildings, industrial processes, and transportation infrastructure such as highways and airports (Oke et. al., 1991). Other factors include air pollution, surface waterproofing, thermal properties of fabrics, and surface geometry (*ibid*, 1991; Shahmohamadi, 2011).

In summary, while many factors affect the heat island effect in Doha, traffic is one of its key contributors. As private cars are the main means of transportation for the city's commuters, traffic is a virtual constant in the center of the city. Therefore, measuring surface temperatures in traffic-heavy regions provides a clear overview of the UHI effect, and in fact is the main tool used in the present research to study it.

1.2 Significance of the Study

The significance of this study is manifold. Most importantly, this research contributes to a general understanding of a phenomenon whose effects include greater health problems, energy consumption, and air pollution, all of which have obvious negative impacts on the public. This thesis suggests that monitoring thermal radiation in urban areas can help city planners to design more livable and sustainable cities. In contrast to UHI, the UCI phenomenon is associated with places that are characterized by lower temperatures than their surroundings. This study draws attention to the driving factors of these changes in air temperature, their connection with the land surface temperature, and the interplay between human activity and urban development and transportation.

1.3 Research Problem

Doha has been experiencing rising temperature levels that can be attributed to rapid changes in the land use patterns of the city. Population growth and urban expansion have been particularly rapid in the recent past. The UHI phenomenon that has accompanied this development has negative effects including health problems, higher energy demand, and a greater incidence of air pollution and water shortages.

All aspects of development of the urban fabric, including the materials used, can have a great affect on local surface temperatures and microclimatic conditions. Motorized transportation systems in car-dependent communities like Doha are a key contributor to UHI effects. Limited literature in regards to the relationship between the traffic volume and the UHI.

1.4 Research Questions

1. What is the relationship between UHI effects and the intensifying traffic problem in Doha?
2. What are the areas that are affected by UHI in Doha?
3. What recommendations can be employed to reduce UHI effects in Doha as related to the urban planning and design?

1.5 Research Hypotheses

1. Motorized transport plays a major role in UHI effects, due to the increase in the number of private cars and the effect of heat generated by car motors in proximity to asphalt material, namely an increased amount of heat absorption by the road surface.
2. New urban development adds to the UHI effect in Doha.
3. Heat exposure during commuting increases land surface temperatures, which adds to the heat island effect and the local air temperature in Doha.

1.6 Research Objectives

A key objective of this study is to investigate the relationship between Land Surface Temperature (LST), traffic volume and topography. This is done by conducting a comprehensive analysis of Landsat imagery to produce maps showing surface temperature as it relates to traffic volume. This study also aims to examine the effect of motorized transportation systems on UHI effects through an analysis of land surface temperature maps.

The study’s detailed objectives are listed below:

- Conduct a detailed overview of the effects of the UHI phenomenon in Doha by downloading the metadata of Landsat images and processing this data using the ENVI program to obtain information about land surface temperatures.
- Analyze land surface temperature data to understand the evolution and current status of the UHI in Doha, with the ultimate aim of discovering whether and to what extent Doha is “heating up.”
- Investigate Doha’s urban expansion from 2003 to 2016 and its impact on the UHI, in order to understand better the microclimatic changes in Doha specifically related to new development. In other words, the goal here is to understand if Doha is warming due to urban development.
- Analyze the traffic volume in Doha, how it affects surface temperatures, and how it may create a heightened UHI effect in the city. In other words, the study seeks to determine the contribution of Doha’s traffic to the creation of a heat island.
- Propose recommendations to reduce the UHI effect in Doha and enable sustainable development that permits greater human comfort in the outdoor environment.

1.7 Thesis Outline

The structure of this thesis can be summarized as follows:

Chapter 2 presents a literature review of recent studies of the UHI and UCI phenomena, in addition to other factors that influence the urban environment, in order to provide an overview of the causes and effects playing a significant role in UHIs. Moreover, the chapter offers means and solutions to reduce negative impacts on the environment and to enhance microclimatic conditions, permitting greater human comfort outdoors.

Chapter 3 describes the research design and methodology used to answer the research questions. This methodology includes the processing of relevant Landsat 8 images as well as field measurements of land surface temperatures across Doha. This chapter also describes the collection of temporal atmospheric data, spatial data, and satellite data, in addition to calculation techniques employed in the analysis of satellite (Landsat 8) images.

Chapter 4 presents the outcomes of the analyses carried out on the data whose collection was described in Chapter 3, including image processing results, as well as analyses of land surface temperatures and traffic volume. Furthermore, the analysis of the field data and ground measurements support the research hypotheses and satisfy the objectives of the thesis.

Chapter 5 presents a discussion of the results and suggests ways to avoid the negative impacts that UHIs have on the environment. Solutions which enhance people's quality of life are offered.

Chapters 6 contains recommendations for how to attain sustainable urban development, in particular by improving human thermal comfort outdoors and taking advantage of the benefits of Urban Cool Island effects. The chapter ends with a statement of limitations of the study.

1.8 Statement of Originality

The present research investigates the UHI effect in Doha through the processing and analysis of data concerning land surface temperatures and traffic patterns, seeking to understand the relationship between the two.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a general overview of leading studies and recent contributions to knowledge concerning the UHI phenomenon; these provide the major framework for the present study. Various scholars have explored issues related to the UHI and its effects on microclimate conditions, including measures that might be adopted to reduce its negative impact on the environment and on people's quality of life.

The first section of this chapter presents a basic definition of the UHI phenomenon and outlines its functional relation with the land surface temperature. In addition, recent theoretical approaches to studying UHI are discussed, in order to elucidate its causes and effects from an analytical perspective, and suggest ways to mitigate the effect of UHI on the environment. The second section starts with a definition of UCI, the counterpart to the UHI effect, and continues with a discussion of the dynamics of outdoor thermal comfort. The third section explores strategies related to transportation and climatic changes.

Urbanization clearly affects microclimatic conditions, and relevant factors are as diverse as surface temperature, urban design, building materials, transportation systems, and topography, in addition to numerous aspects of the natural environment such as wind and other atmospheric conditions. A discussion of these issues will help contextualize this study's hypotheses, as well as provide a good understanding of the relationship between motorized transportation systems and increases in local UHI effects and land surface temperatures. This chapter ends with a discussion of a relevant example: the experience of Stockholm in dealing with congestion.

2.2 Urban Heat Island

UHIs are a phenomenon strongly associated with the development of cities and urban expansion. In 1818, the first known investigation of UHI effects was launched by Luke Howard (Targhi and Dessel, 2015). Heat islands occur in both urban and suburban areas because of the materials commonly used in construction, as these materials tend to absorb more solar heat than natural materials do. There are two main reasons that such materials contribute to the heating of urban areas. First, building materials are typically rigid and waterproof, resulting in a general absence of moisture that would otherwise moderate the sun's heat; second, dark building materials and pavements absorb more of the sun's radiation. For instance, the temperature of dark surfaces in direct sunlight during the day can reach 88 °C. On the other hand, under the same conditions, a moist soil- and vegetation-covered surface will typically have an approximate temperature of only 18 °C (Fernández, 2009).

The UHI occurs when an urban center is warmer than its surrounding environment. This effect may constitute a difference in warmth of up to 10 °C, although there is considerable variation due to different local environments and atmospheric conditions (Tam, 2015). Akbari (2008) defined UHIs as areas that "tend to have higher air temperatures than their rural surroundings as a result of gradual surface modifications that include replacing the natural vegetation with buildings and roads" (Akbari, 2008). Another definition of UHI is the one stated by Kolokotroni (2006), indicating that the UHI phenomenon is caused by microclimatic variations due to "manmade" intervention and modifications to the natural environment (Kolokotroni, 2006).

According to Oke et. al. (1995) anthropogenic heat is one of the main causes of UHIs in cities; this includes factors such as: cooling and heating buildings (waste heat from air conditioning heats up ambient air), surface waterproofing, thermal properties of fabrics, and surface geometry (Oke et. al., 1995). Solar radiation that is reflected from buildings and other surfaces affects local climatic conditions. Industrial processes and transportation (highways and airports) aggravate air pollution with emissions of carbon dioxide, water vapor and particulates from power plants and cars. Atmospheric pollutants affect the amount of ambient radiation by (1) reducing the incident flux of short-wave (i.e., solar) radiation, (2) re-emitting long-wave (i.e. infrared) radiation from the urban surface downward, where it is retained by the ground, and (3) absorbing long-wave radiation from the urban surface and thus warming the ambient air (Oke, 2011).

2.2.1 Radiation Balance of Different Urban Underlying Surfaces

The capacity of the urban surface to absorb solar radiation is called "urban albedo." This is an important factor that contributes to the Heat Island effect (Yang and Li, 2015). Also relevant are the materials used in urban environments, such as asphalts, concrete, and stones. These materials tend to absorb short-wave solar radiation during the day, and then store and release this energy as heat because of a lack of cooling evaporation that vegetation in green areas would provide. This contributes greatly to the UHI effect (Carpio et. al., 2016). Figure 4 illustrates how urban areas tend to absorb solar radiation, while rural areas with open spaces reflect solar radiation.

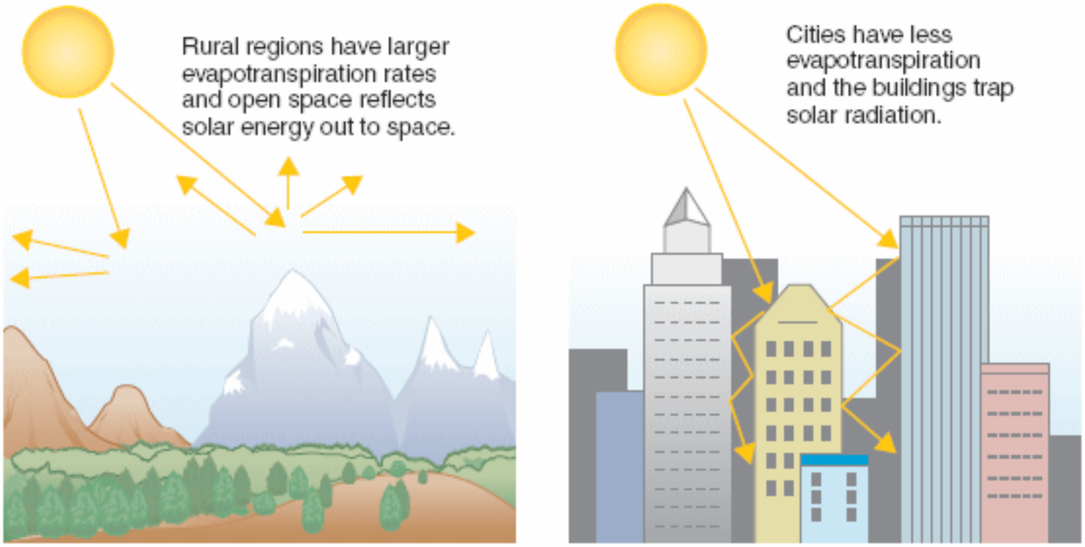


Figure 4. Solar radiation in rural and urban areas (Source: http://cimss.ssec.wisc.edu).

Heat from traffic and building waste heat is also considered a key contributor to UHIs (Oke,1987). The way in which urban areas absorb and release short-wave and long-wave radiation, respectively, is different from what occurs in environments with natural surfaces (Mirzaei and Haghighat, 2010). It is therefore vital to consider the differences in behavior shown by long-wave and short-wave radiation within urban areas, as this distinction underlies much of the UHI effect and the urban climate in general. This is illustrated in Figure 5, which shows the radiation balance and how affects the urban climate.

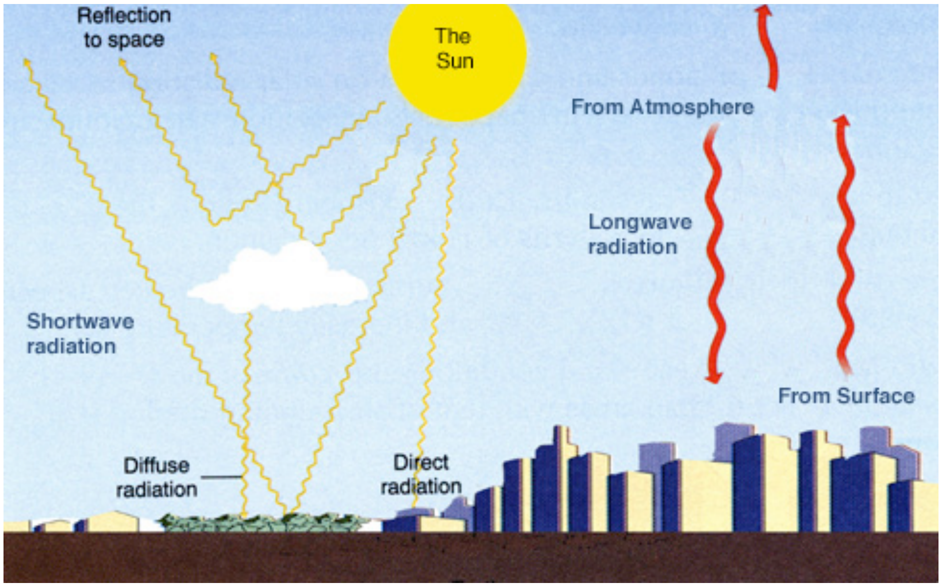


Figure 5. Radiation balance (Source: http://www.ruf.rice.edu).

The effects illustrated in Figure 5 also explain why the ambient warmth radiating upward at night is generally greater in a city than in areas outside the city (Allegrini et. al., 2016). More generally, numerous accounts have been proposed to explain the greater warmth of cities, including:

- Greater absorption of short-wave radiation
- Increased storage of perceptible heat
- Anthropogenic heat production
- Decreased long-wave radiation losses from human activities
- Lower amount of evapotranspiration
- Lower heat loss due to reduced airflow in urban canyons (Oke, 1987).

Other factors such as atmospheric conditions (e.g., wind speed, cloud cover, and height) (Oke, 1998) and topography (Goldreich, 1984) also affect microclimatic conditions. In arid urban environments, there are particular circumstances that can be qualitatively and quantitatively influential. These differences can be summarized as follows:

- High levels of humidity may be present in an arid region during the daytime.
- During the day, the amount of incoming solar energy is high, which leads to upward long-wave radiation at night, resulting in a pattern of thermal extremes over the daily and seasonal cycles.
- Insufficient humidity is often manifested in the local vegetation, which means the natural environment surrounding desert cities exhibits considerable differences from non-arid regions.
- The arid region may be characterized by high albedo and frequent sand or dust storms.
- A harsh thermal environment presents unique challenges for microclimatic improvement when efforts are made to increase human thermal comfort in the urban setting (Pearlmutter et. al., 2007).

2.2.2 Anthropogenic heat production

Anthropogenic heat is one of the main causes of UHI in cities:

- Cooling and heating buildings (heat-waste from ACs heats up ambient air).
- Surface waterproofing; thermal properties of fabrics; and surface geometry.
- Reflection from surface and buildings on each other.
- Industrial processes, and transportation (highways and airports).
- Air pollution: emissions of carbon dioxide, water vapors and Particulates from power plants and cars as vehicles travel along roadways, they release heat (Sailor, 2011).

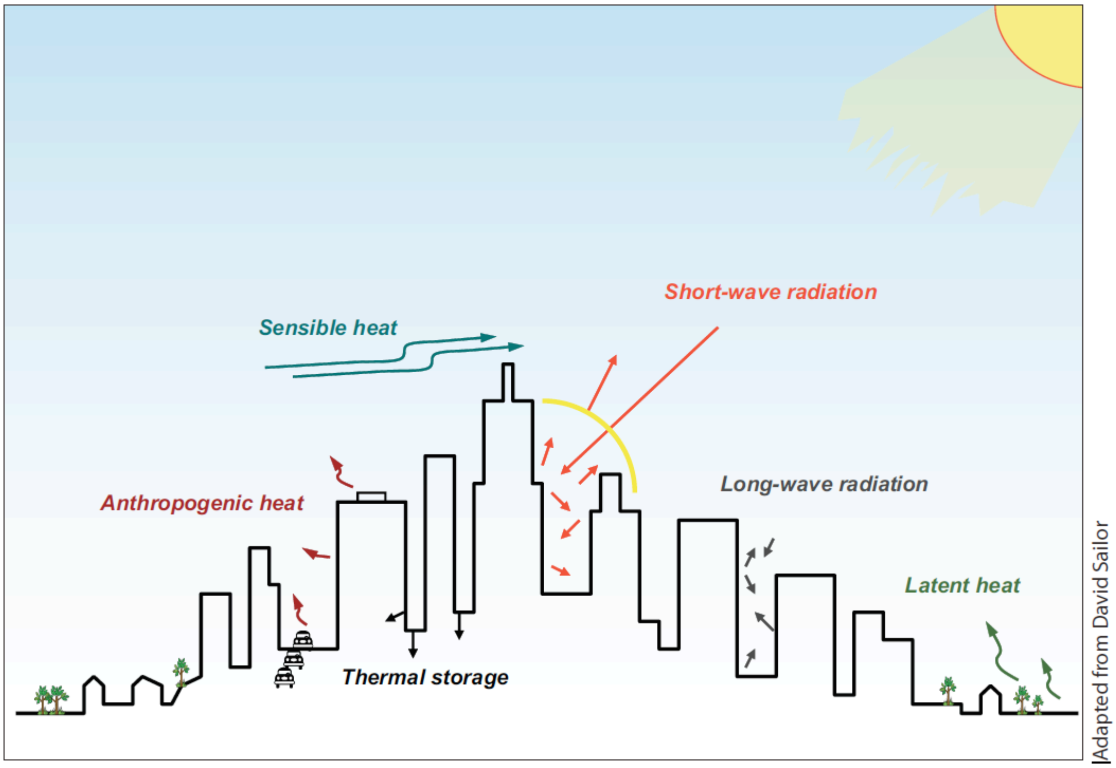


Figure 6. Urban Surface Energy Budget Source: (Sailor, 2011).

The atmospheric pollutants disturb the radiation budget by the reducing the incident flux of short-wave (i.e., solar) radiation, re-emitting long-wave (i.e. infrared) radiation from the urban surface downward to where it is retained by the ground and by absorbing long-wave radiation from the urban surface and thus effectively warming the ambient air (Shahmohamadi et al., 2011). The anthropogenic heat contributes to UHI by the heat that produced by human activities, especially from heating and cooling buildings, transportation and industrial activity see figure 6.

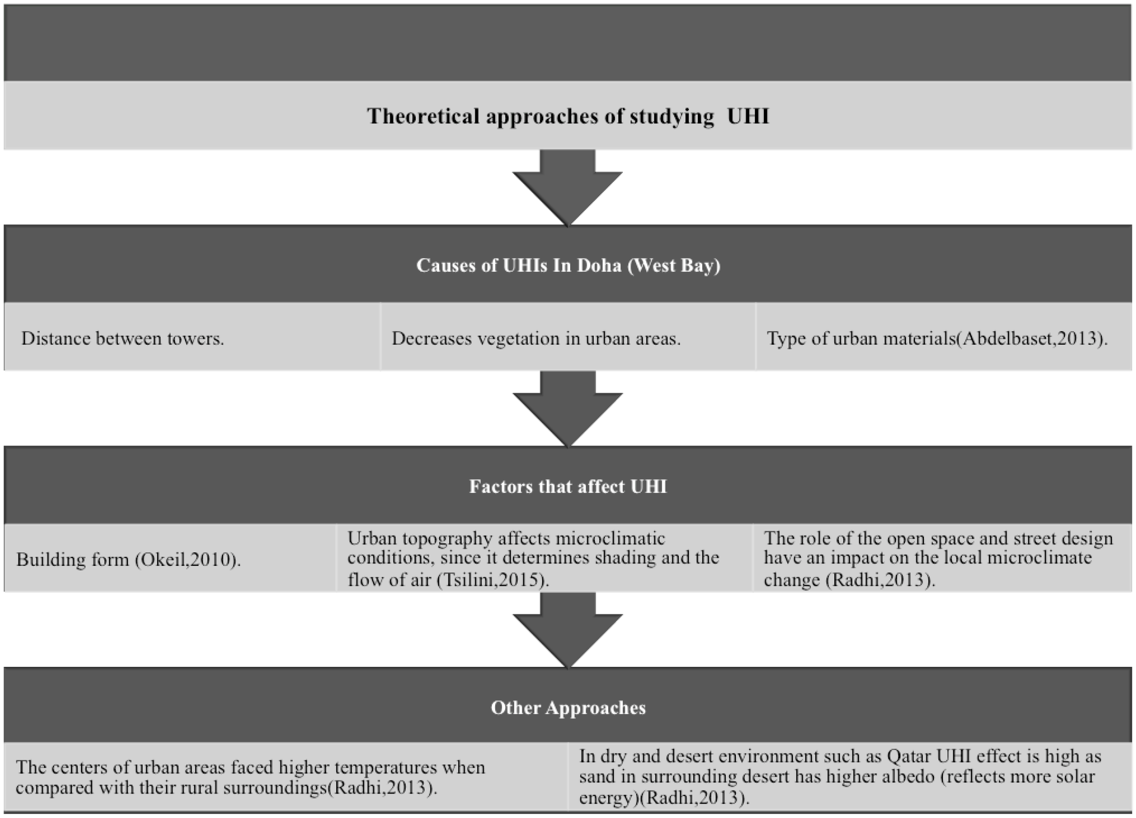
2.2.3 The Relation of the Land Surface Temperature (LST) to the UHI

Several studies of UHI have focused on the connection between the land cover, specifically vegetation, and Land Surface Temperature (LST). Efforts to analyze LST patterns to assess effects related to UHI and UCI often make use of data that have been collected remotely. For example, by measuring the amount of vegetation using the NDVI (Normal Difference Vegetation Index), research has revealed connections between specific surface characteristics and associated types of land use (Zhou, 2011). For this reason, the alternative term "Surface Urban Heat Island" (SUHI) is sometimes used instead of "UHI," reflecting the important role of land surface temperatures in identifying UHI effects. The LST data obtained from high-resolution Landsat images have greatly aided our understanding of the relationship between SUHIs and relevant surface biophysical parameters (Li, 2011). Therefore, understanding the relationship between land surface temperature (LST) and urban surface characteristics is important in any effort to design effective measures to mitigate UHIs (Guo, 2015).

2.2.4 Recent Approaches to Studying UHI

Figure 7 presents an overview of the main approaches to studying UHIs. Some recent studies have argued that the causes of UHIs in Doha's West Bay business district include distance between towers, reduced vegetation in urban areas, and properties of urban materials; these studies have discussed the extent to which these factors can be considered primary causes of UHI effects (Abdelbaset, 2013). Building form is another factor that influences UHIs (Okeil, 2010), as is reduction of air and surface temperatures through the implementation of urban gardens.

In addition, urban topography affects microclimatic conditions, since it determines shading and, to a large degree, the flow of air between buildings (Tsilini, 2015). Other studies have concentrated on the role of open spaces and street designs that can bring about local microclimatic change. One can also attempt to specify the areas that have a significant impact on the microclimate, such as airports. While the centers of metropolitan areas generally experience higher temperatures when compared with their rural surroundings (Radhi, 2013), the UHI effect is particularly noticeable in a desert environment such as that of Qatar. Key indicators of a reduced UHI effect include higher albedo (more reflection of solar energy) and higher porosity, typical of regions, which lose heat faster than urban centers tend to.



Theoretical approaches of studying UHI

Causes of UHIs In Doha (West Bay)

Distance between towers.

Decreases vegetation in urban areas.

Type of urban materials(Abdelbaset,2013).

Factors that affect UHI

Building form (Okeil,2010).

Urban topography affects microclimatic conditions, since it determines shading and the flow of air (Tsilini,2015).

The role of the open space and street design have an impact on the local microclimate change (Radhi,2013).

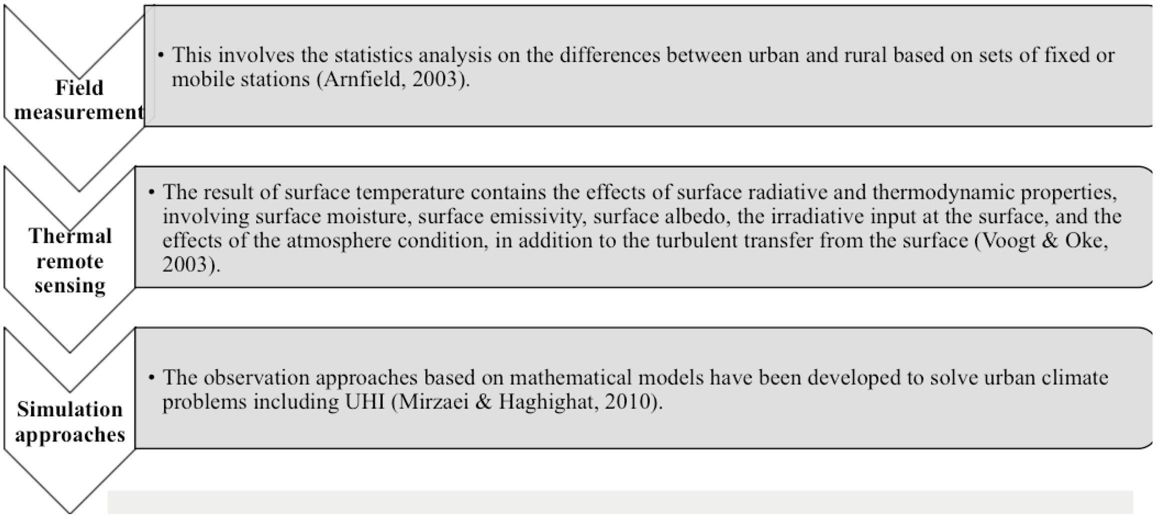
Other Approaches

The centers of urban areas faced higher temperatures when compared with their rural surroundings(Radhi,2013).

In dry and desert environment such as Qatar UHI effect is high as sand in surrounding desert has higher albedo (reflects more solar energy)(Radhi,2013).

Figure 7. Approaches to studying UHI (Source: Author).

The existing literature offers theoretical and practical approaches see figure 8, that approaches to indicate the understanding and mitigating the negative impact of UHIs, which, as already discussed, are associated with a variety of adverse effects such as greater energy consumption and hazards to human health.



- This involves the statistics analysis on the differences between urban and rural based on sets of fixed or mobile stations (Arnfield, 2003).

- The result of surface temperature contains the effects of surface radiative and thermodynamic properties, involving surface moisture, surface emissivity, surface albedo, the irradiative input at the surface, and the effects of the atmosphere condition, in addition to the turbulent transfer from the surface (Voogt & Oke, 2003).

- The observation approaches based on mathematical models have been developed to solve urban climate problems including UHI (Mirzaei & Haghighat, 2010).

Figure 8. Practical approaches of studying UHI (Source: Author).

2.2.5Mitigating UHI Effects

Cities and industrial sites consistently have higher temperatures than surrounding areas because of greater heat retention by buildings, concrete, and asphalt in the former case, and heat generated by machines in the latter. Some had argued that the air temperature at airports is higher than that of urban areas because of the heat generated by plane engines; however, this contention was not supported when the thermal behavior of two models for the two types of region were examined. The study investigated the contribution of urban elements to temperature changes by measuring the impact on temperature of spatial features such as structures, urban design and urban surfaces. It was found that the existence of a UHI can be attributed to a lack of urban planning; for such planning to be effective, it must take into account factors such as climate as well as the absence of green cover and bodies of water (Radhi, 2013).

As noted earlier, building form is one factor that affects UHIs. Research addressing building forms must address factors such as the shape of a building's footprint, its orientation, grid height, building length ratio and aspect ratio; these were described and investigated by Okeil (2010). Along similar lines, Ivajnšič (2014) argued that UHIs are the best indicators of the impact of human activity on the local climate. He further argued that UHIs occur not only in big cities, but also in small towns. Impervious urban cover experiences higher temperatures than non-impervious cover, which in turn leads to changes in energy use and the water balance due to urban modifications and activity (Ivajnšič, 2014).

The increase in warmth due to a UHI effect can be as much as 10 °C, although this is subject to considerable variation, due to the particularities of the local environment and atmospheric conditions. Measuring the day-to-day (DTD) temperature of an urban heat island can be seen as a compelling measure of urban effects in the context of the physiographic characteristics of the area under study. Moreover, there are clear differences in DTD variability that can be used to determine suitable urban-rural pairs for urban impact studies (Tam, 2015).

The term "urban microclimate" means that the climatic conditions prevailing in a specific urban space (e.g., square, park, neighborhood) show significant differences in heat emissions relative to conditions prevailing in the wider area. Urban topography has a significant impact on microclimatic conditions, since it determines shading and greatly influences the flow of air between buildings. One way to reduce air and surface temperature is through the use of urban gardens. Test cases using urban gardens with different types of vegetation can be used in order to assess their effectiveness.

Urban geometry also has an important influence on the local temperature; therefore, DTD measurements can differ significantly over time. Changes in the height at which measurements are taken can also be very important, as surface temperatures can vary greatly depending on the different building materials used (Tsilini, 2015).

Bourbia and Boucheriba (2010) argued that open public spaces can play a major role in influencing the urban climate, based on insights they gleaned from investigating street design. Their study found that a space’s aspect ratio and temperature are inversely related. They suggested that a measure called the Sky View Factor (SVF) should be incorporated into urban geometry design, as an understanding of this quantity can inform designs mitigating the effects of UHIs (Bourbia and Boucheriba, 2010). Figure 9 shows a diagram illustrating the SVF.

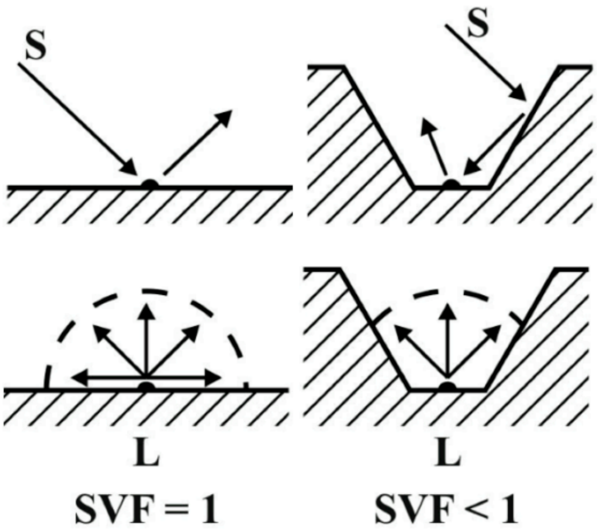


Figure 9. Sky View Factor; S=short-wave radiation and L=Long-wave radiation (Source: Hämmerle et. al., (2011).

Ratti et. al. (2003) focused on a number of key factors including surface-to-capacity ratio, shadow densities, accessible daylight and Sky View Factors, as well as environmental issues such as "solar radiation, thermal comfort and urban temperatures." The authors stressed the importance of the "infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives," stating that "obviously, there is no single solution, i.e. no universally optimum geometry." Further, Ratti et. al. (2003) emphasized that there is a relation between building forms and certain climatic conditions, "such as the courtyard type and the hot-arid climate" (Ratti et. al., 2003). In a similar vein, Morris and Simmonds considered wind speed and cloud cover as factors that influence the intensity of UHI effects (Morris, 2001); these are relevant because clouds prevent radiation from reaching the surface directly, which leads to a reduction in long-wave radiation and the wind corridor. Furthermore, Taleb and Abu-Hijleh (2013) stated that the presence of wind leads to a reduction in temperature, reducing the prevalence of "hot spots." Urban green infrastructure must take into consideration building materials and design, in addition to more obviously related concerns like green open spaces, public parks, tree shade, green roofs, vertical green systems, and green walls and facades. Many other studies have suggested that cooler cities can be created by using green infrastructure in urban areas and on road networks.

Managing extreme heat in urban climates is expected to become increasingly critical as climate change worsens and urban populations continue to rise. Urban green infrastructure is a critical component of planning for sustainable urban areas and for any strategy for adjusting to climate change. This is because such infrastructure provides multiple benefits for urban communities and local ecosystems (Norton, 2015). For example, one mitigating technique is the use of building roofs incorporating cool or reflective materials that present a high albedo, in addition to more traditional green roofs. These techniques can lead to a decrease in the prevailing surface temperature (Santamouris, 2014). Similar benefits can be obtained by increasing the amount of shade and by using white roofing materials, which can also reduce UHI effects. Such strategies reduce heat, maintain comfort in and near buildings, lead to reductions in energy consumption for cooling and in maintenance expenses, and lower electrical demand, all of which reduce the heat island effect and air pollution (Fernández, 2009).

Over the past decade, the sustainable development movement has brought about new conceptual tools to reduce the negative impact of cities on the environment. One such concept, “green urbanism,” attempts to create sustainable urban areas and communities by reducing such areas’ waste emissions and their corresponding ecological impact or “footprint”; the ultimate aim is “eco-urban development” focusing on environmental sustainability. For example, effective landscaping by urban planners reduces a city’s heat impact; such landscaping can be implemented on or in buildings, streets, parking lots (by reducing the net emissions of parked cars), playgrounds, schoolyards (which in some cases would otherwise be completely paved over), and sports fields (Fernández, 2009).

Other concepts such as “Transit-friendly Growth” and “The People’s Urbanism” can play a major role in mitigating UHI effects. Private vehicles present many points of concern for modern cities, because of traffic, the need to provide for adequate parking, and other issues. Investing in public transportation systems is usually an effective way to solve traffic problems in urbanized environments; ideally, such systems provide multiple modes of transportation of good quality (Calvillo, 2016).

“Smart growth” encourages the development of compact and walkable areas within urban regions of strong economic development. There are numerous advantages of making urban districts more compact. For instance, it leaves a smaller footprint on the environment, by decreasing the fuel consumption needed for commuting by motor vehicle. Ensuring that services for residential areas are close together and therefore within walkable distances also reduces the need to own a car and supports a better quality of life (Oktay, 2012).

Integration of various modes of transportation while encouraging pedestrian access, walkability, and public transportation encourages people to engage in a more active lifestyle. If high-density areas are designed with the aim of reducing the number of (and need for) roads, this will tend to reduce the usage of private vehicles and lessen negative impacts on the environment (Wey, 2014). Furthermore, many concepts such as "New Urbanism" and "Transit-oriented Development" (TOD) have made critical contributions to the literature by offering policy trajectories favoring a decrease in the number of cars and distances traveled. This can be achieved by implementing well-designed compact urban development with a high degree of density and diversity; these factors generally have a significant and positive impact on a city’s transportation system (Vos, 2014).

2.2.6 Definition of UCI

In contrast to the UHI, the term “UCI” refers to the fact that urban areas tend to be cooler than surrounding rural areas in the morning and early afternoon. Urban areas with more green parks and vegetation exhibit smaller UHI effects during the day, relative to other cities, and show an improved UCI effect, as determined through the use of atmospheric models (Theeuwes, 2015).

A number of researchers have studied the UCI as a tool with the potential to mitigate UHI effects, and some studies have revealed that partially shaded areas under tree canopies benefit from a significant cooling effect (Kong, 2014). The term UCI is not clearly defined; Xin Cao describes it as the difference between the mean Land Surface Temperature (LST) in a green space and the mean temperature in a specific buffer area (Cao, 2010). On the other hand, Kong defined UCI intensity in terms of the link between the lowest temperature and the size of the UCI (Kong, 2014). Another definition is given by Sun, who describes UCI intensity as the difference in temperature between a wetland and the surrounding landscape (Sun, 2012).

Chena (2014) argues that green areas function as UCIs by improving human thermal comfort in urban areas. He also defined two types of UCI; the first type is atmospheric, referring to air temperature, and the second is based on measurement of a surface, commonly the Land Surface Temperature. He also stresses some important factors affecting the role of the landscape in reducing heat, including shape, edge and connectivity (Chen, 2014).

Planned use of vegetation is important in a hot arid zone, because strong solar radiation accompanied by high air temperatures create a negative impact on human comfort and activity. The “Park Cool Island” phenomenon is related to vegetation in parks, while the term “Green Island” refers to vegetation on streets. The latter causes a cooling effect at a local level, acting in opposition to the UHI effect (Shashua-Bar, 2009). Together, grass and trees can reduce ambient heat by an amount in the range of 5 to 7 °C, although grass alone has just a slight temperature reduction effect (Armson, 2012).

Only a few studies have studied microclimates and human comfort in the context of a hot dry climate. For instance, Johansson’s 2006 study on the influence of urban geometry on outdoor thermal comfort in Fez, Morocco, provided a clear contrast between deep street canyons and shallow street canyons in the historical urban fabric. The findings of this study indicated that deep street canyons are preferable in summer months in a hot dry climate because they enable shaded protection during hot summer weather, effectively acting as cool islands. In contrast, shallow street canyons are uncomfortably warm in the summer, but during cooler winter months, shallow street canyons are preferable because they offer greater solar access. In summary, a compact urban design with very deep street canyons is preferable in a hot dry climate. In contrast, in colder climates the urban design should include wider streets and open spaces to provide solar access. The street network in Fez is irregular and complicated, which increases the mutual shading from buildings at street level. The use of private cars is also relatively low in that city (Johansson, 2006).

2.3 Outdoor Thermal Comfort

Urban areas operate as climate modifiers because the urban fabric affects climatic factors such as air temperature, wind speed, and humidity. Urban areas are often adversely affected as the result of an absence of suitable design tools for effective planning (Farr, 2008).

The higher temperatures generated by UHI effects produce discomfort in outdoor open urban spaces that is reflected in land surface temperatures. Many studies have been conducted on the thermal comfort of urban open spaces. For instance, Targhi and Dessel (2015) argued that designs which give attention to thermal comfort in urban outdoor spaces will reduce the need for vehicles, such as in designs for walkable communities (Targhi and Dessel, 2015). Experts have described a number of factors that have a significant impact on thermal comfort, including climatic aspects of the area (air temperature, humidity, solar radiation and air velocity), personal factors (clothing), and other relevant factors such as a given person’s acclimation to the local weather as well as their sex and age. The climatic factors tend to seem most prominent because they are relatively easy to measure (Younsi, 2016). Open spaces are often affected by UHI effects, as asphalt and other materials in building surfaces release heat during the night, thereby contributing to human discomfort. In addition, in highly urbanized areas, especially those with commercial centers, higher temperatures can be recorded during both afternoon and late night hours because of the heavy presence of human activities (Kikon, 2016). This heat affects microclimatic conditions and therefore impacts human comfort in open urban spaces (Al-Mohannadi et. al., 2015).

In a hot dry climate, urban geometry and design contribute greatly to microclimatic conditions and thermal comfort at the micro level. For instance, providing shade in a compact urban form characterized by deep street canyons results in decreased temperatures in the summer and an increase in the cool island effect. Two important quantities influencing urban climate are first, building heights (H), and second, the distance (W) between the buildings; the ratio between these two quantities largely determines the amount of available shaded areas in an urban space. Furthermore, this ratio affects the amount of incoming solar radiation as well as wind speeds. At night, the heat island effect increases with the H:W ratio because of the scale of long-wave radiation in relation to the Sky View Factor (SVF). As noted earlier, building materials accumulate thermal radiation during the day and release it at night (Johansson, 2006).

Taking microclimatic conditions into account in the implementation of high-quality landscape design can cause a reduction in the UHI effect and hence lower temperatures, creating a more comfortable environment; this is particularly so in hot arid regions (Lehmann, 2010). Comfortable environments can be created through the appropriate use of trees and other vegetation, which can provide shading, evaporation, and air movement. In particular, this reduces the amount of incoming solar radiation. Gartland (2008) showed that the temperature within the shade provided by trees is lower, and in the case of shaded walls, the cooler surface lessens the amount of heat transmitted to the air (Gartland, 2008). The evaporation process helps keep the air cooler and thereby reduces the heat island effect (Fernández, 2009). A targeted green cover ratio of 45% improves thermal comfort and provides an efficient distribution of vegetation across a city (Hassan, 2015). Shashua-Bar and Hoffman (2003) examined the influence of trees on urban streets and courtyards. Their results showed that this improves outdoor comfort by providing more shade, with a cooling effect of approximately 4.5 ^{0}C (Shashua-Bar and Hoffman, 2003).

Urban street design is another factor that merits attention, as it can influence thermal comfort outdoors as well as energy consumption inside adjacent buildings (which as already noted, itself affects outdoor microclimatic conditions). Recent studies have focused on how street design can improve outdoor thermal comfort. Many efforts to provide cooling at the street level rely on shading provided by trees, which affects airflow patterns and ventilation (Shashua-Bara, 2003).

Adjacent building forms also have a strong effect on the urban airflow at lower altitudes. Moreover, green roofs reduce the canyon air temperature, as vegetation limits the radiation that would otherwise be absorbed by the urban surface, with the evapotranspiration process also enhancing microclimate conditions (Ouldboukhitine, 2014). The ratio of building height to street width affects the microclimate because it determines the differences in airflow patterns between shallow and deep street canyons (Park, 2015).

2.4 The influence of traffic on road surface temperatures and the UHI

“Heat will be added to the road surface by sensible heat and moisture fluxes from the engine and exhaust as well as frictional heat dissipation from the tyres and braking” (Chapman & Thornes, 2005) see figure 10.

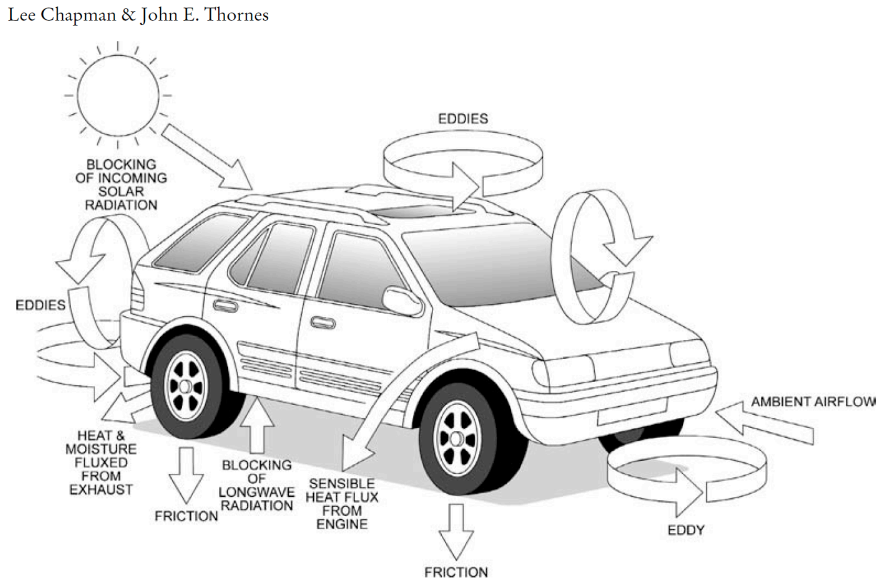


Figure 10. the impact of traffic on road surface temperatures Source: (Chapman & Thornes, 2005).

The geometry of the street canyons, often described using the sky-view factor, controls the radiation budget and thereby the degree of cooling on clear nights (Oke & Maxwell, 1975). Farmer & Tonkinson (1989) examined the effect of traffic on the daytime temperature and found that a higher traffic density caused warmer road surface temperatures.

Radiation is the causes of variation in road surface temperature. The radiation factor controls both the daytime heating, owing to the degree of short-wave radiation reaching the road surface, as well as the nighttime cooling by long-wave radiation. This factor has been quantified in a number of studies using the sky view approach (e.g. Bradley, 2000).

The road surface temperature can be affected by the human activities that release heat and by the warming effects of traffic cased by radiation. The urban heat island has a marked impact on the local air temperature and road surface temperatures. In addition, traffic movement will also cause additional mixing of air above the road surface promoting increased turbulent flow.

2.4.1 Transportation Systems and Climate Change

In many cities, the number of people who commute regularly has increased greatly in the recent past, especially in cities that have undergone significant urban development. This is the case in many developing countries. Urban expansion and sprawl lead to a reduction in public spaces and increase the need for private cars (Hassan, 2015). This creates a number of difficulties, such as the negative impact on the environment caused by pollution, concerns about social and health issues, and traffic jams (a major contributor to pollution) (Kwan, 2016).

Transportation systems have a major influence on climate change and carbon emissions, as traffic congestion produces pollution, noise and delay, all of which undermine the quality of life (Salcedo-Sanz, 2014). Therefore, a city's transportation system is one of the most important factors affecting the city's environment and quality of life; an efficient transport system can reduce pollution and preserve public health. Well-organized transport systems also allow a savings of energy and time (Calvillo, 2016). Three major factors contribute to CO_2 emissions and impact the environment in other ways: road distance, vehicle speed, and vehicle size. Perhaps more significantly, congestion is a key factor affecting the emissions from road traffic at many scales, including single intersections, corridors, and the overall road network (Grote, 2016).

Numerous studies have explored the effects of incorporating trees into the urban fabric. These studies have found that the resulting canopies have a significant cooling effect. When tall shade trees are used, the tree canopy provides reliable shading, with the effects of geometry and orientation on shading being practically non-significant (Shashua-Bara, 2003). Traffic flow can have negative consequences in the context of street canyons, as traffic moving in the same direction as the prevailing airflow tends to lead to more polluted areas. This can be mitigated significantly by implementing appropriate regulations; for example, regulations on speed for certain types of vehicle when entering urban centers may lead to a net reduction in air pollutants, leading to better air quality and improved public health (Thaker, 2016).

2.4.2 Experience of Congestion in the Swedish City of Stockholm

It is instructive to consider some examples from abroad that can provide insights for the case of Doha. To reduce traffic in Stockholm, a “congestion fee” was implemented in order to reduce the city’s traffic, increase accessibility, and improve the quality of the urban environment. Vehicles were charged both when entering and leaving the city center, with the exception of particular days and particular vehicles. Those that were not subject to the fee included taxis, motorcycles, emergency vehicles, and vehicles using low-emission fuels. The use of public transportation was promoted through the provision of more bus stops, buses that ran frequently during rush hour periods, and additional bus lines in the city center. Furthermore, additional parking spaces were provided near bus stations, which encouraged car owners to shift to public transport. The public acceptance of this fee was poor at first, before it was actually implemented.

However, public acceptance improved greatly after implementation, because of visible and significant improvements in the city, including a general absence of traffic congestion, wider availability of parking, and reduced pollution (Schuitema, 2010).

2.5 Chapter Summary

In conclusion, UHI is defined as the temperature difference between an urban area and its surroundings. The term “UCI” refers to relatively cooler places within urban areas, but there is no specific definition for this term as yet. Urban design and development have a tremendous impact on the microclimatic conditions within cities, and thus play a major role in the UHI effect and global warming.

Doha’s rapid growth and the increasing expansion of its urban areas have led to ever-greater creation of heat. A review of the relevant literature has shown that urbanization and urban sprawl tend to have a number of negative impacts, one of which is the creation of UHIs that increase the temperature of the urban environment.

In the long run, high-density urban development may reduce dependency on the use of private vehicles. Indeed, this would help decrease traffic and promote the use of walkable pathways. Furthermore, the literature also indicates that sustainable urban development and related concepts such as green urbanism, landscaping and green infrastructure can serve as useful tools to reduce urban heat and improve microclimatic conditions in the city.

Many factors discussed in the literature have the direct or indirect effect of increasing UHI effects, including some that will be explored in the present research. The following chapter covers the methodology of this study.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter presents the research methodology and data collection tools used in this study, as well as the methods of data analysis. The methodological framework covers the research plan and provides an overview of the methods, analysis and results, focusing on the key aspects of the research, including the research approach, data definitions, data collection tools, and data description. A discussion of the methodological background presents the analytical structure used to test the research hypotheses.

As the first stage of the project, a comprehensive literature review of relevant theoretical research was conducted, in order to understand better the UHI dynamic in different locations. The second stage involved data collection to determine changes in air temperatures and specify urban areas and surface temperature measurements. The third stage incorporated tools used to measure the surface temperatures obtained by the remote sensing ENVI program. The thermal bands were calculated and converted to surface temperature data, which in turn were combined with the Geographic Information System (GIS) in order to process spatial data and to produce maps of surface temperature; this permitted a better understanding of the existing UHI in Doha.

Field measurements were conducted on selected study areas to measure Land Surface Temperature. These were then synthesized with results of analysis of satellite images of the thermal bands, together with established maps of the relevant regions.

3.2 Research Approach

In order to illustrate the growth in urbanization and the heat capacity in the local climate of Doha and its surroundings, four main stages of data collection and processing were required. Figure 11 presents the general methodology used at each of these stages.

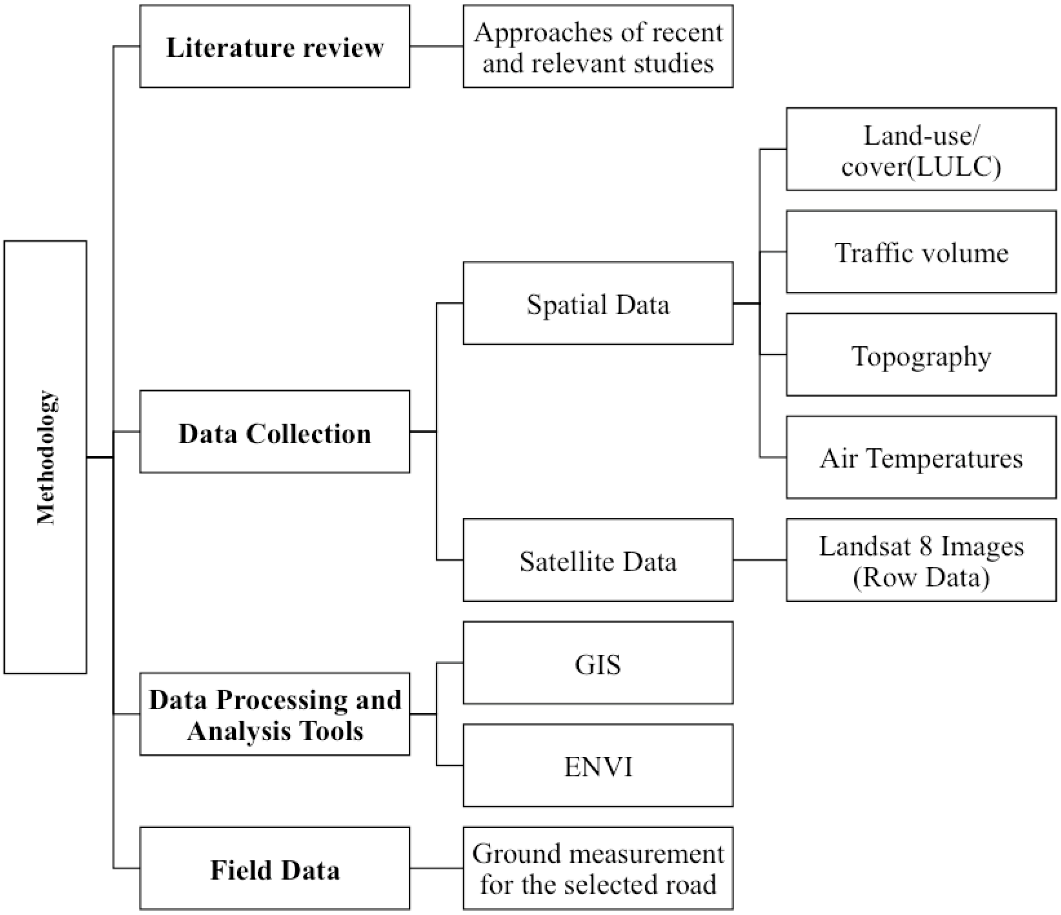
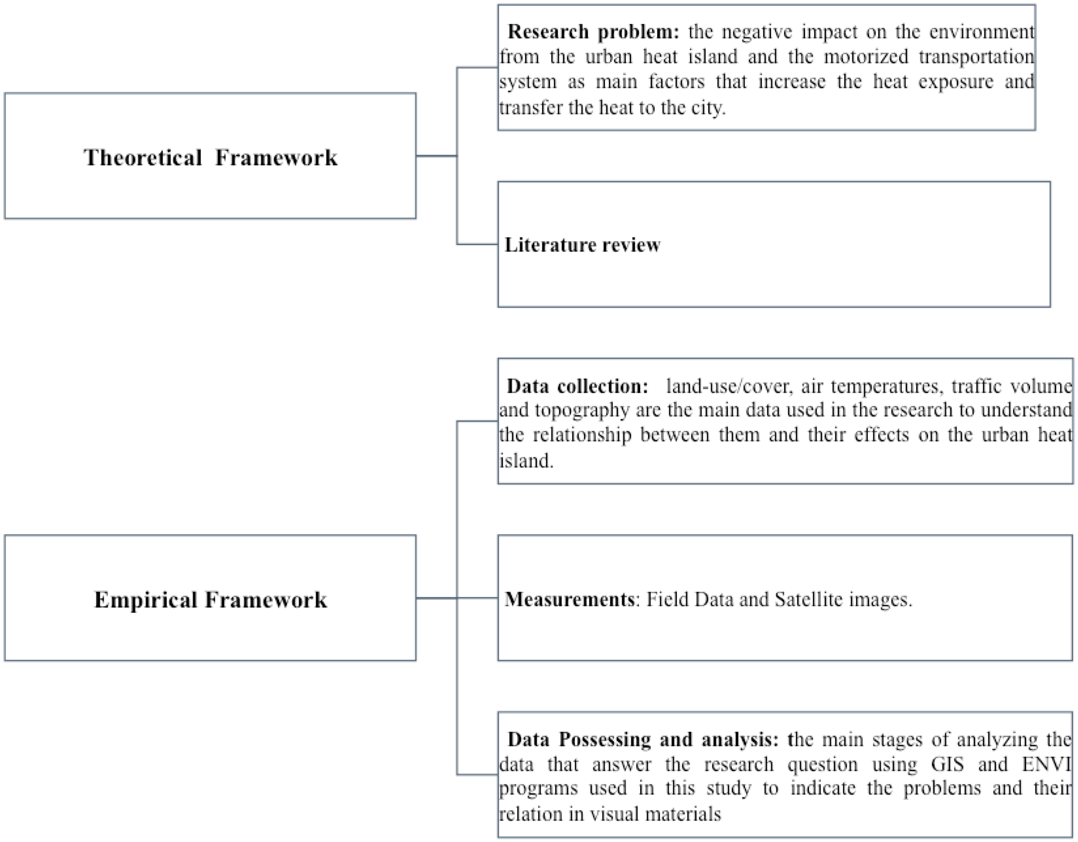


Figure 11. Research methods for data collection, including the processing tools for measuring raw spatial and satellite data (Source: Author).

Quantitative researchers seek to explain the causes of change primarily through objective measurements and quantitative (statistical) analysis. In the present case, numerical data are used to obtain information about Land Surface Temperature (LST). The objective is to achieve an understanding of the relevant phenomena, concepts and case study area by creating an overview of the many factors that affect microclimatic conditions in hot arid regions such as Qatar, and more specifically in the capital city, Doha. The primary focus is on the transportation system and traffic volume in relation to the UHI in Doha. Furthermore, efforts are made to understand how traffic can cause variations in the heat island effect.

3.2.1 Theoretical and Empirical Framework

The research design consists of two parts: the theoretical underpinnings and the empirical focus. The theoretical part specifies the research problem and explores aspects of the UHI phenomenon that lead to a negative impact on the environment, incorporating a review of the recent literature. The empirical part consists of analysis of the data collected from satellite images and field measurements, which may either support or refute the research hypotheses presented earlier. Figure 12 presents this study's theoretical and empirical framework, covering five main categories.



Theoretical Framework

Research problem: the negative impact on the environment from the urban heat island and the motorized transportation system as main factors that increase the heat exposure and transfer the heat to the city.

Literature review

Empirical Framework

Data collection: land-use/cover, air temperatures, traffic volume and topography are the main data used in the research to understand the relationship between them and their effects on the urban heat island.

Measurements: Field Data and Satellite images.

Data Possessing and analysis: the main stages of analyzing the data that answer the research question using GIS and ENVI programs used in this study to indicate the problems and their relation in visual materials

Figure 12. Theoretical and empirical framework of the research (Source: Author).

3.3 Obtaining Data

Urbanization in Doha has led to fundamental transformations in the area's landscape over the last ten years, as both urban extent and population have more than doubled during that timeframe. This expansion has required a great deal of energy to meet the needs of development. The purpose of the present study is to examine the relationship between the motorized transportation system and the UHI in Doha, though the use of two main methods of data collection and analysis.

Spatial data was useful in understanding the dynamics of urban planning through changes in land use and land cover, and in uncovering patterns of activity and urban development. The topographical data assisted in understanding effects of topography on land surface temperature; these data were collected from the Ministry of Municipality and Environment.

Air temperature data were collected from the Qatar Meteorology Department, and permitted a better understanding of the interplay between air temperatures and surface temperatures.

It also proved useful to analyze changes in traffic volume within the transportation system in Doha. Traffic volume data for Doha were collected from the Ministry of Transport and Communications, which helped establish the number of cars in circulation during rush hour periods.

Satellite data enabled an overview of land surface temperatures after these data were subjected to a suitable analysis. The satellite images were downloaded as row data from http://glovis.usgs.gov, and calculations related to Landsat images were subsequently carried out by the author.

Field data collection used CR8000 measurements and a control data logger to measure surface temperatures, and was used to verify accuracy of the satellite data.

By combining results obtained using the various methods outlined above, this study is able to determine key aspects of the UHI effect in Doha, as well as its connection with land-use/land-cover (LULC) and the city's transportation system.

3.3.1 Study Area selection

Doha is the capital of Qatar and is the largest and most populated city in the country. All government agencies, as well as most of the country's large-scale infrastructure and mega-projects, are located there. The city has undergone an extremely rapid process of urbanization and growth in the recent past. Figure 13 shows the study area location that was chosen for the present research project.

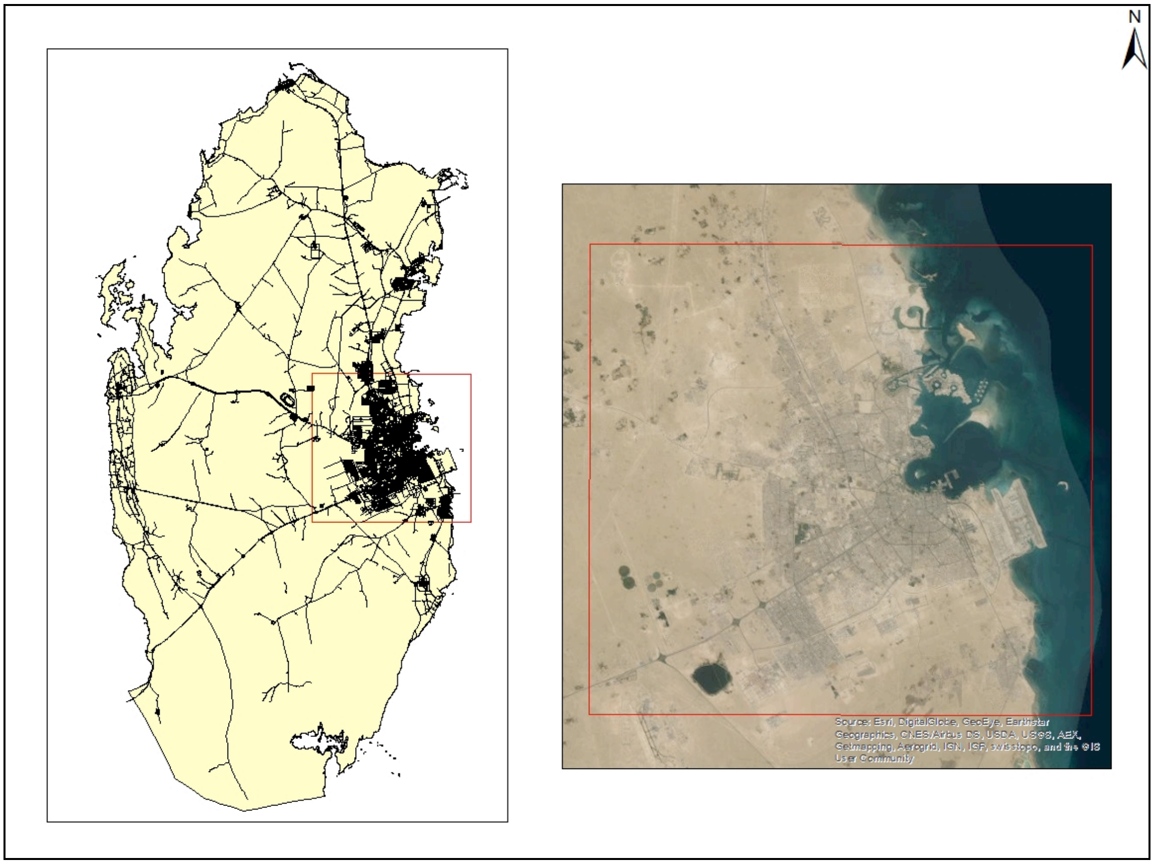


Figure 13. Study area location (Source: MMUP; edited by Author).

3.4 Data Collection Tools

3.4.1 The Assessment of UHI in Doha

The assessment of the UHI in Doha consists of two major components.

1. Assessing the impact of urbanization on the UHI.

2. Assessing the impact of traffic volume on the UHI.

Figure 14 illustrates the process of data collection and analysis.

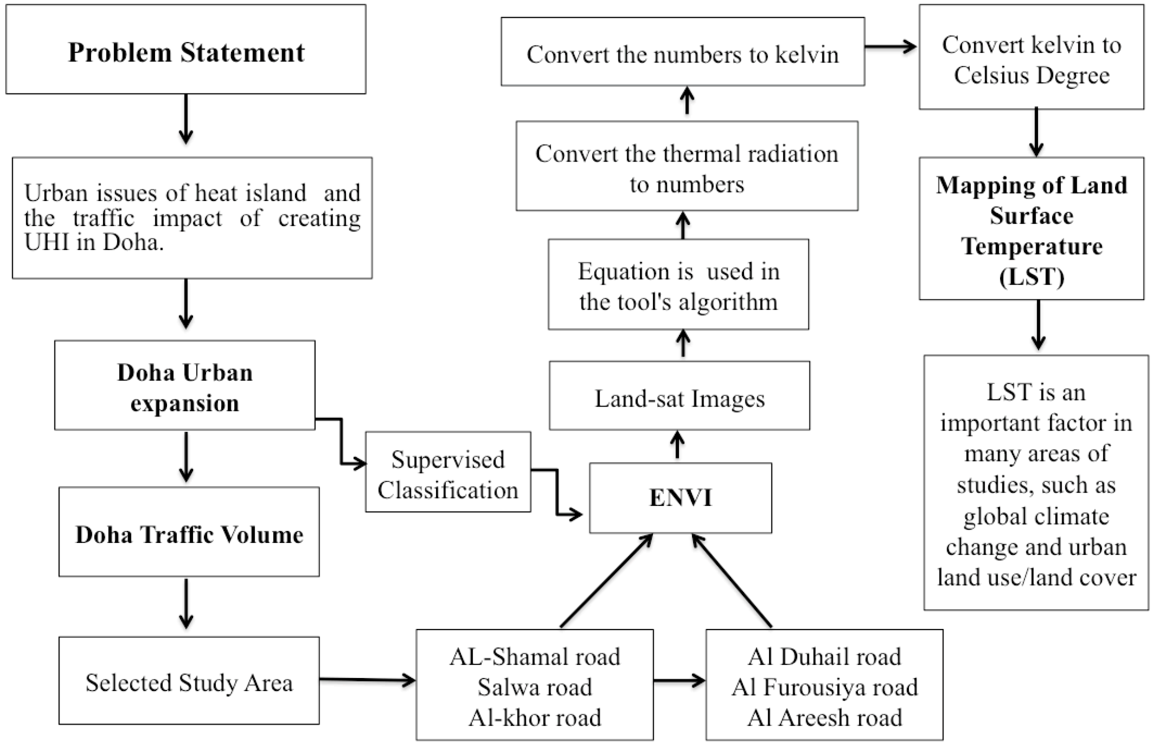


Figure 14. The process of data collection and analysis (Source: Author).

3.4.2 Assessing the Impact of Urbanization on the UHI

Assessment of the impact of urbanization on Doha's UHI was carried out through advanced statistical analysis of weather data, along with the application of Geographical Information System (GIS) and remote sensing (ENVI) data.

3.4.3 Satellite Images, Landsat 8

In order to collect remote sensing data, satellite images were obtained from Landsat 8 (USGS, 2016). Temperature values and other weather data were collected as digital copies. Those data had been measured by fixed meteorological stations at the local airport and other sites during 2014. Satellite images were collected from (http://glovis.usgs.gov) as row data, and the relevant temperatures were calculated using the algorithms described by Coll et. al. (2010) and were used to produce LST information.

3.4.4 GIS Applications and Remote Sensing

A number of GIS applications were used in this analysis, including the following:

- The Google Earth (2010) application was used to identify sites for study and to zoom into "hot spots."
- ArcMap 10.2 was used to compile data (concerning land use, topography and traffic volume), to manage geographical information, and to register and apply the raster overlay process.
- The environmental modeling software ENVI 4.5 (2008) was used to ensure accurate spatial and geostatic analyses.

3.4.5 Assessing the Impact of Urban Elements on the UHI

Assessment of the impact of urban elements on Doha's UHI was performed by using software packages to study the thermal behavior of newly built-up areas. This involved both an urban expansion modeling approach, and a modeling of LSTs.

The analysis in this quantitative research examines the impact of urbanization on thermal characteristics of an area. Analyzing temperature data and the urban development area enables the production of graphs showing temperatures for different months, one aim of which is to identify the highest temperatures during a given year. Calculations relating areas of urban expansion with various types of land use reveal interesting trends in different land use categories during different time periods. Comparisons of mean temperatures at the study sites help to identify UHI areas in newly urbanized areas. Spatial analysis reveals relevant patterns in mean temperatures at the study site during the period from 2015 to 2016. The findings of these analyses show:

1. Temperatures are elevated on the order of 2 to 3 degrees Celsius in the study area.
2. The strength of the urban heat island effect depends primarily on weather conditions, urban geometry, urban surfaces, and particularly on the availability of vegetation and water elements.
3. Traffic jams contribute greatly to heat island effects.
4. The entire road system in Doha exhibits elevated temperatures.

These findings should prove extremely useful to urban planners in any effort to improve the thermal conditions associated with future developments in the city.

3.4.6 Calculating Field Surface Temperatures

CR8000 measurements and a control data logger were used to calculate surface temperatures within the selected study area.

3.5 Data Description

3.5.1 Doha Land Use/Land Cover Data

The term “land use/land cover” (LULC) incorporates a large number of categories including residential, commercial, mixed-use, industrial and light industrial, agricultural, health, governmental and educational institutions, as well as hotels, parks, roads, parking areas, utilities, airports and seaports. These components represent the urban core of Doha in which UHI and UCI effects are most likely to happen. LULC data were used in this study to determine thermal conditions in Doha in relation to land surface temperatures.

Multiple factors affect land-use decisions in urban environments. One of the most significant of these in Doha is the hosting of mega-events, which involve the initiation of large-scale urban transformation projects related to Qatar’s National Vision. The implementation of Qatar National Vision 2030, the Qatar National Master Plan and the Comprehensive Transportation Plan, currently in progress, will establish a detailed design plan for physical land use and transport systems through 2032. Optimal use of land resources and sustainability are key themes of the Master Plan. Developments related to land use in Doha are taking place mainly toward the west and north, one effect of which is to increase residents’ dependence on car transportation.

The changes in land use in Doha and the rapid growth seen in the city from 2003 to 2016 can be best understood by considering the LULC characteristics of the city’s urban areas, streets, open spaces, parks and highways. The GIS model is used to determine categories in terms of uses of land. The shapefile data (GIS data) with LULC information are taken from the Ministry of Municipality and Urban Planning (MMUP), including detailed simulations of land use.

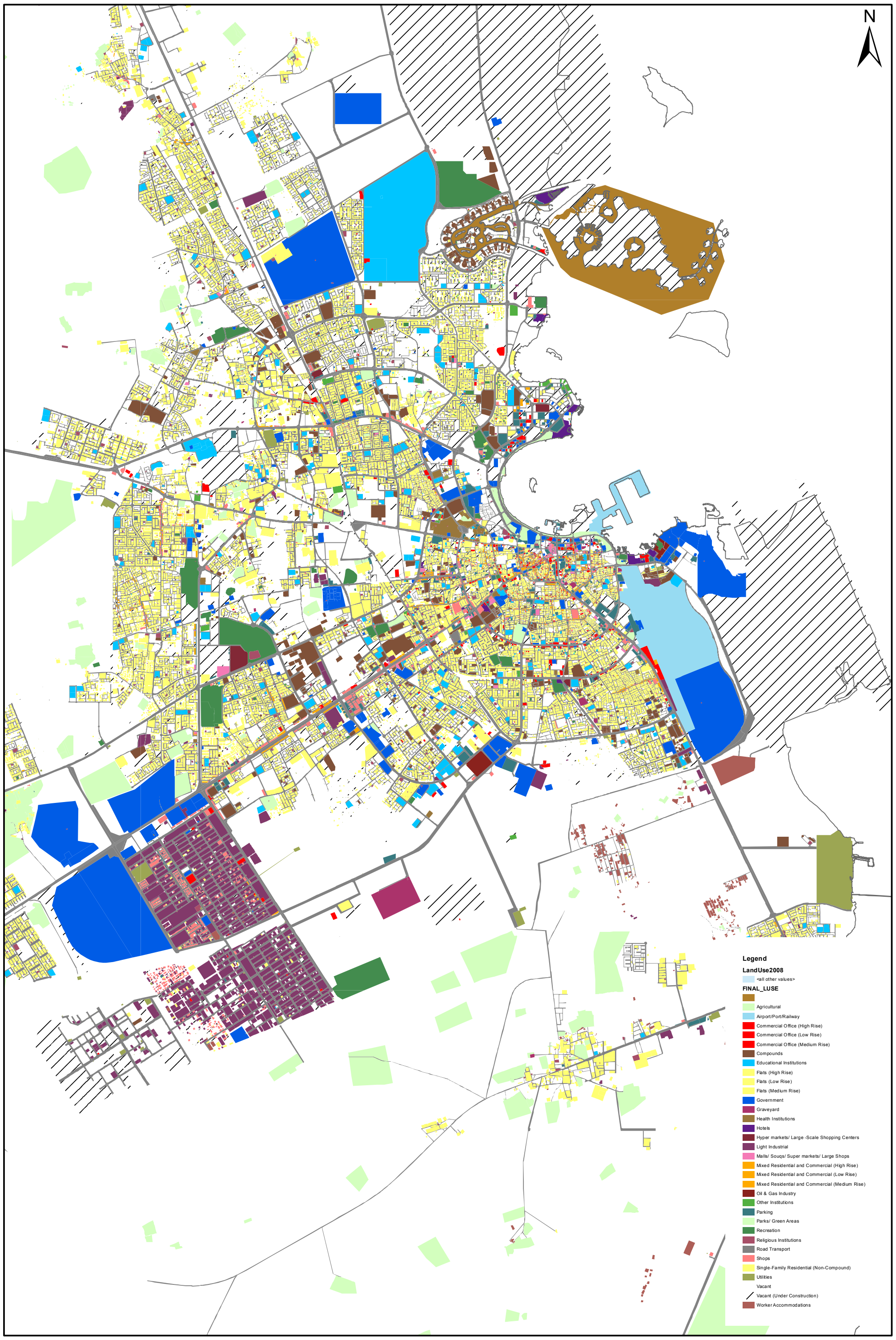


Figure 15. Doha land use/cover, 2008 (Source: MMUP).

3.5.2 Air Temperature

There are many weather stations in the city of Doha which track changes in air temperature and register maximum and minimum temperatures on a daily basis.

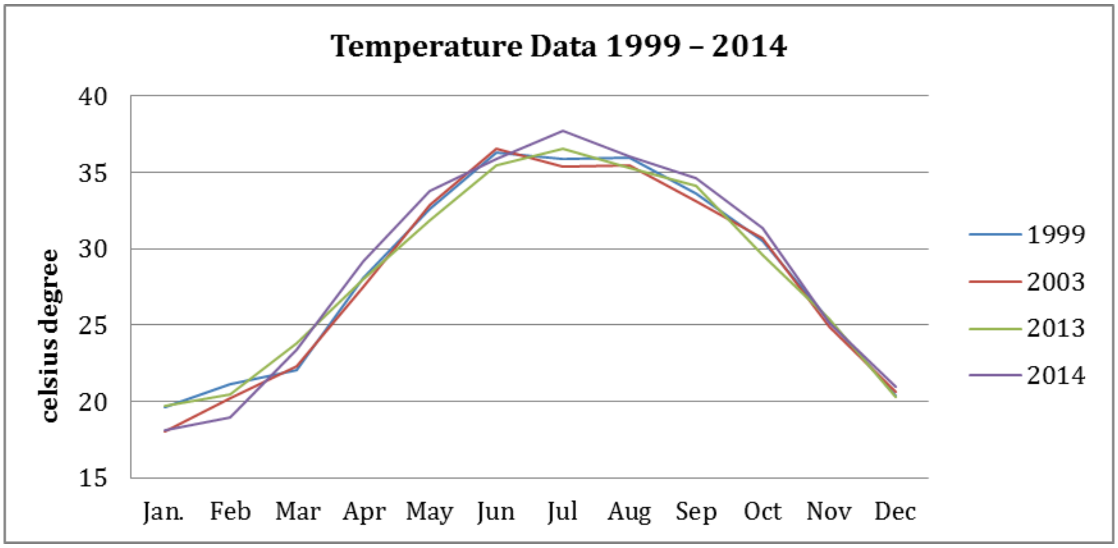


Figure 16. Temperature values from 1999 to 2014 Source: (QMD2014).

Air temperatures fluctuate sharply between the summer and winter periods. Figure 16 shows how temperatures increase during the summer. Peak values in 1999 and 2003 were about 36 °C, while the highest recorded value during summer 2014 was 38 °C. The data show clearly air temperature was particularly high during those years.

Anthropogenic heat is one of the main causes of UHI effects in cities. Key contributors include climate control inside buildings as well as solar radiation reflected from buildings and other surfaces. The relationship between UHI effects and air temperature is not straightforward to study in Doha because of the already-hot weather in the desert environment. It is also difficult to measure to what extent the UHI raises air temperature due to the materials and atmospheric conditions prevalent in the city. In addition, there is no clearly established technique for measuring the UHI effect.

Generally, it is expected that microclimate changes will be seen in highly developed areas due to the UHI. As the city continues to develop, increases in temperature occur and are intensified by specific building typologies seen in areas with large numbers of high-rise buildings. Increased temperatures lead to a cycle in which demand for air-conditioning increases, leading to more burning of fossil fuels, which in turn causes air pollution, which in turn results in increasing temperatures (El Morjani, 2013).

3.5.3 Topography

Qatar can be classified as a low-lying surface. Figure 17 shows a contour map of the city indicating elevation in meters. GIS was used to convert the contour lines into values in meters, with the relatively small differences reflecting the fact that Doha is relatively flat.

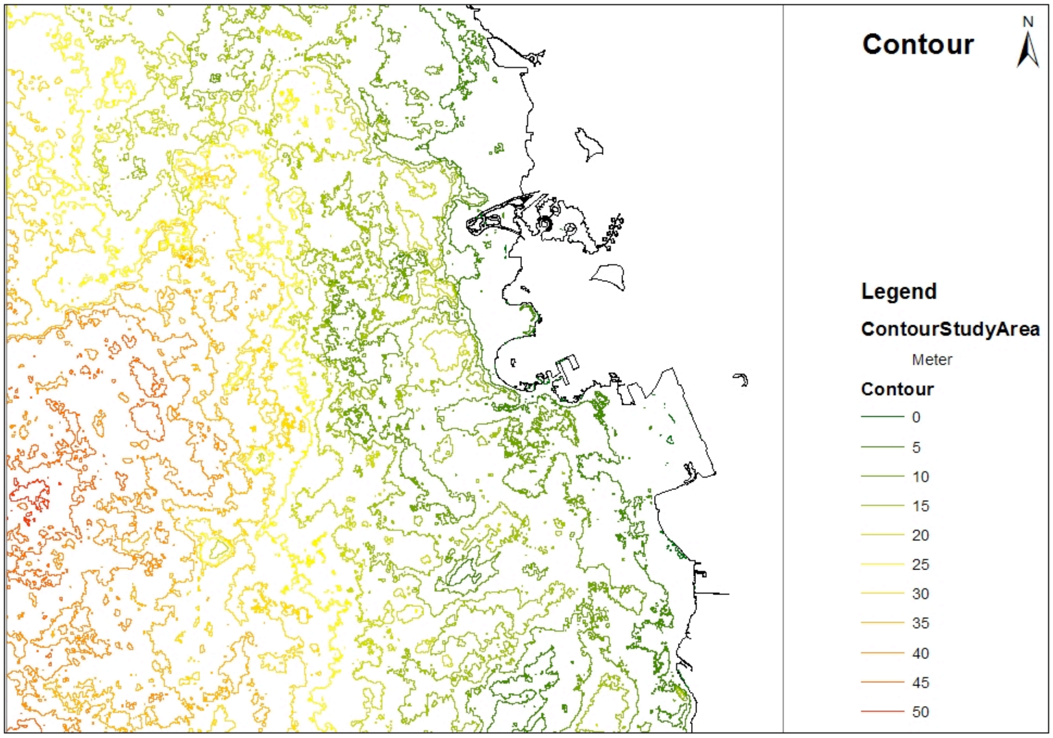


Figure 17. Topography (Source: Ministry of Environment).

3.5.4 Traffic Counts

By analyzing the volume of motorized traffic in the city and its effect on heat capacity in Doha, one can attempt to determine to what extent traffic adds to the UHI effect.

The Qatar Strategic Transport Model (QSTM) forecasts traffic volumes and, for the purposes of planning, offers a database containing information on population, employment, education, personal business, shopping and leisure for approximately 1350 Traffic Analysis Zones (TAZ). The TAZ planning data are derived from official land use maps published by the Urban Planning Department of the Ministry of Municipality and Environment. The Ministry of Transport and Communications makes use of forecasts in updating the QSTM, in addition to comprehensive census data collected in 2010, and plans for new urban development projects such as malls, schools, and so on. Human behavior is also incorporated as activity chains and time profiles in the model structure. The city's transportation systems are also encoded into the QSTM model.

- The components of the transportation system of Doha are classified as follows:
    - *Highway network:* there are five main freeways connecting Doha to other cities. These include the Al-Shamal highway, the Al-Khor expressway to the north of Qatar, and the Dukhan highway to the west. Finally, Wakrah-Messaid Road to the south and Salwa Road continue as far as the Saudi border.
    - *Ring roads:* there are circular routes acting as ring roads in Doha. These include the A Ring Road, B Ring Road, C Ring Road, D Ring Road, and E

Ring Road. Some of them are directly connected to highways (e.g. Al-Shamal highway connects to the D Ring Road), and most of them are characterized by congestion, especially during rush hour.

Figure 18. Roads in Doha (Source: Author).

Recently, Qatar has seen major improvements in its transportation infrastructure, with specific targets set for the years 2020 and 2030. These are largely intended to address needs related to the mega-event FIFA 2022 and to make progress toward fulfilling the Qatar National Vision.

Al-Shamal Road is the main road with the highest density of traffic in the city, followed by Salwa Road and the Al-Khor expressway. These roadways were selected for analysis in this study because of their heavy traffic. The goal is to determine how traffic relates to surface temperature, including that of the surrounding areas, to develop a better sense of the areas affected by traffic and the resultant exposure to car heat. The entire road that we investigated are =1 SVF.

Rush hour periods	Morning peak (AM) from 6:00 to 9:00	Mid-day peak (MD) from 11:00 to 14:00	Evening peak (PM) from 17:00 to 20:00
Al-Shamal Road	11000 cars	7000-10180 cars	7087 cars
Salwa Road	8871 cars	9189 cars	7580 cars
Al-Khor expressway	6012 cars	6365 cars	3647

Table 1. Traffic volume on main roads (Source: Ministry of Transport and Communications).

3.5.5 Satellite Data

In order to understand the thermal conditions in Doha, Landsat 8 images in the thermal bands were used. This analysis begins by converting digital data to radiation values, and then applying an atmospheric correction using appropriate values for several parameters. This results in more accurate land surface temperature readings. Images were taken at different times and on different dates in order to best understand how motorized transport generates heat. As discussed already, it is this heat that plays a major role in changing the microclimate and land surface temperatures, creating thermal differences that define the UHI. The raw data were measured using remote sensing and consisted of the following:

- Land surface temperatures: these characterize the UHI effect in Doha as well as UCI locations.

- Normalized Difference Vegetation Index (NDVI): this clarifies the amount of vegetation in Qatar, contrasting urban areas and desert.
- Doha Urban Expansion, 2003- 2016: Landsat images were obtained, and processed in ENVI with supervised classification techniques. These make use of multiple categories to identify urban areas, vegetation, and desert, with each of these characteristics being represented by a specific pixel.

All of the data just described were collected as row data, and then processed using the following calculations. The goal is this was to re-form the metadata into maps that represent surface temperatures, green areas and urban areas.

3.5.5.1 Measuring Normalized Difference Vegetation Index (NDVI)

NDVI is a numeric indicator representing ground parameters such as percentage of ground cover and vegetation. Landsat 8 images were downloaded as metadata and then processed using ENVI software, in particular bands (band 4 Red and band 5 Infrared), using the following equation:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

NDVI values range from -1 to +1. Negative values characterize water bodies, positive values represent high-density vegetation cover, and values closer to 0 represent bare soil.

3.5.5.2 Calculating Surface Temperatures Using Landsat Satellite Thermal Imagery

This study aims to investigate temperature differences in Doha due to the UHI that results from urban expansion and heavy traffic. Temperature data were analyzed along with map analyses covering long-term time periods throughout the years 2003 to

2016. Furthermore, analysis of surface temperatures during 2015 and 2016 were carried out in order to test Doha's UHI for long-term increases of heat, and to learn to what extent such changes have affected the city's microclimatic conditions. Such effects can be expected given the local context of urbanism and rapid growth, in which infrastructure and buildings are replacing the natural surface, thus affecting the land temperature.

Changes in land surface temperatures create microclimatic change, which results in increased energy consumption and at the same time contributes to various health hazards. Therefore a key question is whether or not there is in fact a consistently rising temperature in the Doha area. To determine whether or not traffic is leading to increased temperatures, the range of surface temperatures over the summer and winter of 2015-2016 was determined. This analysis was possible through the use of Landsat 8 images in the thermal band, as raw data downloaded from http://glovis.usgs.gov and subjected to research-based analysis using the ENVI program. The ENVI program was used to process the metadata provided on the website, resulting in land surface temperature maps. This use of Landsat images in the thermal band thus helped to identify and examine temperatures within the urban fabric. Moreover, the Geographic Information System (GIS) was used in order to examine possible correlations among Land Surface Temperatures (LST), traffic volume and the local topography.

3.5.5.3 Techniques for Satellite Image (Landsat 8) Data Sorting and Analysis

The research depended on analysis of Landsat 8 images using the ENVI program in the thermal band, and conversion of the thermal data into degrees following several steps using particular formulas. The following steps were followed in order to calculate land surface temperatures and produce maps, following procedures used by Coll et. al. (2010):

- Convert the digital number (DN) to radiance.
    - $CV_{R1} = gain * DN + bias$

Here, **CV$_{R1}$** is the cell value indicating radiance, **DN** is the cell value digital number, **gain** is the gain value for a specific band, and **bias** is the bias value for a specific band.

- Apply Atmospheric Correction.
    - $CV_{R2} = \frac{CV_{R1} - L\uparrow}{\varepsilon\tau} - \frac{1-\varepsilon}{\varepsilon} L\downarrow$

Here, **CV$_{R2}$** is the atmospherically corrected cell value as radiance.

CV$_{R1}$ is the cell value indicating radiance, as given just above.

L↑ is upwelling radiance.

L↓ is downwelling radiance.

τ is transmittance.

ε is emissivity (typically **0.95**).

- Convert radiance to degrees Kelvin.
    - $T = \frac{K_2}{\ln\left(\frac{K_1 * \varepsilon}{CV_{R1}} + 1\right)}$

Here, **T** is in degrees Kelvin, **CV$_{R1}$** is the cell value indicating radiance, and **ε** is emissivity (typically **0.95).**

- Convert Kelvins to degrees Celsius.

For **atmospherically corrected** data, the formula to convert radiance to temperature is

- $T = \frac{K_2}{In\left(\frac{K_1}{CV_{R1}}+1\right)}$

where **T** is degrees Kelvin and **CVR2** is the atmospherically corrected cell value indicating radiance.

3.5.5.4 Establishing Land Surface Temperatures

The satellite data (Landsat 8 images) were analyzed using the formulas and equations just given, in order to calculate land surface temperatures. The maps in Figures 19 and 20 show the results of these calculations, created from Landsat images by converting the thermal bands into land surface temperatures corresponding to the years 2015 and 2016. For LSTs corresponding to the years 2003 and 2016, see Figure 21.

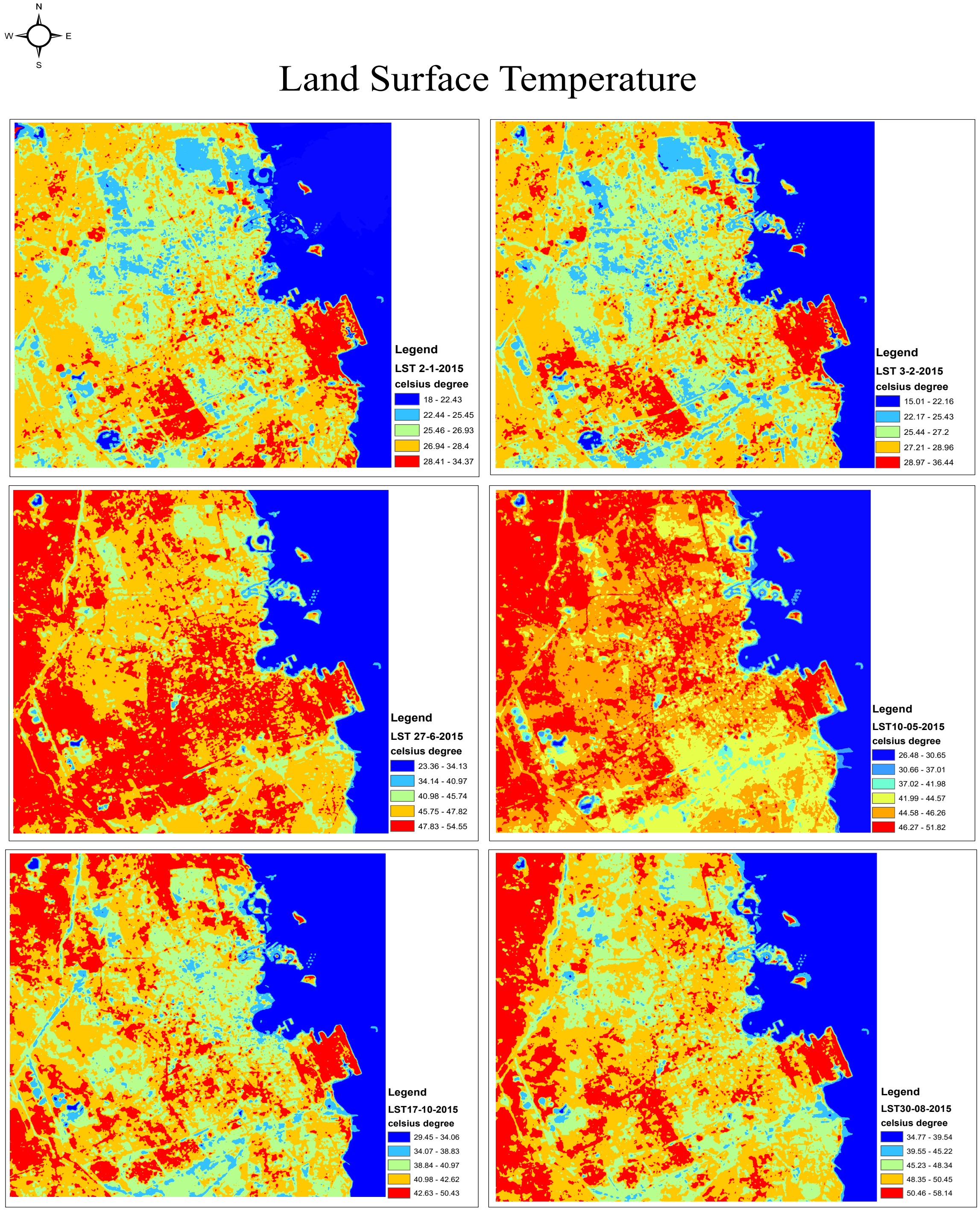


Figure 19. Doha land surface temperatures, 2015.

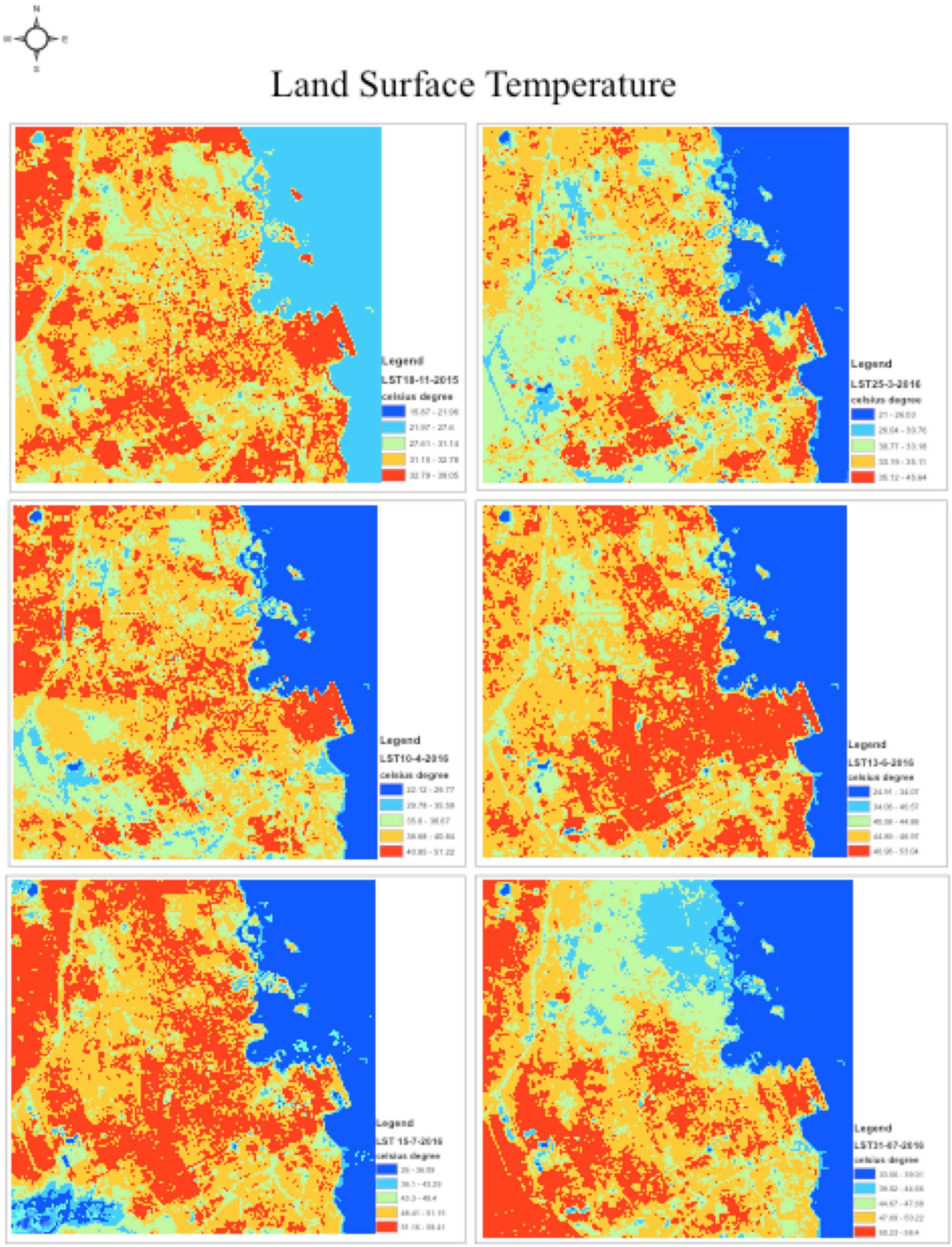


Figure 20. Doha land surface temperatures, 2015-2016.

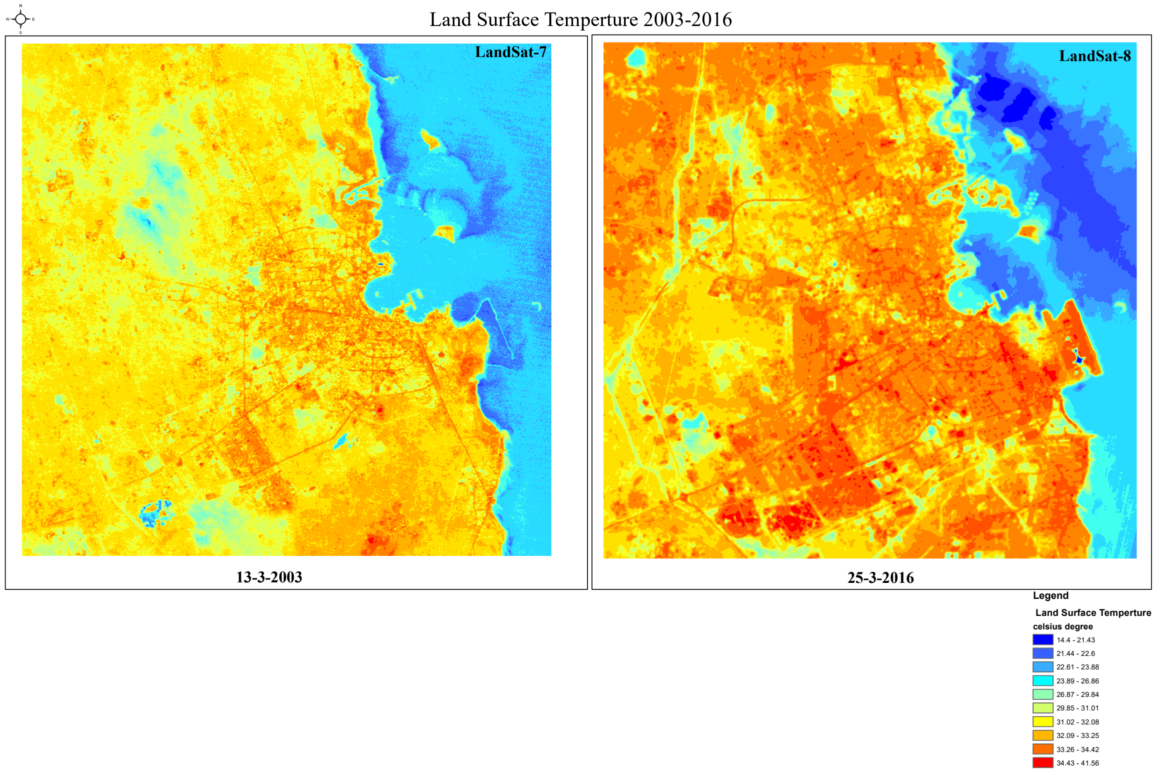


Figure 21. Doha land surface temperatures, 2003 and 2016.

3.5.5.4.1 Field Measurements

CR8000 measurements and a control data logger were used to determine the surface temperature at 10-minute intervals on selected roads, in order to understand how traffic volume relates to surface temperature, and the impact of this interplay on surrounding areas. These measurements also allowed a determination of the number of cars entering Doha during particular time periods. Furthermore, the data so collected made it possible to find out if discrepancies existed between satellite images and field measurements.

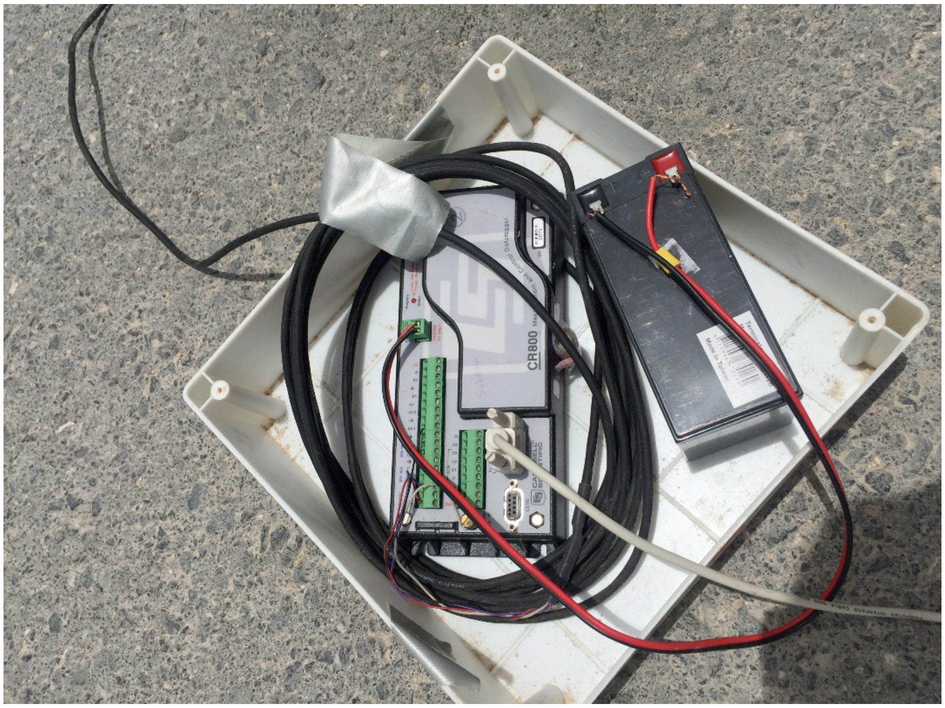


Figure 22. Data logger (Source: Author).

Table 2 presents measurements taken at Al-Khor Road, as discussed earlier when this study's data collection methods were outlined. The results show that the road surface does indeed reach high temperatures. The analysis presented in the next chapter makes use of the data presented in the table.

Date and Time	**Surface Temperature (degrees Celsius)**
Morning Measurements 28-5-2016	
5/28/16 11:10 AM	53.87
5/28/16 11:20 AM	53.8
5/28/16 11:30 AM	54.13
5/29/16 9:40 AM	46.74
5/29/16 9:50 AM	46.87
5/29/16 10:00 AM	47.72
5/29/16 10:10 AM	47.99
5/29/16 10:20 AM	49.1
5/29/16 10:30 AM	49.22

5/29/16 10:40 AM	49.53
5/29/16 10:50 AM	49.01
5/29/16 11:00 AM	48.94
Morning Measurements 15-7-2016	
7/15/16 9:10 AM	42.51
7/15/16 9:20 AM	46.56
7/15/16 9:30 AM	47.04
7/15/16 9:40 AM	47.89
7/15/16 9:50 AM	48.47
7/15/16 10:00 AM	49.09
7/15/16 10:10 AM	49.32
7/15/16 10:20 AM	50.22
7/15/16 10:30 AM	50.63
7/15/16 10:40 AM	50.18
7/15/16 10:50 AM	51.01
7/15/16 11:00 AM	51.23
Evening Measurements 15-7-2016	
7/15/16 7:00 PM	38.84
7/15/16 7:10 PM	38.72
7/15/16 7:20 PM	38.61
7/15/16 7:30 PM	38.51
7/15/16 7:40 PM	38.21
7/15/16 7:50 PM	38.07
7/15/16 8:00 PM	37.9
7/15/16 8:10 PM	37.78
7/15/16 8:20 PM	37.6
7/15/16 8:30 PM	37.63
7/15/16 8:40 PM	37.63
7/15/16 8:50 PM	37.46
7/15/16 9:00 PM	37.34
7/15/16 9:10 PM	37.29
7/15/16 9:20 PM	37
7/15/16 9:30 PM	36.89
7/15/16 9:40 PM	36.8
7/15/16 9:50 PM	36.62
7/15/16 10:00 PM	36.48
7/15/16 10:10 PM	36.36
7/15/16 10:20 PM	36.17
7/15/16 10:30 PM	36.16
7/15/16 10:40 PM	35.96
7/15/16 10:50 PM	35.88
7/15/16 11:00 PM	35.78
Morning Measurements 16-7-2016	
7/16/16 7:00 AM	37.7

7/16/16 7:10 AM	38.24
7/16/16 7:20 AM	38.93
7/16/16 7:30 AM	39.49
7/16/16 7:40 AM	40.01
7/16/16 7:50 AM	40.48
7/16/16 8:00 AM	41.1
7/16/16 8:10 AM	42.01
7/16/16 8:20 AM	42.33
7/16/16 8:30 AM	43.07
7/16/16 8:40 AM	43.67
7/16/16 8:50 AM	44.41
7/16/16 9:00 AM	45.2
Evening Measurements 16-7-2016	
7/16/16 7:10 PM	37.48
7/16/16 7:20 PM	37.48
7/16/16 7:30 PM	37.32
7/16/16 7:40 PM	37.25
7/16/16 7:50 PM	36.94
7/16/16 8:00 PM	36.74
7/16/16 8:10 PM	36.55
7/16/16 8:20 PM	36.38
7/16/16 8:30 PM	36.2
7/16/16 8:40 PM	36.24
7/16/16 8:50 PM	36.15
7/16/16 9:00 PM	35.7
7/16/16 9:10 PM	35.76
7/16/16 9:20 PM	35.5
7/16/16 9:30 PM	35.34
7/16/16 9:40 PM	35.21
7/16/16 9:50 PM	35.1
7/16/16 10:00 PM	34.87

*Table 2***.** Field data -- Ground measurement of surface temperatures (Source: Author).

3.6 Chapter Summary

This chapter described the theoretical and empirical framework of the present study. By outlining research approaches used to determine surface temperatures using remote sensing and GIS applications, the chapter explained how image metadata and field measurements were obtained. Furthermore, an overview was provided of the methods used to assess the impact of urbanization and traffic on the UHI in Doha.

In order to examine the effects of urbanization and motorized transportation within the UHI and its effect on microclimatic conditions in Doha, there was a need for temporal data, spatial data and satellite imagery. These permitted a clarification of the interactions of those factors, as well as “cause and effect” aspects of the UHI. This was also the case for the UCI effect and its relationship with land-use/land-cover (LULC) and motorized transportation and traffic.

Landsat 8 data obtained through remote sensing were also subjected to analysis. Row data in the thermal band were converted to degrees Kelvin and then to degrees Celsius, and Geographic Information System (GIS) data was incorporated. Data processing steps were presented which constitute the main tool utilized in examining these data and producing maps.

The hypotheses of the study are evaluated through data collection covering key parameters such as land use, land cover, traffic volume, and land surface temperature (LST), followed by analyses of those data. Processing and analysis of the obtained data provide the means to effectively evaluate (i.e. support or refute) the study hypotheses.

This chapter discussed the main sources from which data were collected, analysis of which should provide an understanding of the phenomena in question. This should make it possible to offer informed answers to the study's research questions. The next chapter presents analyses of the data and the findings of those analyses.

CHAPTER 4: ANALYSIS AND RESULTS

4.1 Introduction

This chapter presents outcomes of the analyses of the data collected for this study. The focus is on urban expansion and development in Doha from 2003 to 2016, and the resulting impacts on the city's UHI.

The rapid economic and population growth of Doha is a primary driver of the city's urbanization and development. NDVI[2] data clarify the extent of green areas in Doha; road surface temperatures, traffic volume, land surface temperatures, and development in the city are also relevant. The analysis, which focused on the period between 2003 and 2016, found that each of the just-mentioned factors plays an important role in the UHI. These variables have a connection with each other, as urbanization and congested roads contribute to the UHI effect in Doha.

Furthermore, surface temperature maps clarify the spatial variations in surface temperature in Doha, which determine the areas most affected by the UHI. In analyzing the surface temperatures of the hottest parts of Doha, it was decided that a focus on the most affected areas of UHI in relation to traffic volume might be informative. This was achieved using GIS tools to produce maps while taking into account the density of traffic in targeted areas of study.

To investigate how the city's vehicles contribute to the UHI, the study focused on locations with the heaviest traffic in the city of Doha. The focus was therefore on the three streets (Al-Shamal Road, Salwa Road, and Al-Khor) whose traffic volume was

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[2] Normalized Difference Vegetation Index

highest.

This chapter concludes with a review of the most important factors adding to the UHI effect. As part of this discussion, measurements of traffic volume and surface temperature are presented. As already discussed, the city’s transportation system profoundly affects the urban environment, in part through the heat generated by car engines, which strengthens the UHI effect.

4.2 Impact of Doha’s Urban Expansion from 2003 to 2016 on UHI

During the period 2003-2016, Doha experienced a major transformation through rapid urban development, and such development is known to increase the likelihood that heat islands will form. As Ponzini (2011) stated, “large scale projects are neither a new formula nor immune to uncertainties and imbalanced effects” (Ponzini, 2011). This implies that mega-projects have a limited number of actors, including government-linked companies with little or no public participation.

In Qatar “the separation between public and private sectors is practically non-existent because the actors have key positions in public decision making and in the management of private companies” (Ponzini, 2011). According to official statistics, Doha’s population has doubled from about 700,000 to 1.4 million during the last 15 years. In response, the MMUP initiated collaboration with a Japanese engineering conglomerate, Oriental Consultants, in 2005 to develop Qatar’s National Master Plan, in coordination with Qatar National Vision 2030 and the National Development Strategy of 2011-2016.

The growth of population and accompanying urbanization patterns has led to changes in local land use/cover. Figure 23 shows the urban environment in 2003. The implementation of mega-projects has reduced the city's open spaces since that time. Figure 24 displays the locations of new development areas, clearly showing the presence of urban expansion areas representing new mega-projects such as Lusail City, the Pearl (in the north of Doha), and Hamad International Airport. The implementation of new roads and highways is also clearly visible. These aspects of development have a substantial impact on the environment.

Figure 23. Doha, 2003 (Source: http://glovis.usgs.gov).

Figure 24. Locations of new developments, 2016 (Source: http://glovis.usgs.gov).

By using Landsat images, this study attempts to clarify the volume of urban expansion in relation to the UHI; Figure 25 shows the urban expansion map.[3] Every urban development affects the city's surface and environment, which and tends to warm the urban climate and raise the temperature of particular areas. How this plays out depends on many factors, including building forms, building materials, and energy consumption.

In addition, an increase in the number of commuters adds to the need for private cars, which in turn adds to the UHI and increases pollution levels. Because the city's expansion includes new roads and new urban areas, further increases in surface temperatures and reductions in the amount of open spaces are likely. One of the pillars of Qatar National Vision 2030 deals with the management of the environment, which involves controlled growth and attention to sustainable urban expansion.

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[3] The blue areas indicate urban areas as of 2003, while the red areas represent urban areas as of 2014.

Figure 25. Doha's urban expansion and development, 2003-2016 (Source: Author).

4.3 Estimates of Variations in Surface Temperature from 2003 to 2016

Land surface temperatures have been increasing along with the increasing amount of urban development in different parts of Doha. The average temperature has increased continually from 2003 to 2016, evidently due to the fast pace of urbanization. Figure 26 shows average temperatures over the past 13 years. The graph illustrates how land surface temperatures have fluctuated monthly in different years due to atmospheric conditions. For instance, on 13 March 2003, the highest recorded surface temperature was 41.5 °C; the corresponding figure for 25 March 2016 showed an increase to 45.6 °C. The land surface temperature in 2015 decreased to 36.6 °C on 3 February 2015 before then hitting a peak of 51.8 °C on 10 May 2015.

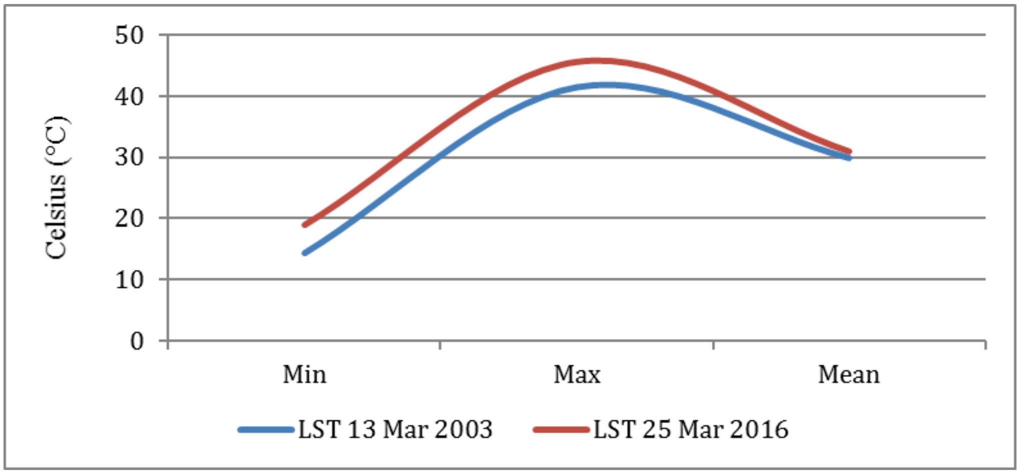

Figure 26. Land surface temperatures, 2003 and 2016 (Source: Author).

The mean temperature increased by approximately 5 °C during the period 2003-2016 in urban areas of Doha. Figure 27 presents land surface temperature maps, using the thermal band of Landsat 7 data for 2003 and Landsat 8 data for 2016 (the most recent imagery available). The increase in UHI is due to many factors, the most important among them being the city's rapid urbanization since 2003.

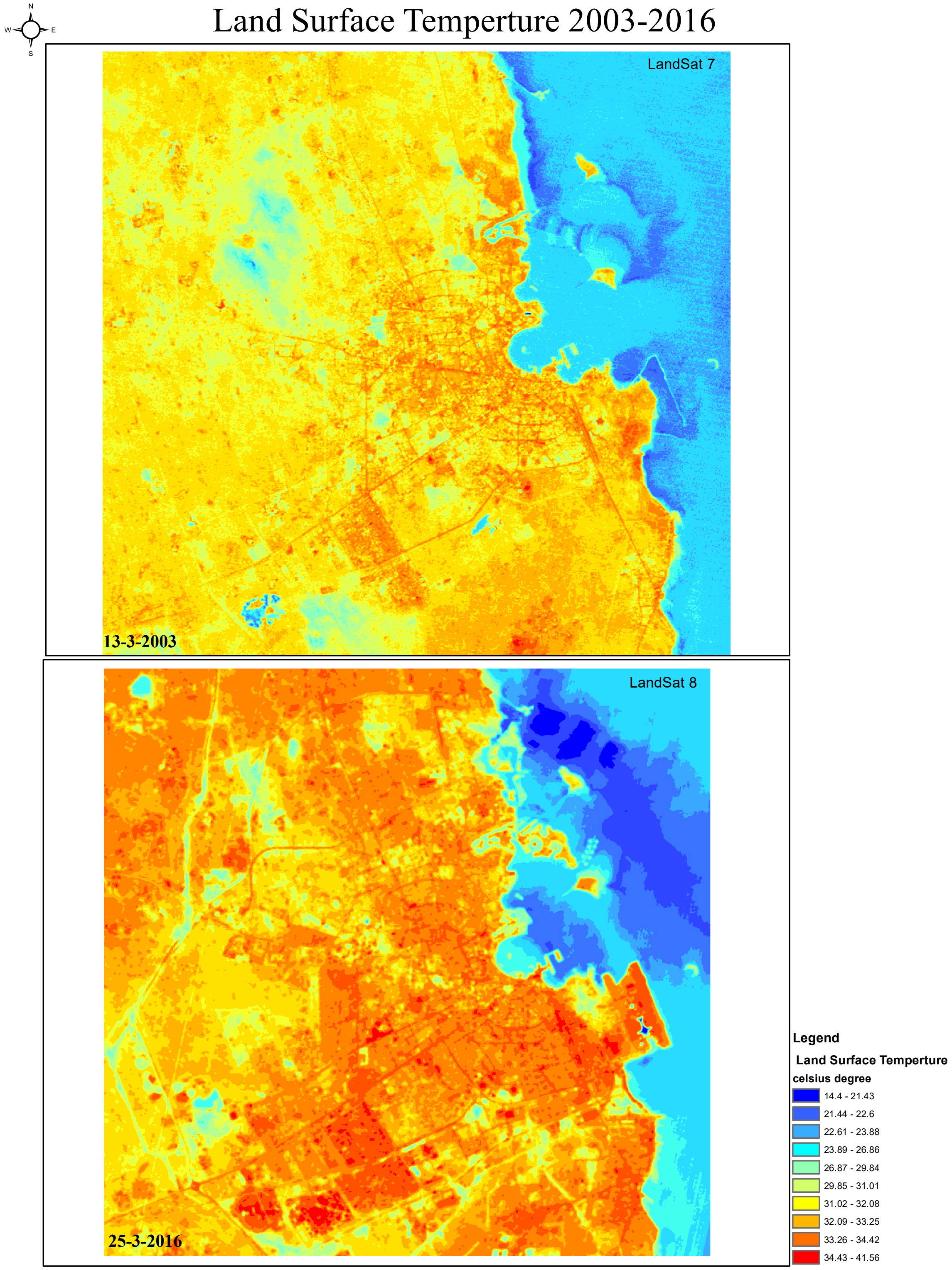

Figure 27. Land surface temperatures, showing the increase of UHI in Doha from 2003 to 2016 (Source: http://glovis.usgs.gov; metadata processed by Author).

These maps make clear that surface temperatures are increasing in Doha, especially in areas with heavy human activity. Such activity includes commuting by vehicle, industrial activity, and airport traffic. Heat-affected areas in Doha also include coastal areas, although these tend to benefit from the sea breeze, which enhances thermal comfort.

Figure 28 shows clearly that an increase in urban projects leads to a stronger UHI effect; the number of heat islands at present is visibly greater than it was in the past. It is also clear that the addition of new roads and urban settlements likewise strengthens UHI effects. In short, urban areas play a major role in the creation of UHIs.

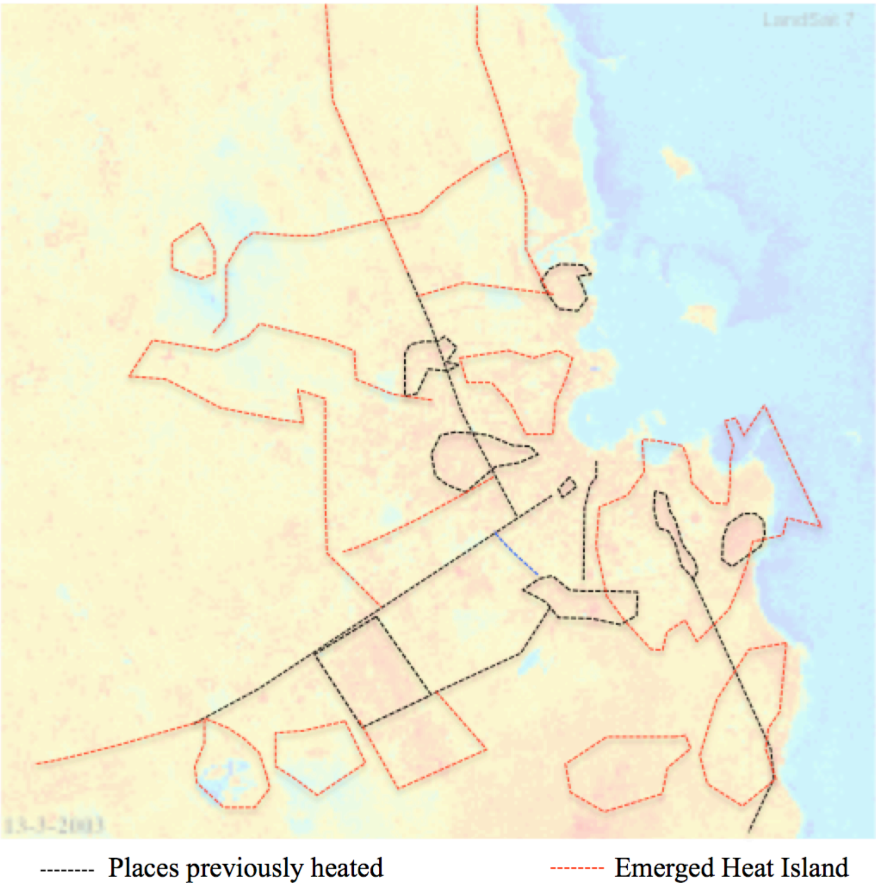

Figure 28. Extent of heat island effect in Doha (Row Source: http://glovis.usgs.gov processed by Author).

Urbanization patterns have been changing the land surface in Doha, adding new buildings and typology that generate more heat. UHI effects are greater in the inland parts of the city, which affects the outdoor thermal environment in those areas. Figure 29 depicts a cross-section of Al-Shamal Road in 2003, showing the presence of trees. Trees are valuable in that they lead to lower car speeds and enhance the urban thermal environment.

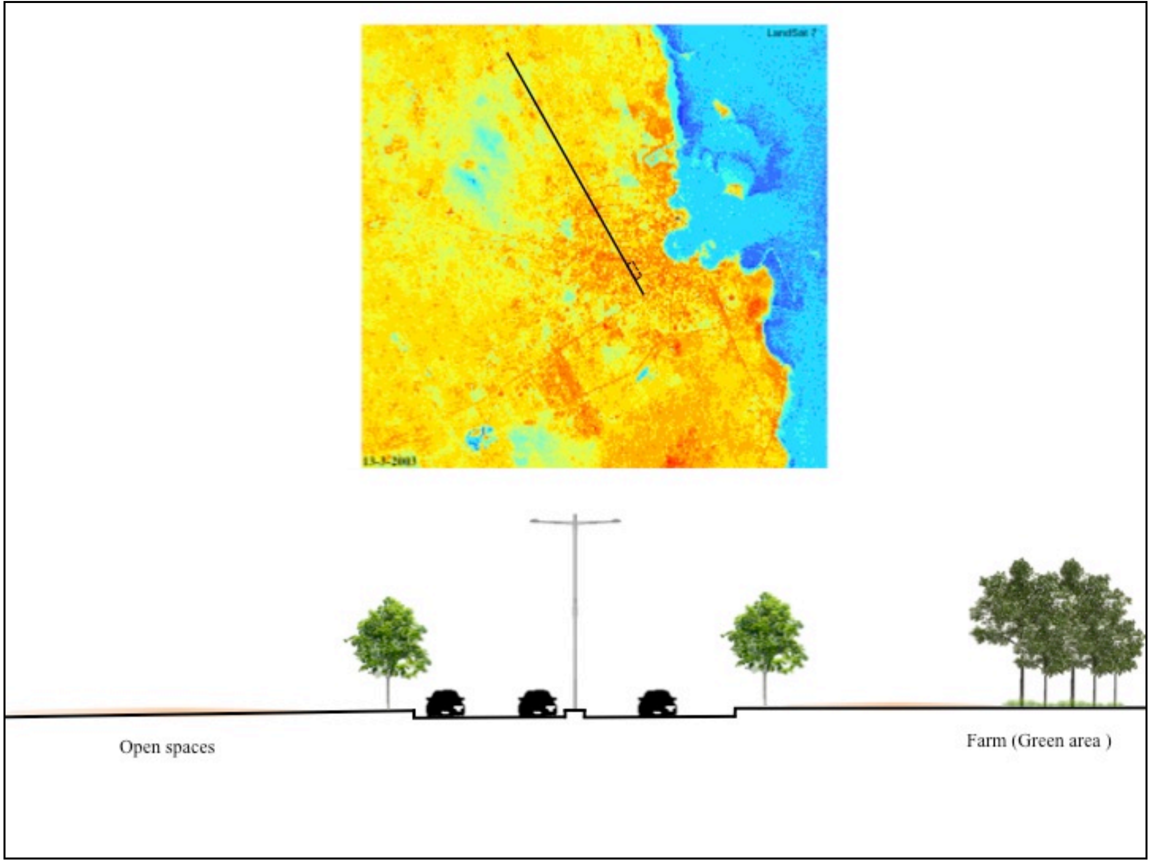

Figure 29. Al-Shamal Road cross-section, 2003 (Source: Author).

Figure 30 shows a similar cross-section of Al-Shamal Road in 2016. At this point in time, the roadway has been widened to accommodate three lanes, allowing an increase of traffic capacity. In addition, the replacement of the green areas with buildings increases the likelihood that urban areas near the road will undergo warming. The new buildings also reflect population growth and increased urban density, which also tend to increase a city's heat. The decreases in open spaces along the city streets result in urban canyons, which, along with building forms and materials, play a major role in influencing UHI effects.

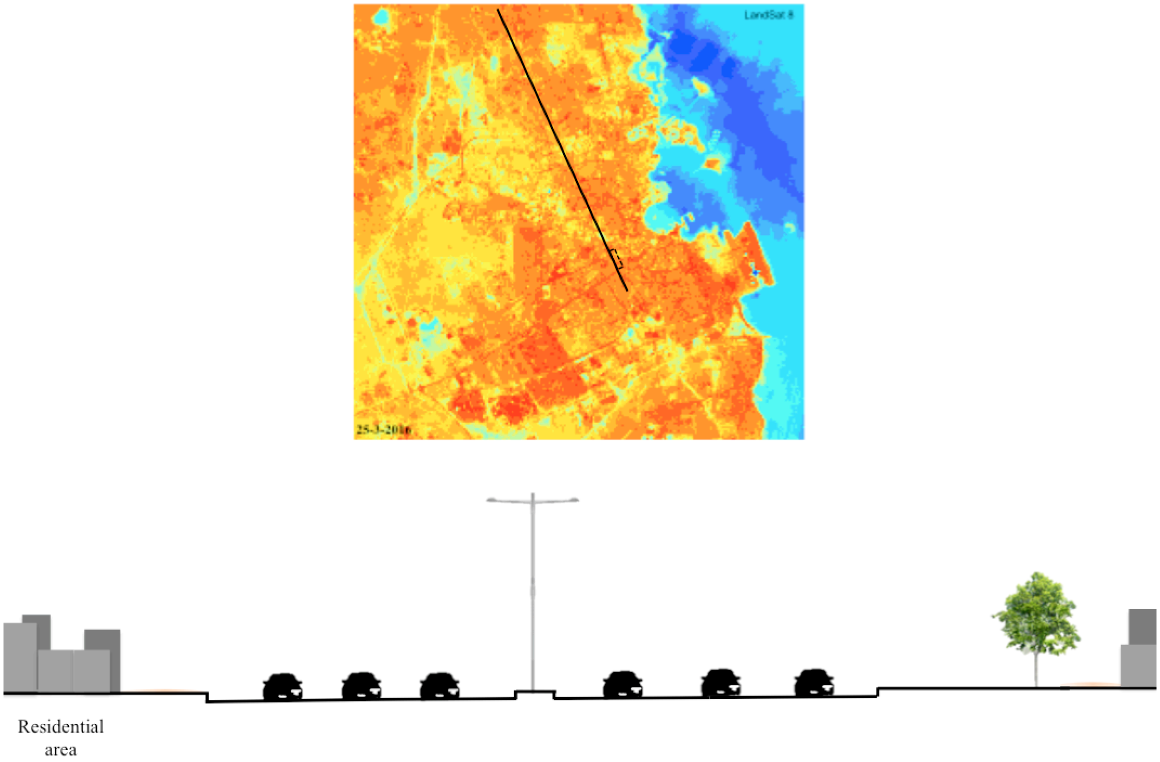

Figure 30. Al-Shamal Road cross-section, 2016 (Source: Author).

Building materials absorb solar radiation during the daytime and the resulting heat is released at night, which increases nighttime temperatures in the city. More generally, the temperature tends to increase in the presence of large-scale human activity such as commuting and urbanization. Topography is another key parameter that might be expected to affect the local microclimate, because topography greatly affects airflow (Tsilini, 2015), and lower land areas tend to have higher temperatures than areas at higher altitudes. However, Doha’s topography in fact has a relatively minor effect on local surface temperatures, because the land in Qatar is relatively flat.

Analysis of streets with heavy traffic provides a general understanding of how they and their surroundings are affected by UHI effects. Creation of green areas incorporating trees to produce shade decreases temperatures, enhances microclimatic conditions, and thus weakens UHI effects; conversely, UHIs are more likely to exist when green areas and water bodies are reduced in number or extent (Radhia, 2013).

4.3.1 Spatial Variations in Urban Land Surface Temperature, 2015 – 2016

Surface temperatures are greatly affected by atmospheric conditions as well as human activity, and also vary by season. The analyses of surface temperature maps for 2015 and 2016 that will be presented here provide an important illustration of UHI variation. Furthermore, an analysis of Land Surface Temperatures (LST) will permit a detailed overview of temperature patterns in Doha and the effect of green areas.

In 2015, Doha's LST pattern showed significant variation. This was due to many factors, including some particularly high air temperatures that are evident in the temperature data. It can be seen that the temperature started to increase in May, reached a peak in July, and then declined from October to January. Many areas in Doha acted as hot spots throughout the year. The images shown on the next few pages show LSTs during 2015 and 2016.

In January 2015, surface temperatures were high in very active areas such as central Doha and regions undergoing large-scale construction. In addition, the road network showed higher temperatures than nearby areas, reaching 34 °C and increasing gradually to around 36 °C by February 2015. Figure 31 shows surface temperatures in January and February 2015. Temperatures then continued to increase, reaching 45 to 48 °C on 10 May 2015, and exceeding 50 °C on 27 June 2015 in the town center. Figure 32 shows surface temperatures in May and June 2015. The surface temperature was clearly highest during the summer, reaching 48 to 50 °C in June and 47 to 54 °C in August. Figure 33 shows surface temperatures in August and October 2015. Surface temperatures in May and June are warmer than those in August, while in contrast, air temperatures are higher in August, as shown in Figure 34.

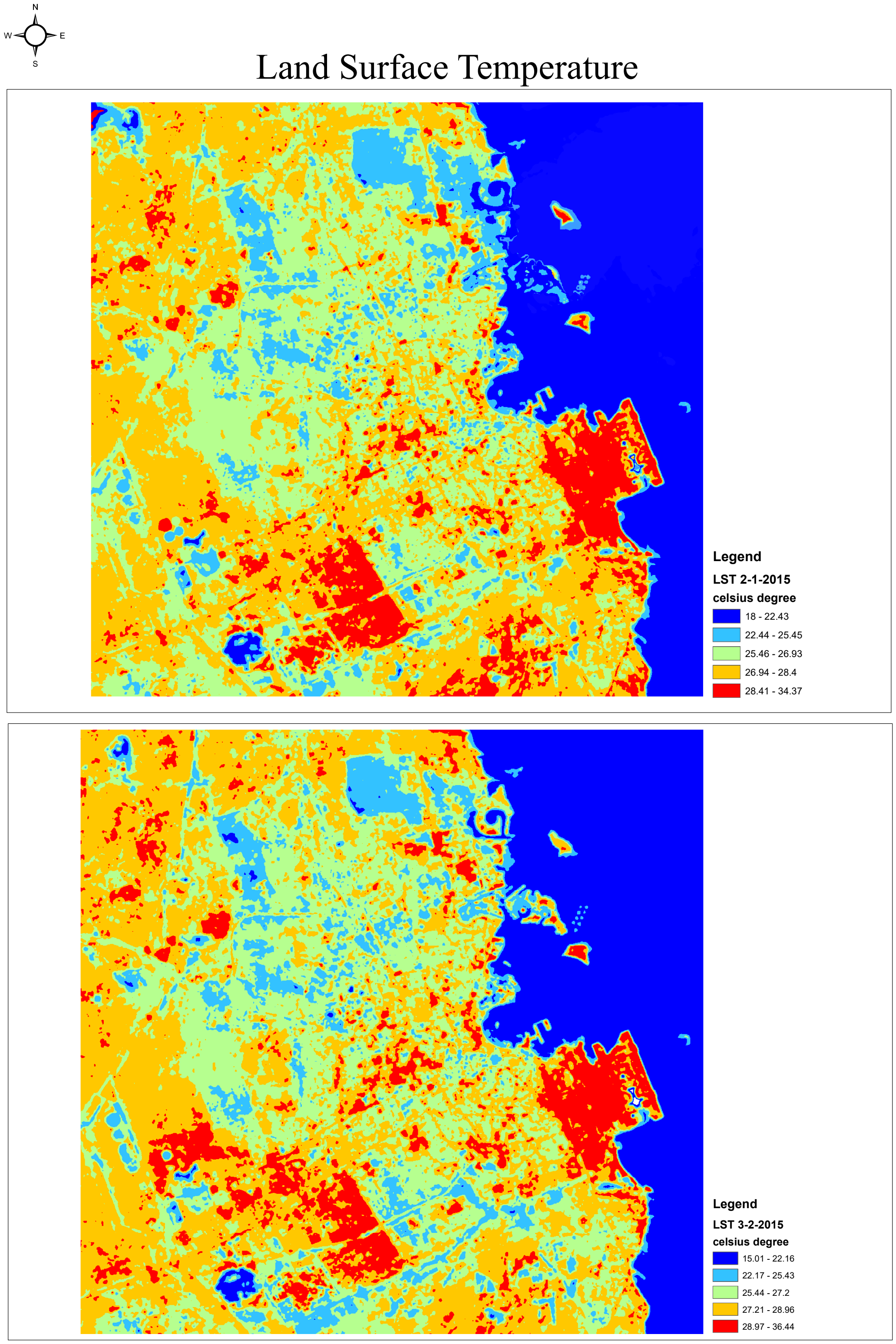

Figure 31. Surface temperatures in January and February 2015 at 10am; the heat island effect is about the same (Source: http://glovis.usgs.gov; metadata processed by Author).

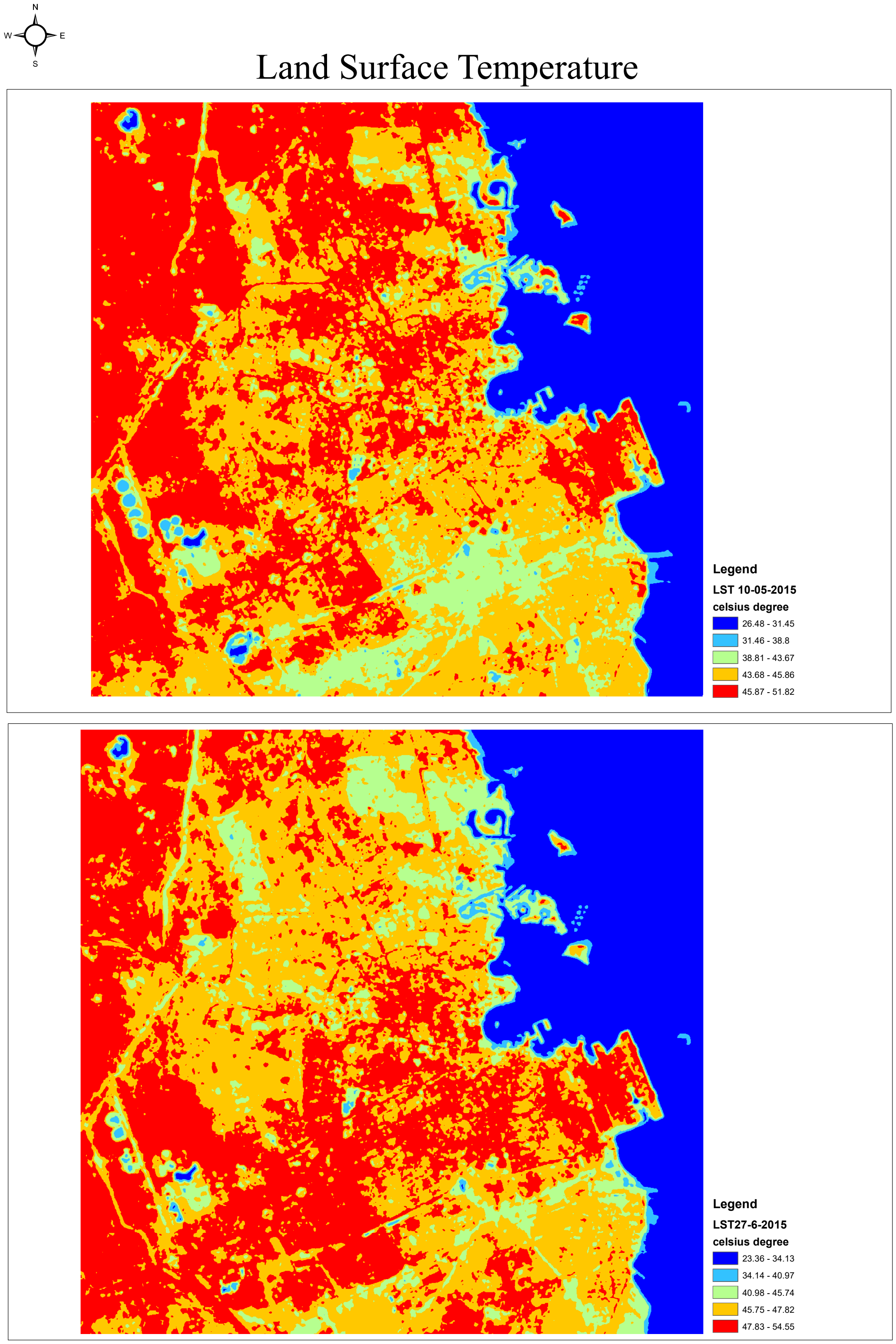

Figure 32. Land surface temperatures in May and June 2015; the surface temperature rises in June at 10am (Source: http://glovis.usgs.gov; metadata processed by Author).

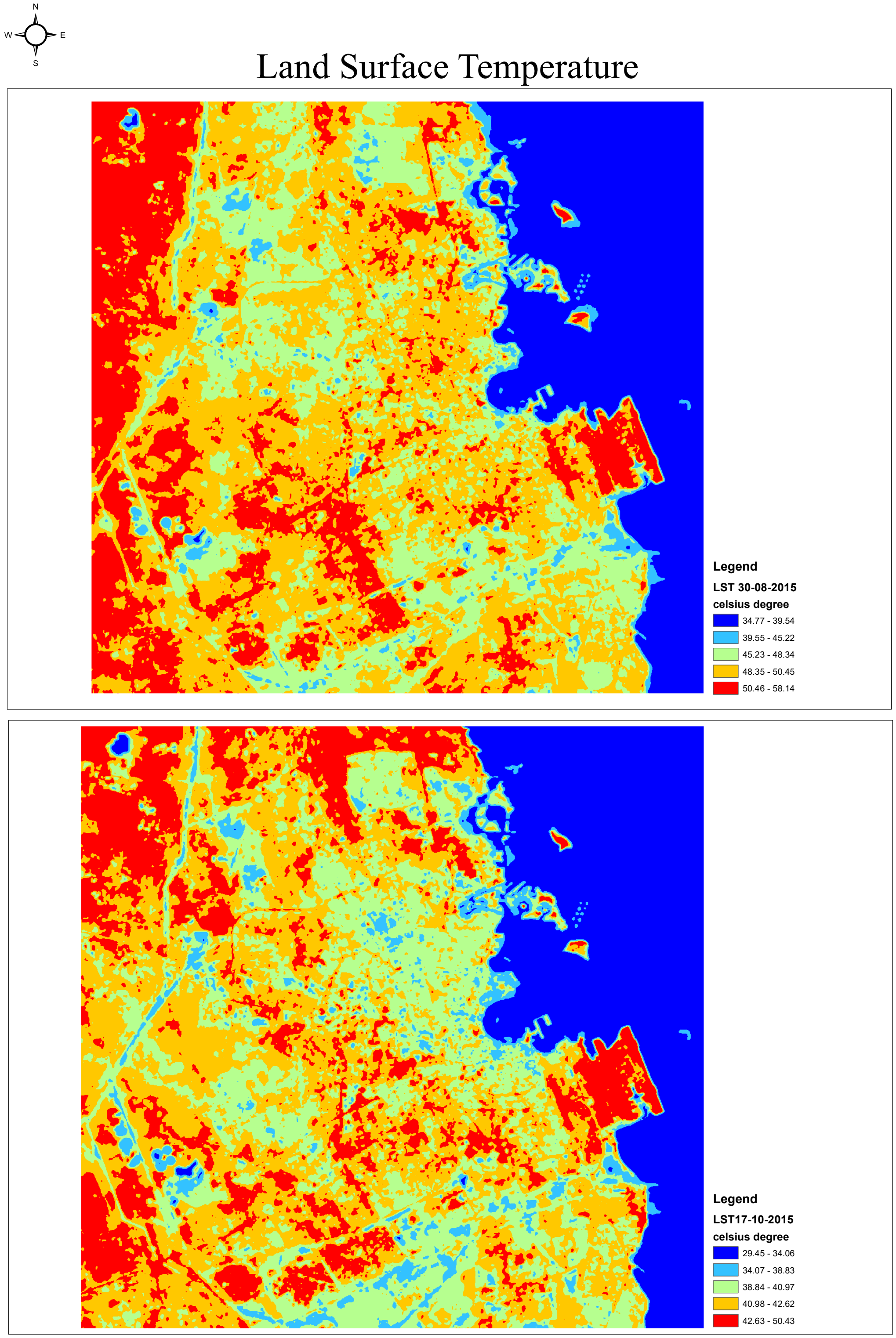

Figure 33. Surface temperatures in August and October 2015 at 10am; the surface temperature in August is lower than in May and June (Source: http://glovis.usgs.gov; metadata processed by Author).

The absence of cars reduces the surface temperature of roads. Consequently, land surface temperatures in August are lower because that is a vacation period during which car traffic is reduced. Because road surface temperatures do not indicate a heat island effect during this time, this is clear evidence that cars are a primary contributor to the UHI effect in Doha.

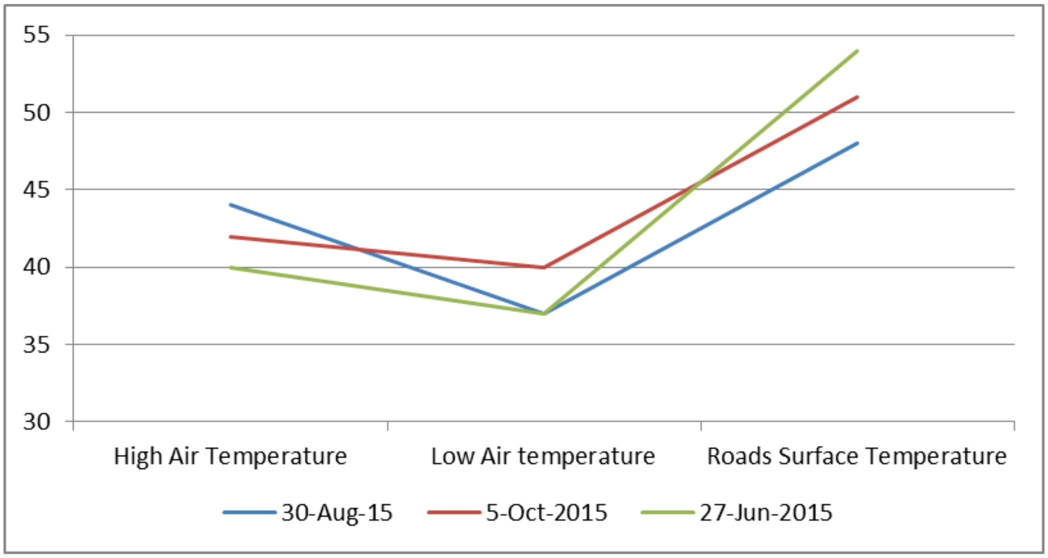

Figure 34. Air temperatures and road surface temperatures in August, October and June 2015; in August, air temperature is highest while road surface temperature is lower (Source: QMD).

On 18 November 2015, surface temperatures decreased and the highest temperature recorded was 39 °C. These measurements were taken in urban areas of Doha consisting of roads and their immediate surroundings, regions where the relative amount of human activity tends to be greater.

In winter of 2016, the only available images from the Glovis website were taken in March and April, because the sky over Doha was generally not clear during the winter of that year. On 25 March 2016, the temperature was relatively high at 45 °C, indicating that surface temperatures had already started to increase in March. Figure 35 shows surface temperatures in November 2015 and March 2016.

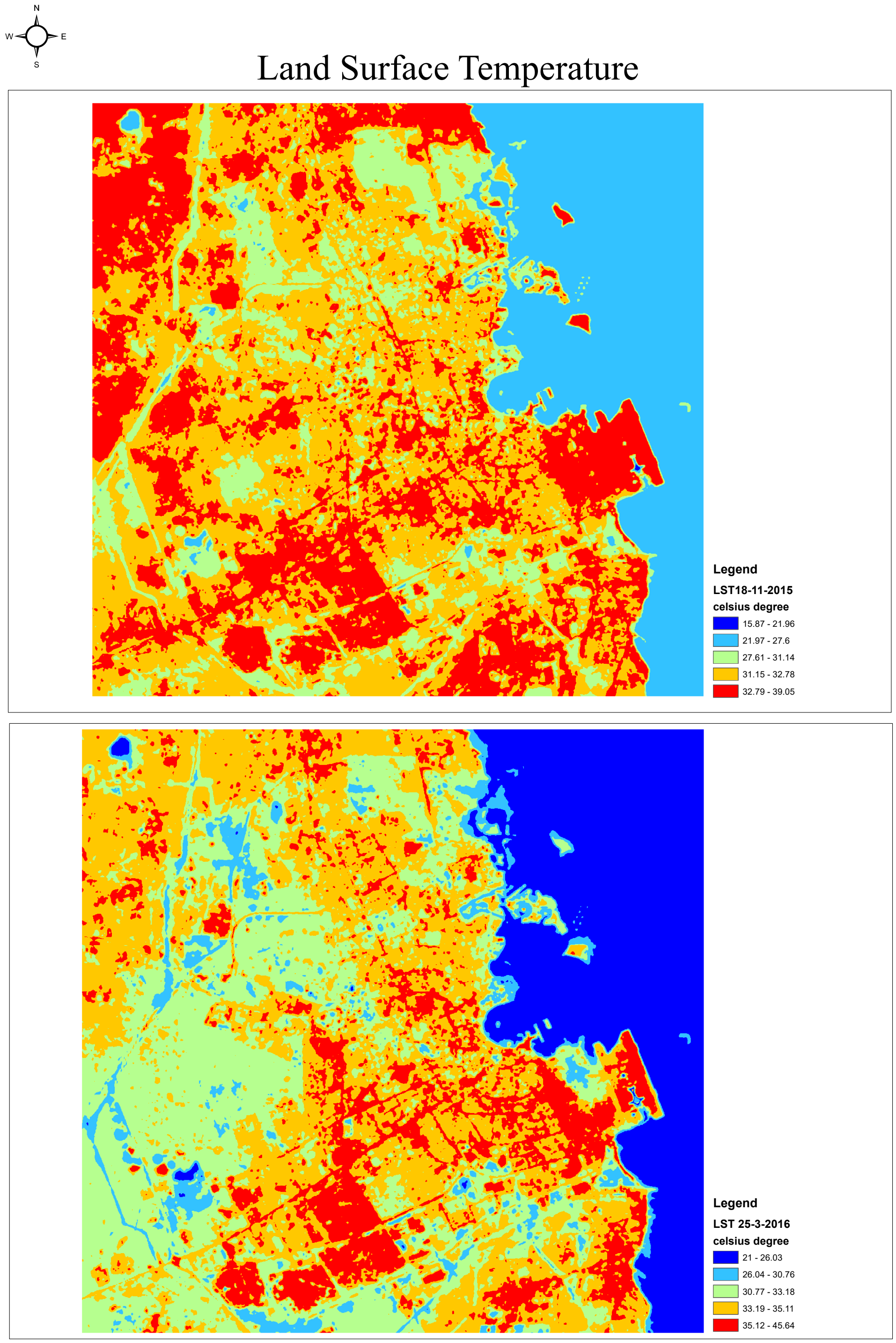

Figure 35. Surface temperatures in November 2015 and March 2016 at 10 am; temperatures start to rise in March (Source: http://glovis.usgs.gov; metadata processed by Author).

Surface temperatures then continued to increase, reaching 51 °C on 10 April 2016, the highest temperature recorded that month, and regularly exceeded 50 °C during the summer. Furthermore, land surface temperatures tended to be higher in areas with compact urbanization lacking open spaces, and in areas with large-scale construction, as shown in Figure 36. The figure shows that areas surrounded by open spaces tended to record lower temperatures. On the other hand, water elements, acting as cool islands, reduce surface temperatures. Every newly developed urban area showed an increase in heat, reflecting a number of factors including a decrease in open spaces and an increase in the need for private cars (Hassan, 2015).

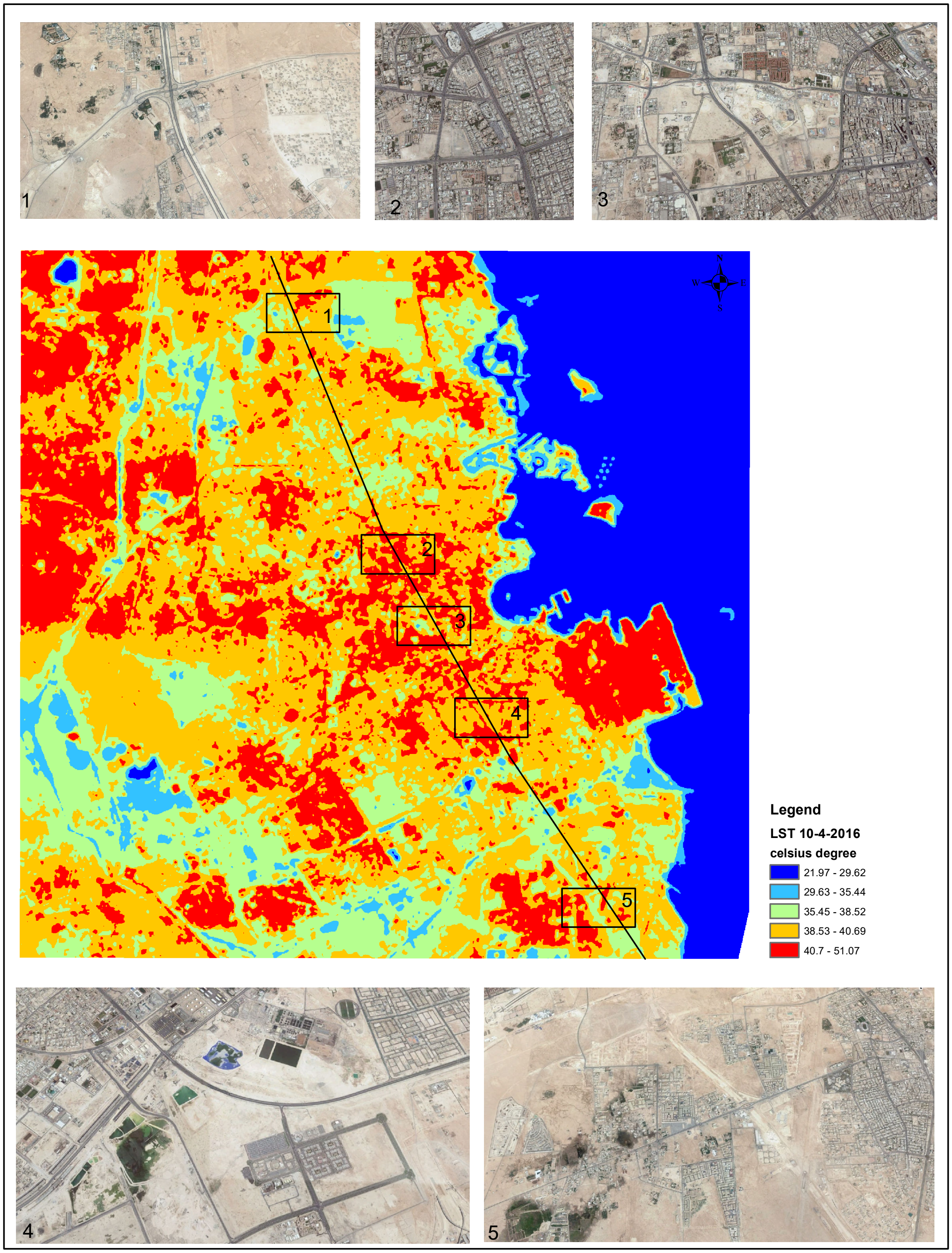

Figure 36. Cross-section of Al-Shamal Road and surrounding regions; urban areas recorded higher temperatures than areas surrounded by open spaces (Source: http://glovis.usgs.gov and Google Maps; processed by Author).

On 13 June 2016, most urban areas exhibited high temperatures, with a peak recorded at approximately 53 °C. Figure 37 shows surface temperatures in April and June 2016. Temperatures in the urban business center of Doha and its affiliated roads exceeded 50 °C; these areas showed the strongest UHI effects on 15 July 2016. Temperatures showed a decrease in urban areas and roads on 16 August 2016, especially in the north. Figure 38 shows surface temperatures in July and August 2016. Surface temperatures in August 2015 were generally lower than in August 2016, but still reflected lower temperatures on Doha roads.

In the summer of 2016, urban areas recorded particularly high temperatures due to the atmospheric conditions prevailing at that time, namely high air temperatures. Moreover, areas with large-scale construction work recorded even higher figures.

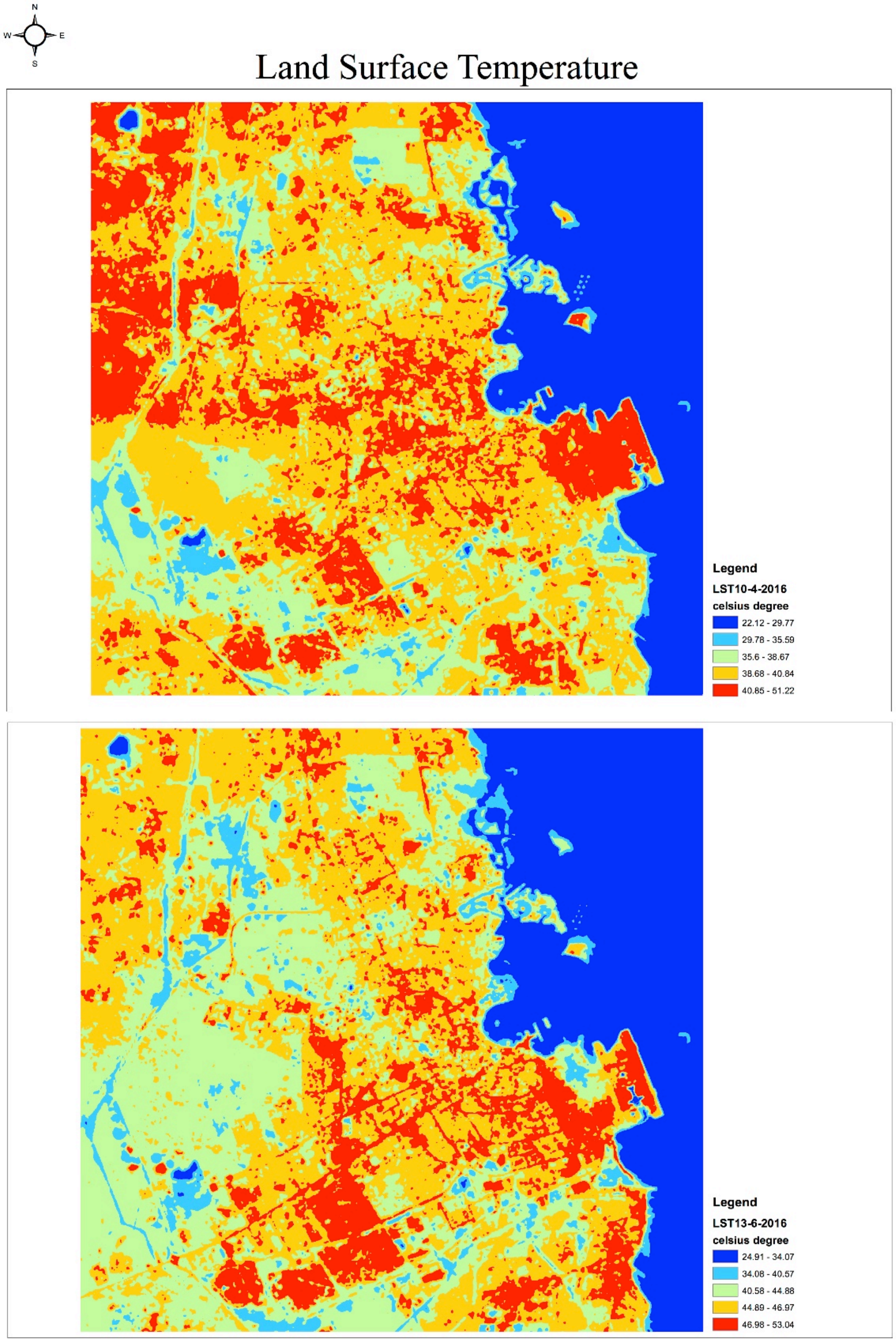

Figure 37. Surface temperatures in April and June 2016; the temperature increases in June; particularly on roads (Source: http://glovis.usgs.gov; metadata processed by Author).

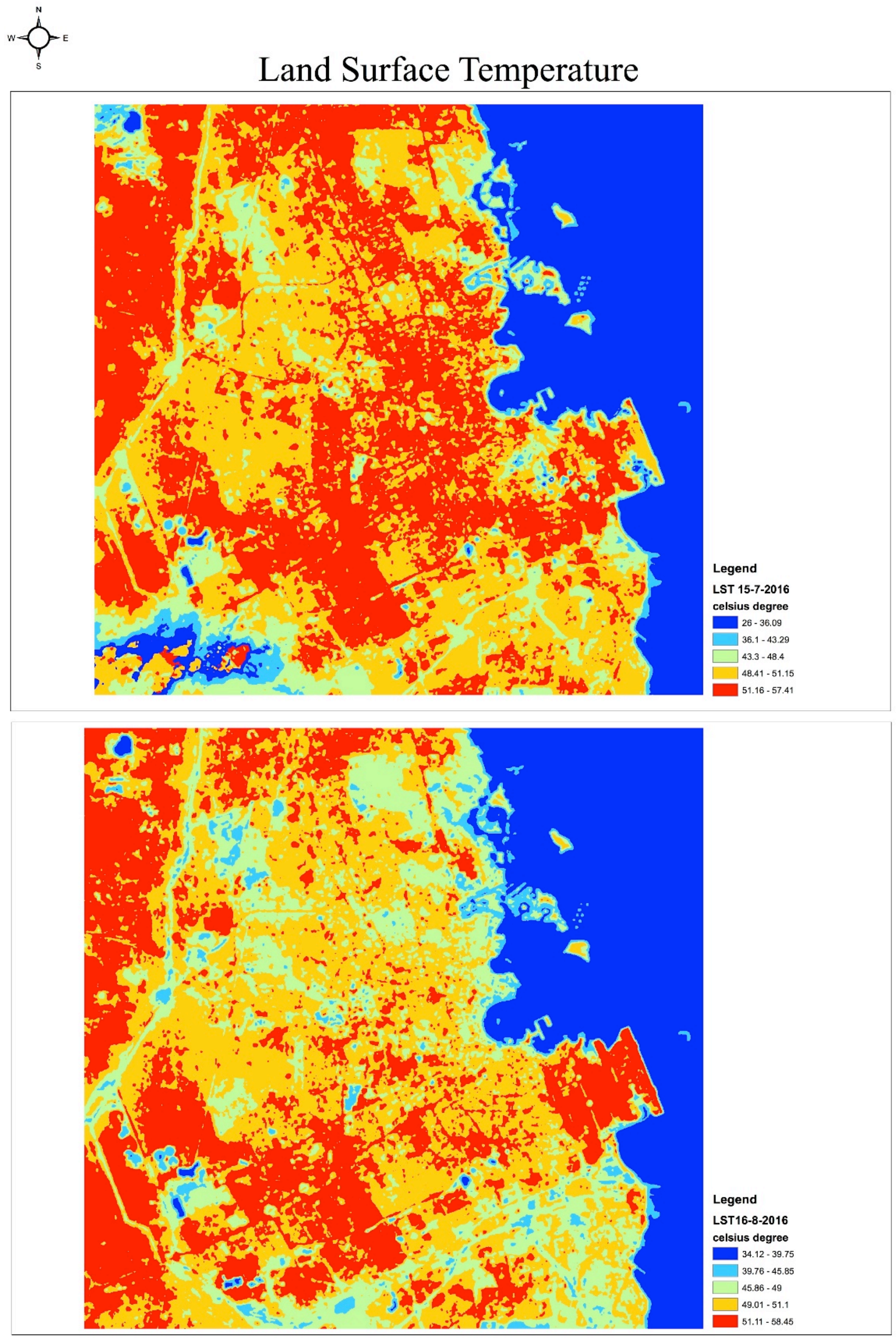

Figure 38. Surface temperatures in July and August 2016; the surface temperature in August is lower than in July. (Source: http://glovis.usgs.gov; metadata processed by Author).

The UHI effect can be partially attributed to the dark pavements commonly used on streets and parking lots. Roads are relatively easy to identify on the maps shown in Figure 39. Also, the effects of new roads can be clearly seen in the urban expansion that had occurred as of 2016, for which heat levels were elevated by approximately 3 to 5 ◦C, relative to the surrounding areas. This heat affects the surrounding urban environment and microclimatic conditions. As explained earlier, the heat island effect is driven by solar radiation and urban emissions. This leads to temperature increases in the city center, by as much as 5 degrees Celsius, relative to the surrounding areas (Lehmann, 2010).

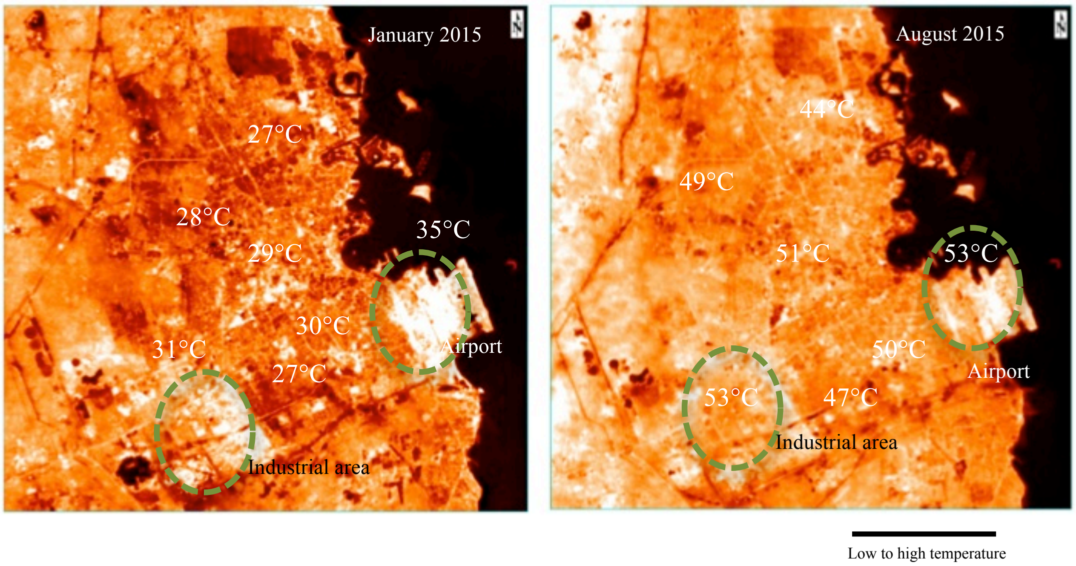

Figure 39. Doha Land Surface Temperature (LST) maps (Source: http://glovis.usgs.gov; metadata processed by Author).

From the foregoing, it is clear that a UHI effect exists in Doha. UHIs are mainly found in the center of Doha’s urban areas, in the vicinity of commercial zones, business centers, Doha's international airport, industrial areas, and areas in which large-scale construction is taking place.

Some root causes of the UHI are not very easy to mitigate; these include the presence of buildings, human activities that release thermal energy, land cover, street signs and building materials that generate heat. On the other hand, cool islands that persist even in the hottest months are located in and around coastal areas, farms, green areas, and other places containing water elements. Open spaces and green areas play an especially crucial role in decreasing heat.

4.3.2 Percentage of Green Area Density in Doha City

Normalized Difference Vegetation Index (NDVI) is a key graphic indicator that uses remote sensing to determine the density of green vegetation in a given region. The percentage of Doha's surface area containing green vegetation is relatively low at 5.71%; see Figure 40. The NDVI is calculated by determining the relative amounts of green and urban coverage in a given study region.

Increasing the number and extent of green areas, such as by planting trees, is generally a key requirement in efforts to reduce a city's heat, and also has the effect of enhancing the urban environment. As noted earlier, materials used in urban settings tend to absorb more solar radiation than green areas do.

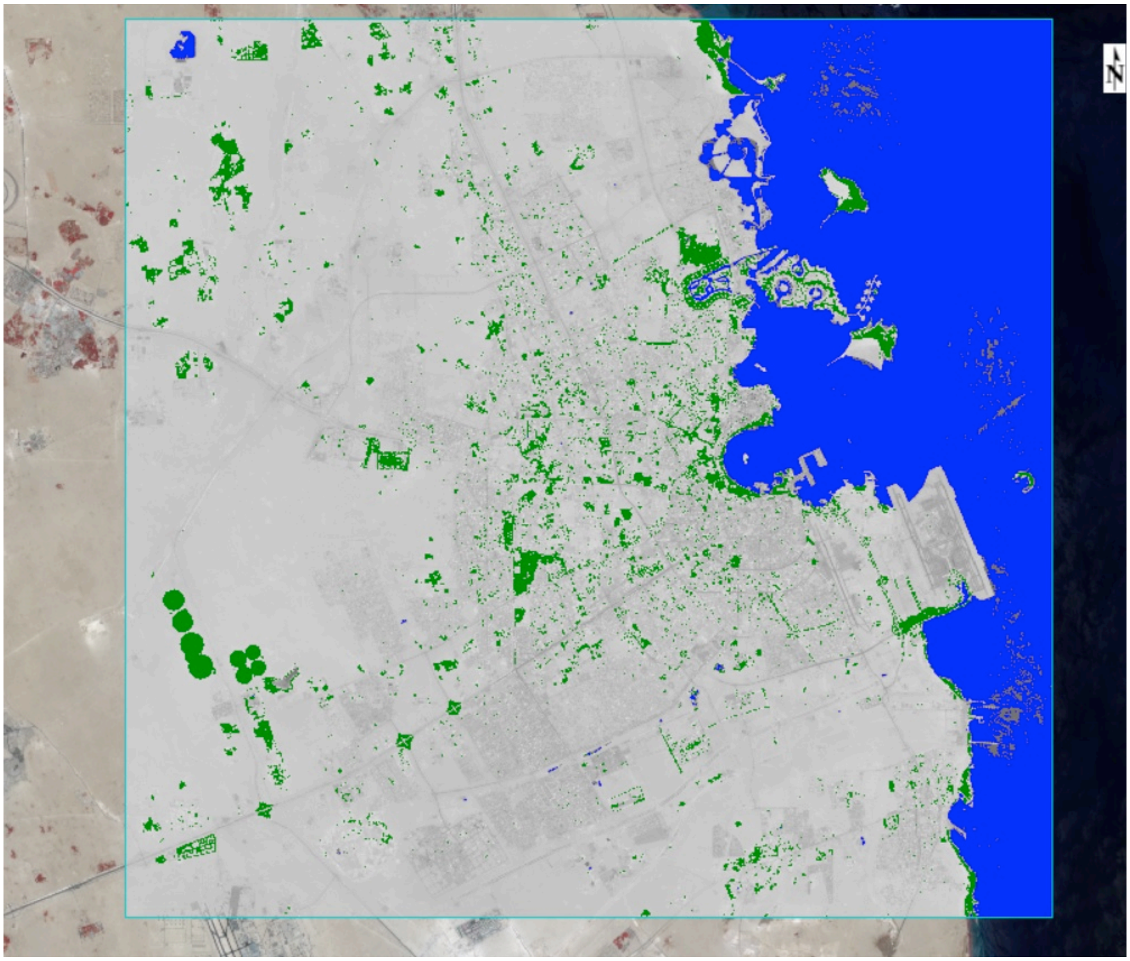

Figure 40. Doha green area mapping using NDVI tools; the percentage of green areas in Doha is 5.71% (Source: http://glovis.usgs.gov; metadata processed by Author).

A study carried out by Armson et. al. (2012) found that areas with grass recorded higher temperatures than those with trees, and had a relatively minor effect on human thermal comfort. However, areas with trees providing shade can reduce temperatures by approximately 5 to 7 °C, thus enhancing the urban climate (Armson et. al., 2012).

The temperature of green areas is generally lower than that of areas with typically urban surfaces. This difference varies, but is usually in the range of 4 to 6 °C. Green areas with trees tend to reduce the UHI effect, as the shading provided by trees has a cooling effect and enhances microclimatic conditions in the adjacent urban area. People's thermal comfort thus benefits from green areas. An analysis of land surface temperatures indicates that green urban roads – those having trees on both sides -- have lower temperatures than other streets do. Furthermore, green areas at Hamad Airport had a recorded average temperature of 43 °C, which is lower than the rest of the airport surface temperature by about 10 °C.

Green areas that include trees thus function as UCIs, lowering air temperatures and enhancing microclimatic conditions in urban areas.

4.4 Variation in Doha Road Surface Temperatures, 2016

Urban road networks in Doha paved with dark surface material impart a great deal of heat to the city, especially at night. As a large proportion of urban surfaces is covered, there is a great capacity for the absorption of solar radiation.

Temperatures in Doha in 2016 have been high, especially on urban roadways. Determining road surface temperatures helps us to understand the heat variation of such temperatures during the year. Most main roads in Doha showed high temperatures during both the summer and winter, and those with heavy congestion and high traffic volumes recorded even higher temperatures throughout the year.

Figures 41 and 42 show temperatures on Doha's road networks. Surface temperatures are elevated in places that have heavier traffic volume. This adds to the UHI effect, especially during periods of particularly heavy congestion, i.e. traffic jams. In such situations, car engines produce heat that raises surface temperatures. These places can be considered the hottest areas in Doha, recording high temperatures throughout the year, as can be seen in the Landsat images.

What follows is an analysis of traffic volume in Doha and its relationship with the UHI. Remote sensing provides an aerial, large-scale view of surface temperatures, showing how heat is distributed over wide areas. This analysis also takes into account the temperatures of other urban features including walls, green areas, and shaded locations.

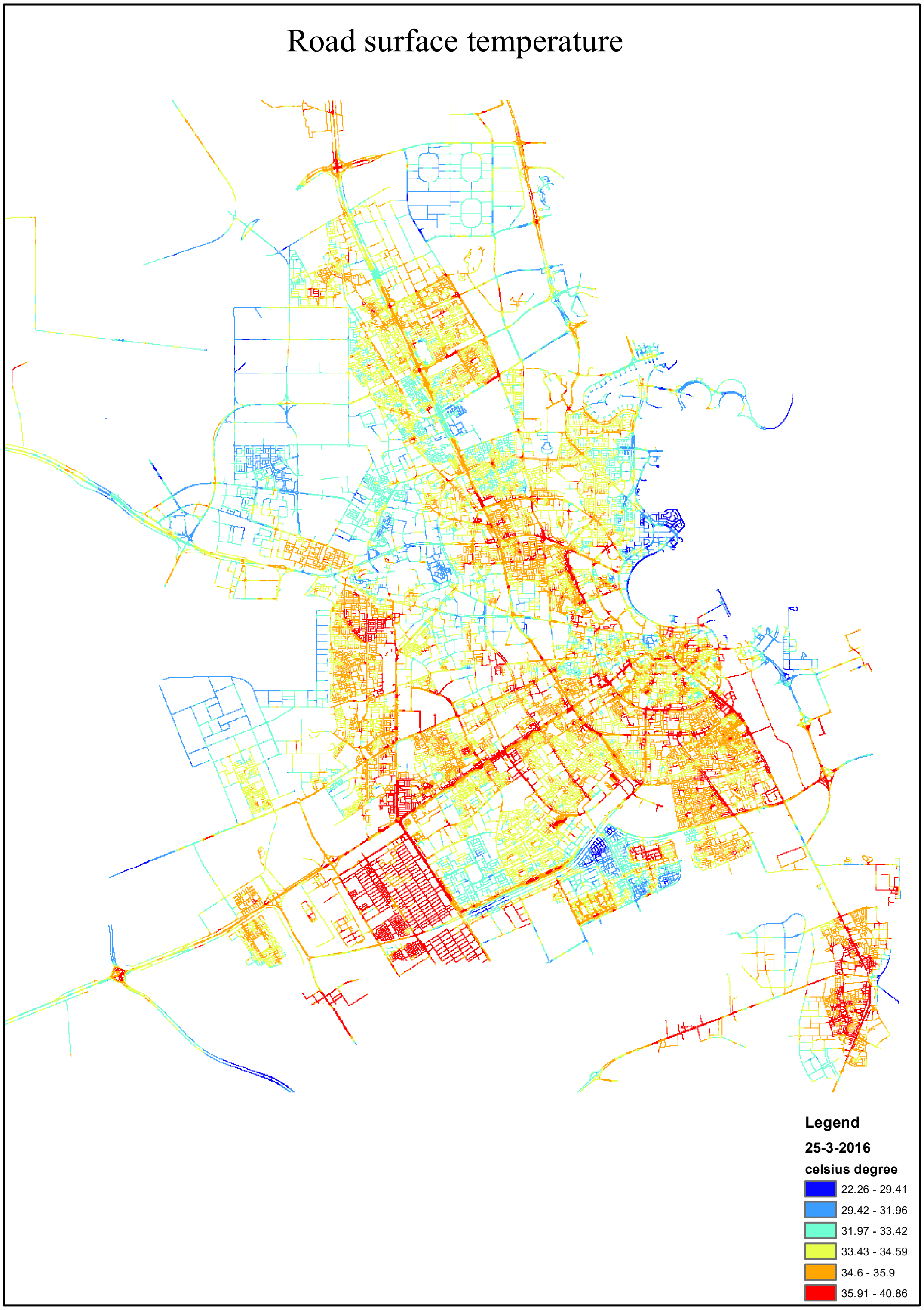

Figure 41. Road surface temperatures on 25-3-2016 (Source: http://glovis.usgs.gov; metadata processed by Author).

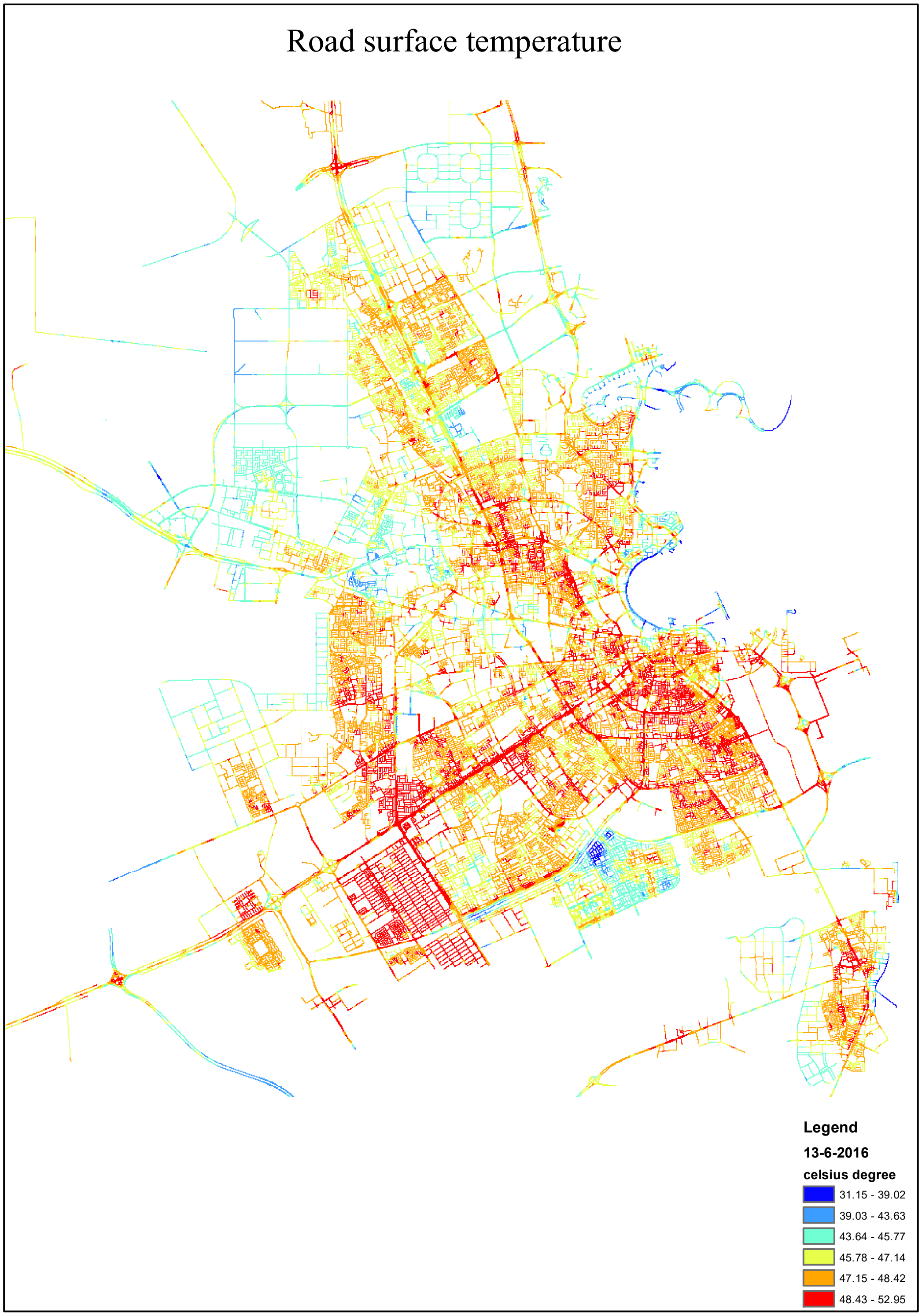

Figure 42. Road surface temperatures on 13-6-2016 (Source: http://glovis.usgs.gov; metadata processed by Author).

4.4.1 Ground Measured Surface Temperature

Al-Khor Road was chosen as a surface temperature measurement site using CR8000 measurements and a control data logger. The road direction is the same as the prevailing north wind, increasing the probability of heat transfer toward to the city along this direction. This roadway was also a preferable site because measurements could be made more conveniently and with a greater degree of safety also it's the olley road that totally expose to sun (solar radiation) . Figures 43, 44 and 45 show surface temperatures that were measured at various times and dates in order to learn how temperatures vary during the day. Additionally, these measurements enabled a verification of Landsat image accuracy.

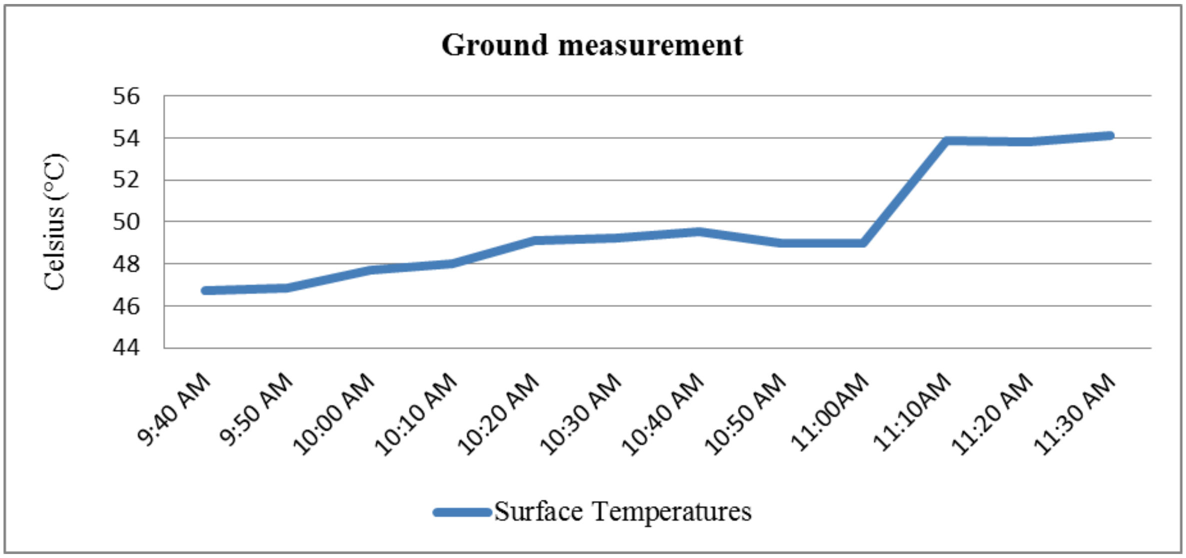

Figure 43. Ground measurements on 28-5-2016 and 29-5-2016 (Morning) (Source: Author).

The figures reveal differences in surface temperatures between the morning and evening due to atmospheric effects, amount of traffic, and the materials and forms of adjacent buildings. On 28/5/2016, the data logger recorded from 11 am to 11:30 am and the temperature reached a high of around 53 °C. Figure 42 shows the surface temperature as determined by satellite at 10 am on the same date.

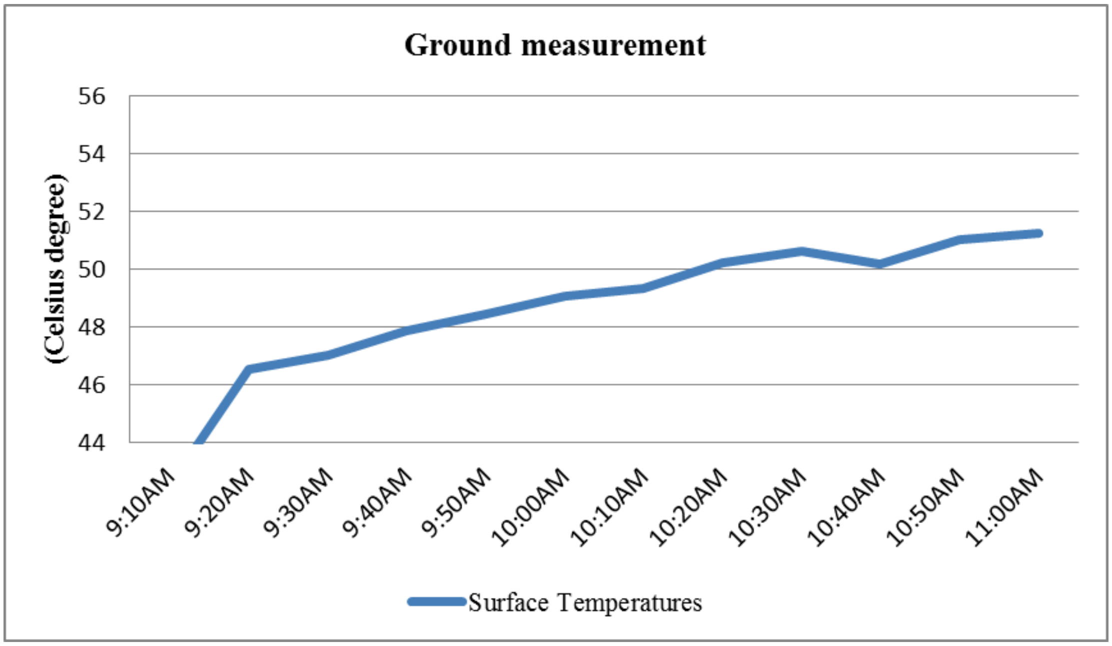

Figure 44. Ground measurements on 15-7-2016 (Morning) (Source: Author).

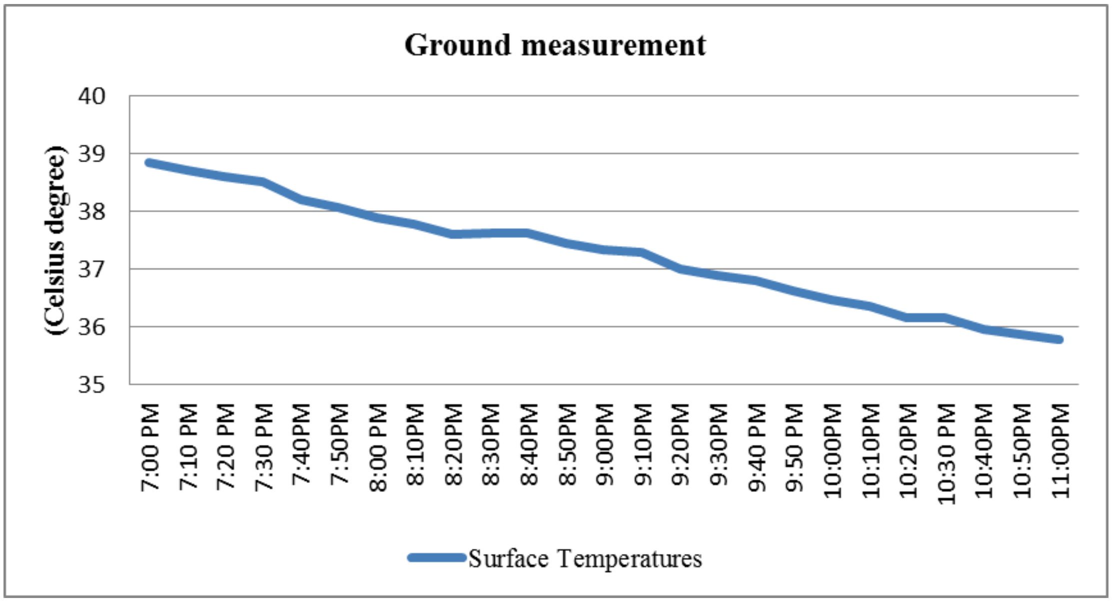

Figure 45. Ground measurements on 15-7-2016 (Evening) (Source: Author).

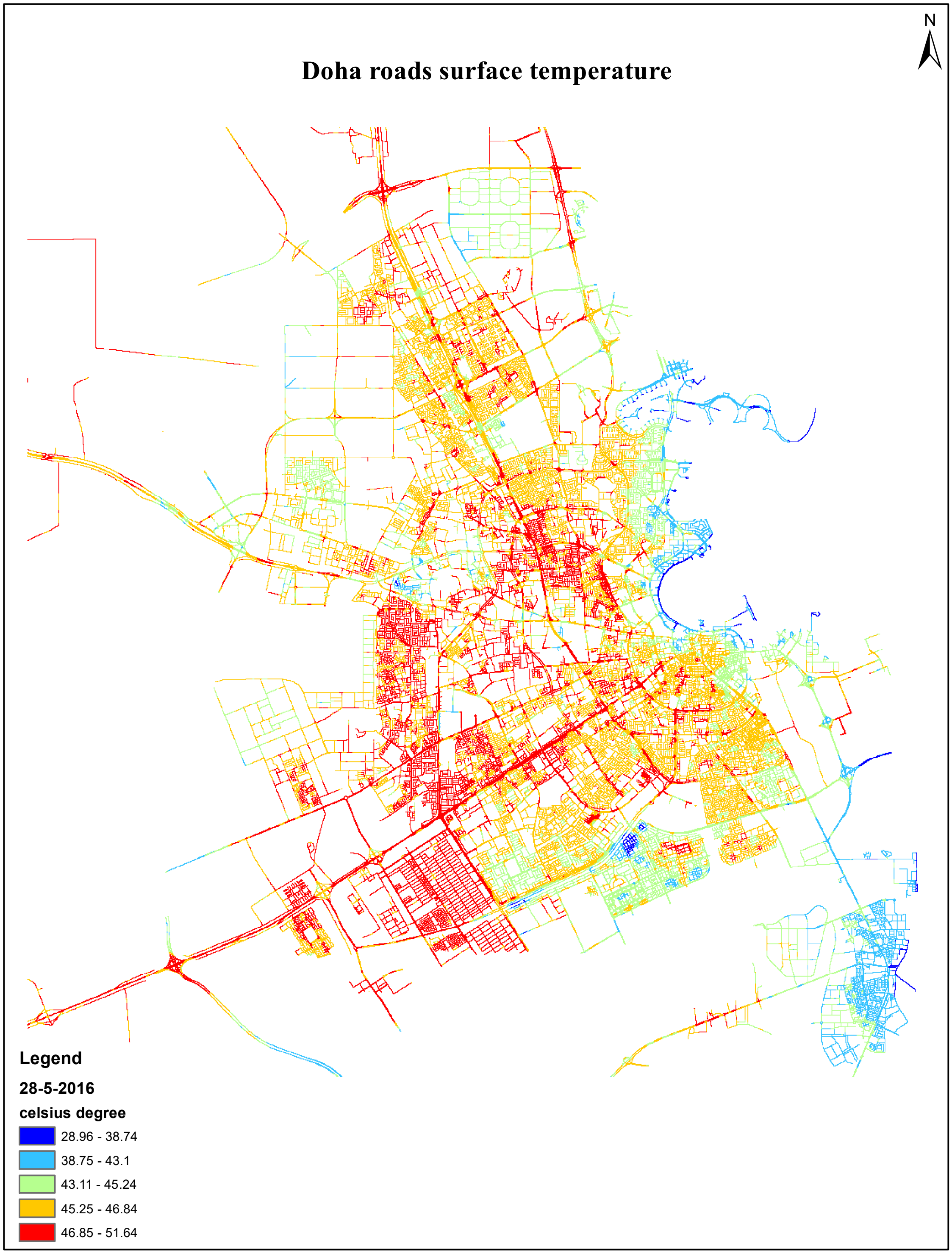

Figure 46. Doha road surface temperatures on 28-5-2016 (Source: http://glovis.usgs.gov; metadata processed by Author).

Additionally, the data reveal differences between the morning and evening rush hour periods; temperatures were measured from 7:10 am to 11 am (morning rush hour), and again from 5:40 pm to 9 pm (evening rush hour).

The flow of motorized vehicles was high during the busy morning and evening periods. Given that surface temperature is directly related to air temperature and traffic volume, it can reasonably be expected that an increase in traffic would tend to lead to an increase in measured temperatures. This is in fact what occurred, with measured temperatures increasing during peak traffic periods to as high as 51 to 54 °C. As traffic congestion decreased in the evening, measured temperatures decreased in parallel, from 40 °C to approximately 35 or 36 °C. These data show clearly that traffic density had a considerable impact on the UHI and surrounding environment. Similarly, Landsat imagery like that shown in Figure 47 indicates that road temperatures increased to a peak of 51 °C on 15-7-2016 at 11 am, and then decreased during the evening, reaching 35 °C by 11 pm.

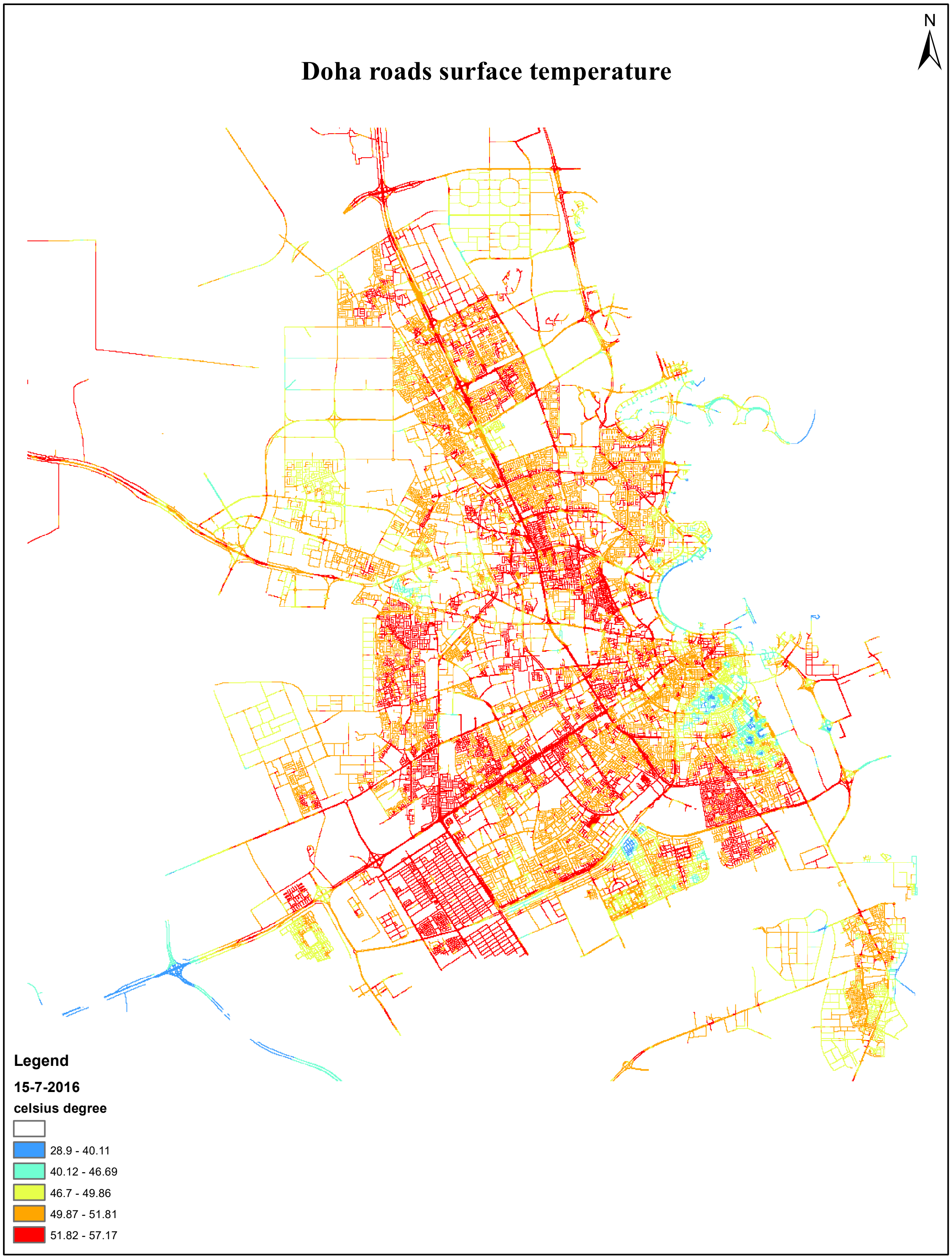

Figure 47. Doha road surface temperatures on 15-7-2016 (Source: http://glovis.usgs.gov; metadata processed by Author).

There was a large difference between the highest temperatures recorded in the morning and evening that day, because of differences in traffic volume and atmospheric conditions at those times. First, the greatest traffic volume on Doha's roads is found during the peak hours of the morning. Second, the wind direction from the north that day, as shown in Figure 48, evidently affected the movement pattern of the ambient heat.

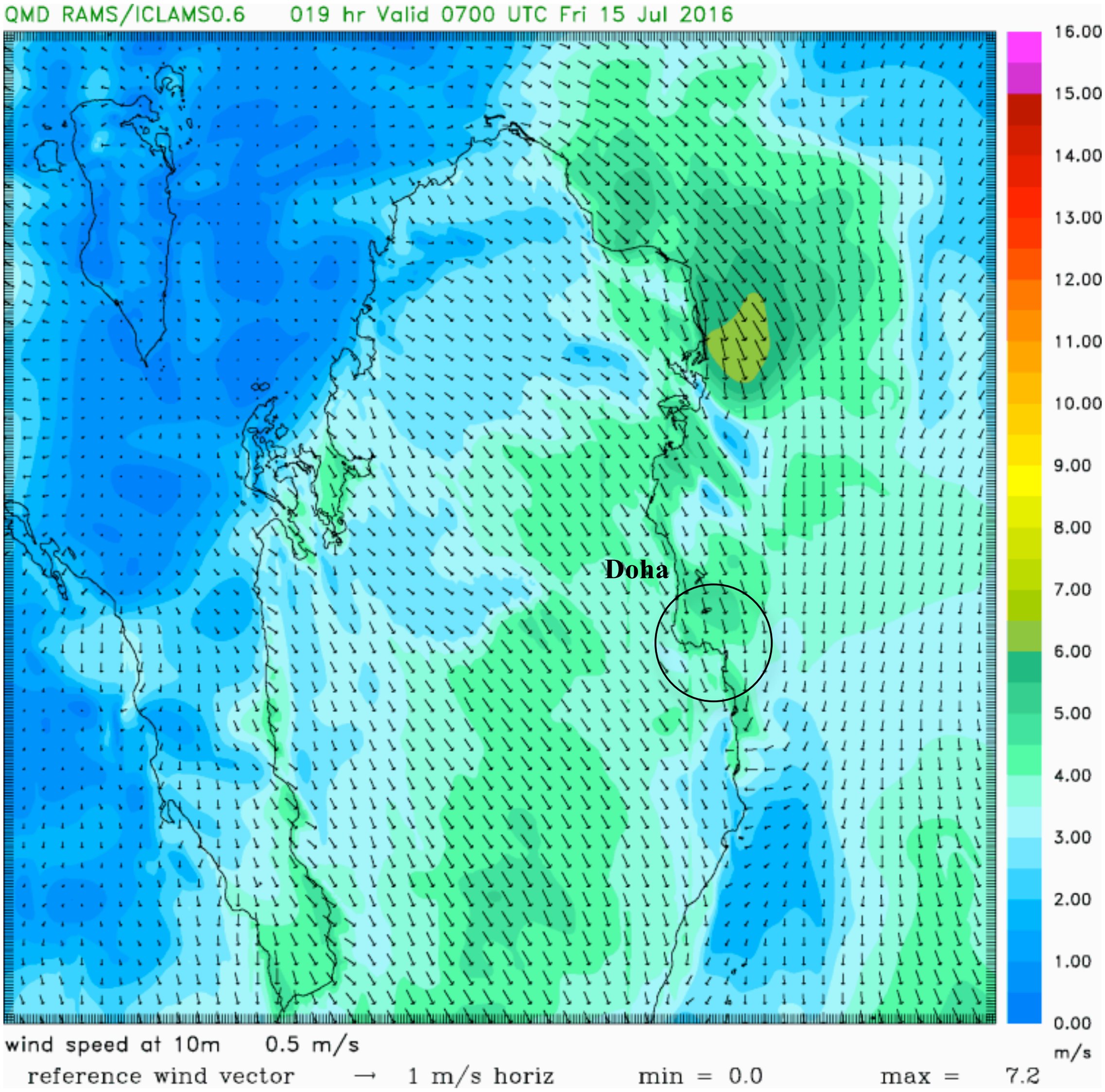

Figure 48. Wind direction and speed (Source: QMD).

As already noted, the surface temperatures just discussed were measured on 15-07-2016. The satellite image was taken at 07:04 GMT, which corresponds to 10:04 am Doha time. The temperature measurement at the same time was 49 °C on the Landsat image and 50 °C on the data logger, which confirms the consistency of these measurements. The data thus show that atmospheric conditions, traffic volume, and building material all have significant impacts on microclimatic conditions in Doha. Furthermore, the traffic volume itself contributed significantly to the UHI, increasing the temperature in the city through heat transferal. On the other hand, those green areas containing grass but without trees also registered high temperatures, meaning that green areas with grass alone do not significantly enhance the city's microclimatic conditions.

The maps just discussed show that the highest temperatures tended to be found on the densest roads; residential areas also recorded lower temperatures than were found on the main roads. It was also found that road surface temperatures were usually higher those of surrounding areas. It should be noted that many other factors contribute to surface temperatures; these include road direction, sea breezes, wind and humidity, and their influences can be difficult to quantify. The comparison of Landsat images and field measurements has shown that they do give consistent results, which constitutes evidence of the accuracy of each.

4.4.2 Traffic Volume Counts

Private vehicles are the primary means of transportation in Doha, and a general lack of accessible public transport is considered a key reason for the city's heavy traffic. Doha's traffic volume has increased greatly in recent times, especially on main roads; this is due to many factors that include population growth and the affordability of private transportation (each family owns an average of three to four cars). According to figures published by the Ministry of Interior (MOI), as of June 2013 there were approximately 876,000 cars, 1533 school buses and 153 public buses used each day on Qatar's highways (Qatar Construction News, 2016).

Centralization of primary economic activities, governmental organizations, and universities also appears to increase the number of cars entering the city. Figure 49 depicts the quantity of cars using Doha's highways, mostly during rush hour periods. The main thoroughfares giving access to Doha from other cities in Qatar are Al-Shamal, Al-Khor, Salwa, and Al-Wakra Roads. Poor accessibility by road, resulting in heavy traffic, is due to limited road access between different destinations and to continuing rapid urbanization. This is aggravated further by limited public transportation as well as social norms favoring a high degree of privacy.

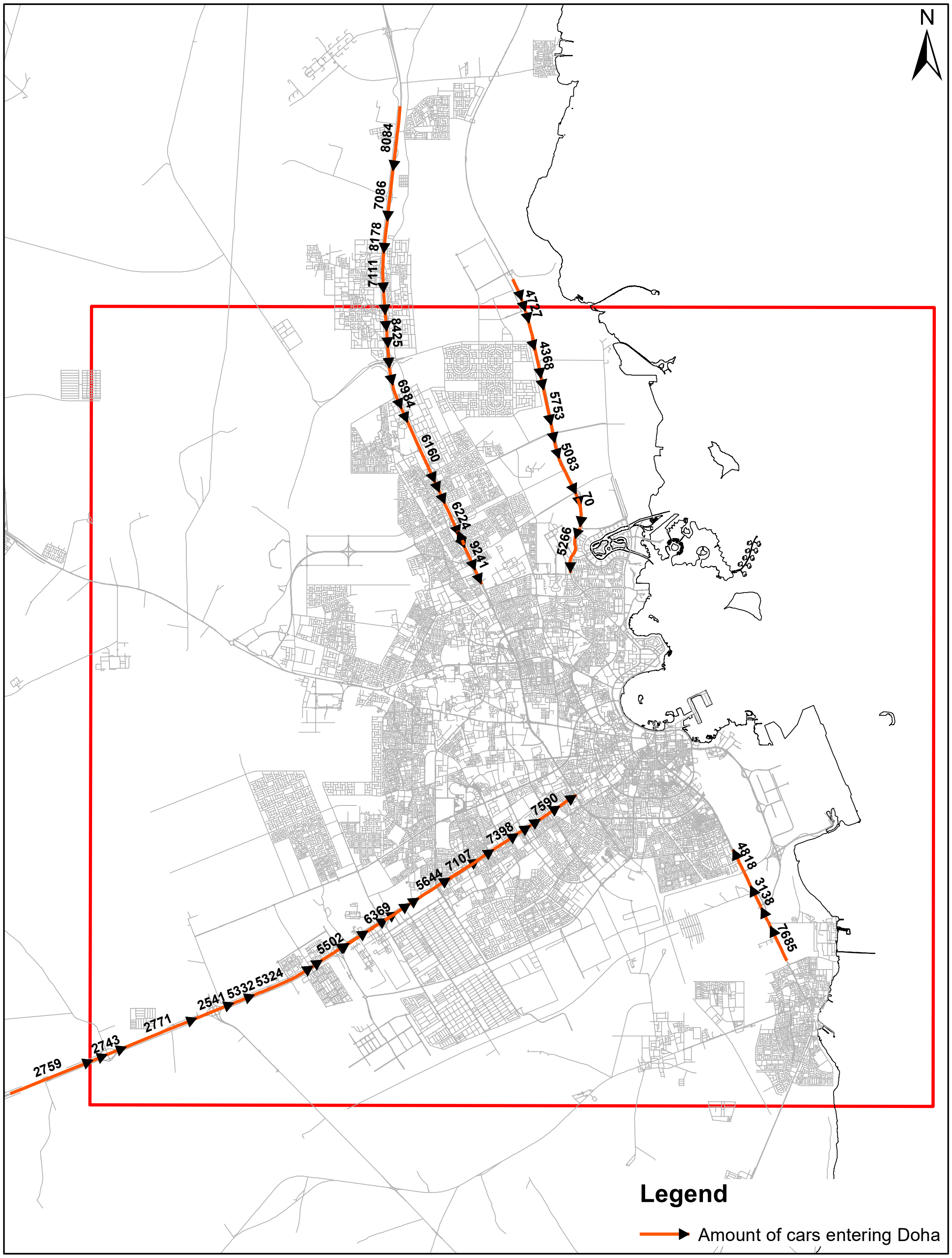

Figure 49. Number of cars entering Doha (Source: Ministry of Transport and Communications; processed by Author).

Figure 50 illustrates traffic volume categories on Doha’s roads, ranging from low traffic volume to the heaviest traffic volume of around 11000 vehicles during the morning rush hour. The number of cars is highest in the center of Doha and on the main highways that connect Doha to other cities in the north, west and south of the country. These areas are heavily impacted by this traffic and see a significant number of cars passing through daily, most of which are private vehicles (refer to Appendix A).

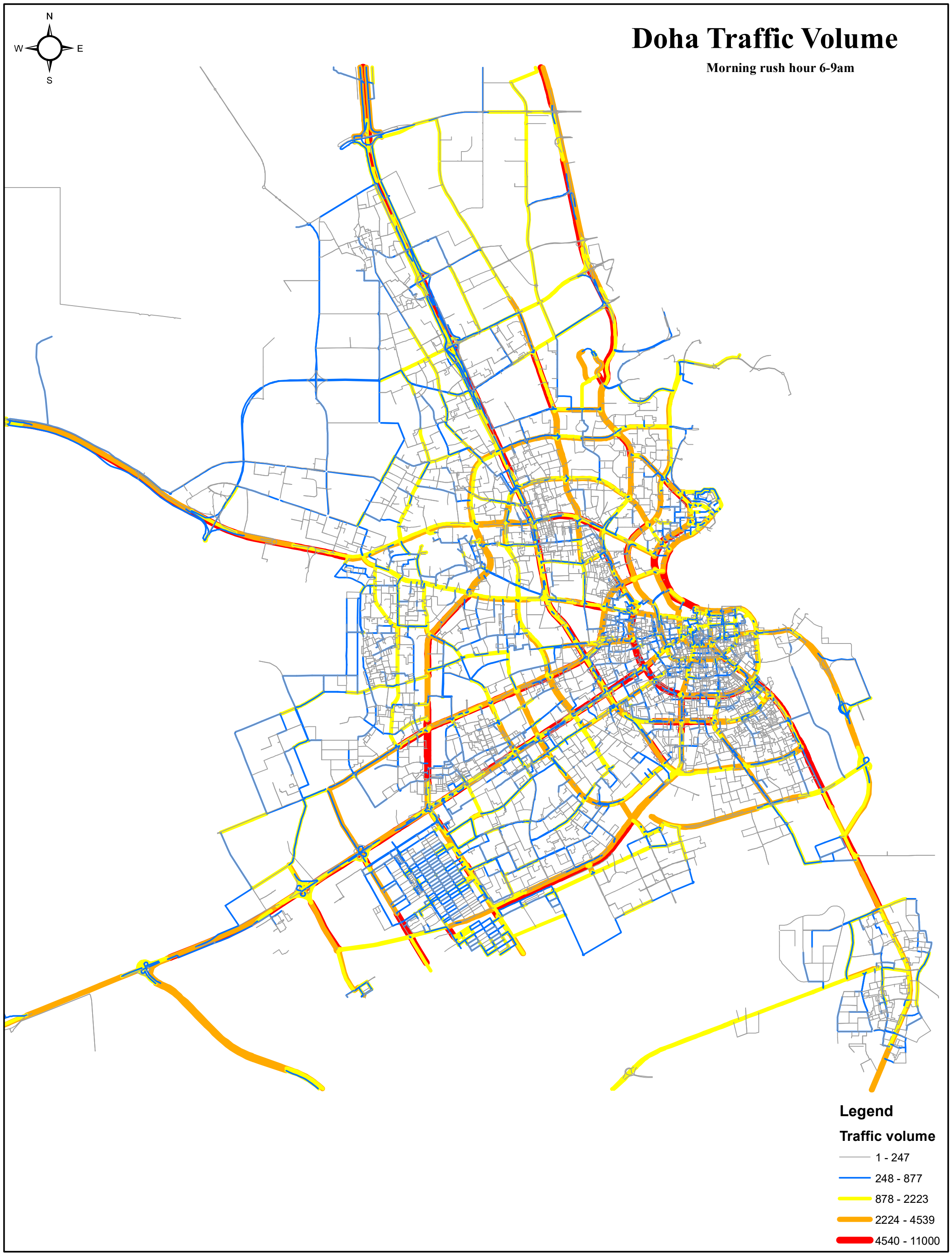

Figure 50. Doha traffic volume categories (Source: Ministry of Transport and Communications; edited by Author).

By referring to a detailed overview of traffic volume data, one can see that heavy traffic in rush hour is concentrated on the main roadways in Doha (Al-Shamal Road, Salwa Road and Al-Khor expressway); as shown in Figure 51, they recorded the greatest traffic volume. These roads can be described as follows:

- Al-Shamal Road runs through the north of Doha and connects the north to the south, leading to Ras Laffan, an industrial region managed by Qatar Petroleum, the area's largest employer. This is an important route for the country's northern cities, especially Al-Khor and Al-Shamal. Land use along the road is influenced greatly by urbanization near residential and commercial areas.
- Salwa Road runs through southern Doha and connects the city to industrial areas and to the Saudi Arabian border at the southern end of the country. It is one of the most frequently used routes. A variety of companies in different business sectors are located along Salwa Road, ranging from showrooms to restaurants, hardware shops and warehouses. Land use nearby changes constantly; most recently (beginning around 2008), there has been a large-scale transition from single-use commercial offices to mixed-use commercial offices.
- The Al-Khor expressway is the second most important access route to Al-Khor, Ras Laffan city and central Doha. It is a critical road in large part because of the new mega-projects located along its route.

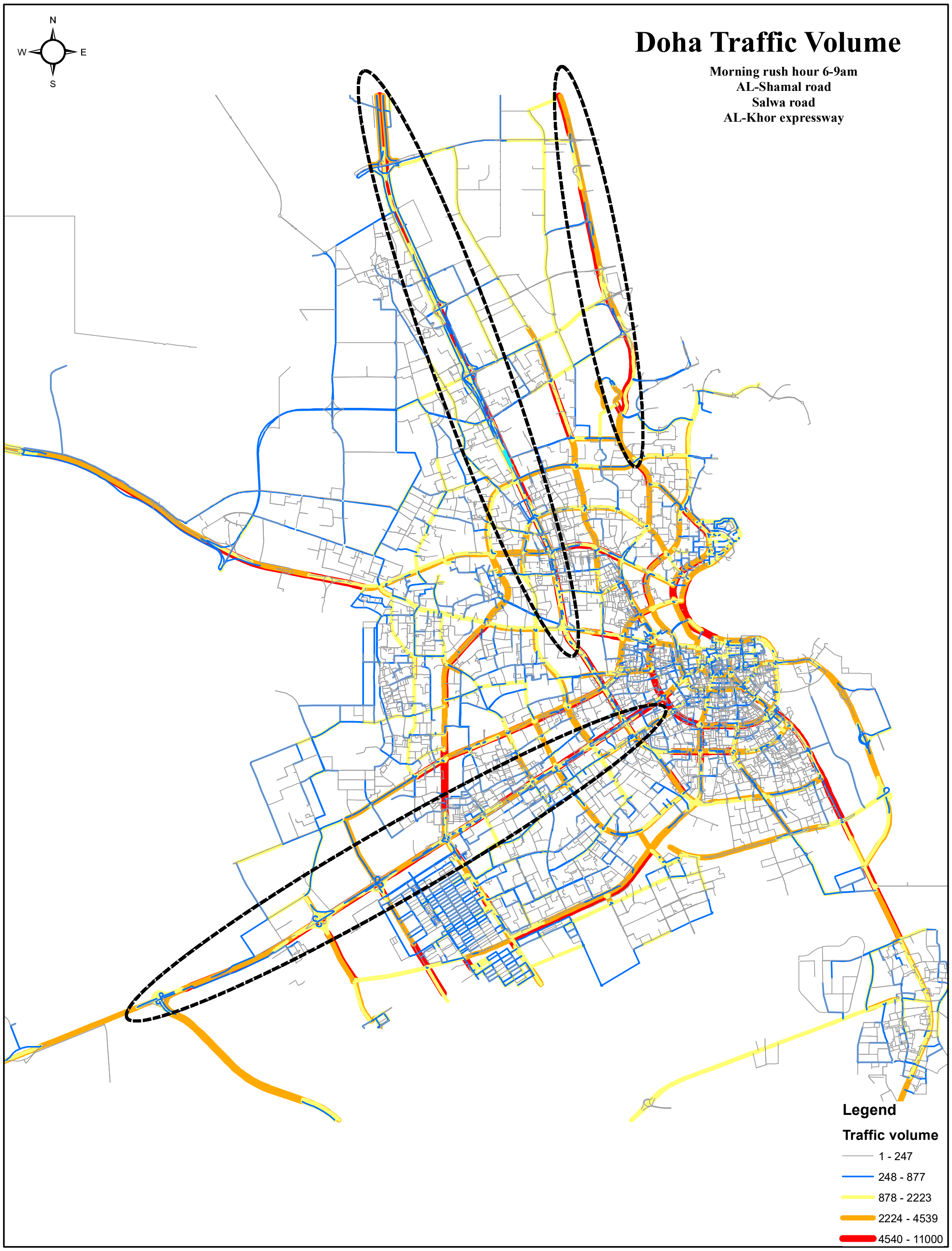

Figure 51. Selected roads with the heaviest traffic volume (Source: Ministry of Transport and Communications; edited by Author).

Figure 52 shows traffic volume during rush hour periods in the selected study areas. Al-Shamal Road, which measures 0.598 km in length and 16.60 m in width, had the highest traffic volume, reaching 11000 cars during the morning rush hour from 6 to 9 am. The heaviest traffic is observed in the morning because most important business activities happen during this time of day, including the opening of schools and the start of workdays in the governmental and private sectors. Traffic volume then decreased to 10180 cars in the afternoon between 11 am and 2 pm, during which time most school and business activities tend to start winding down. There followed a further decrease to 7087 cars during the evening rush hour from 5 pm to 8 pm. Almost all of the land use at these times was centered around travel to residential compounds and other living areas surrounding the selected roads. Therefore, traffic volume was heavy because of low accessibility in areas surrounding destinations such as Qatar University and various shopping malls.

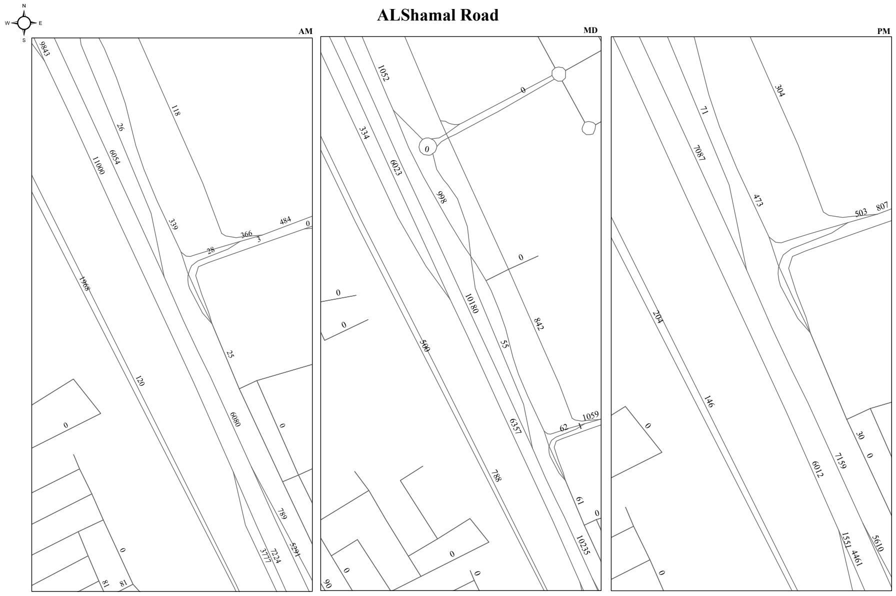

Figure 52. Al-Shamal Road traffic volume (Source: Ministry of Transport and Communications).

In contrast, as shown in Figure 53, traffic volume showed a different pattern on Salwa Road, which measures 0.554 km in length and 7.30 m in width. The highest volume of traffic, at 9189 cars, was observed in the middle of the day, from 11 am to 2 pm, and decreased to 7580 in the evening period between 5 pm and 8 pm. Traffic was at a moderate level of about 8871 cars in the morning from 6 am to 9 am. The traffic density on Salwa Road stayed at a relatively constant and heavy level throughout the day, due to continuous activity centered around commercial places such as shops, showrooms and offices.

Figure 53. Salwa Road traffic volume (Source: Ministry of Transport and Communications).

Finally, Figure 54 shows traffic volume on the Al-Khor expressway, which was lower than that on Al-Shamal and Salwa Roads. Traffic on this road has recently become heavier because of urban development in Lusail City, the Lusail international circuit, and a new residential development. This roadway is 0.550 km long and 6.59 m wide. Traffic volume was recorded at 6012 vehicles in the morning from 6 am to 9 am, increased to 6365 from 11 am to 2 pm, and then dropped to 3647 during the evening rush hour from 5 pm to 8 pm.

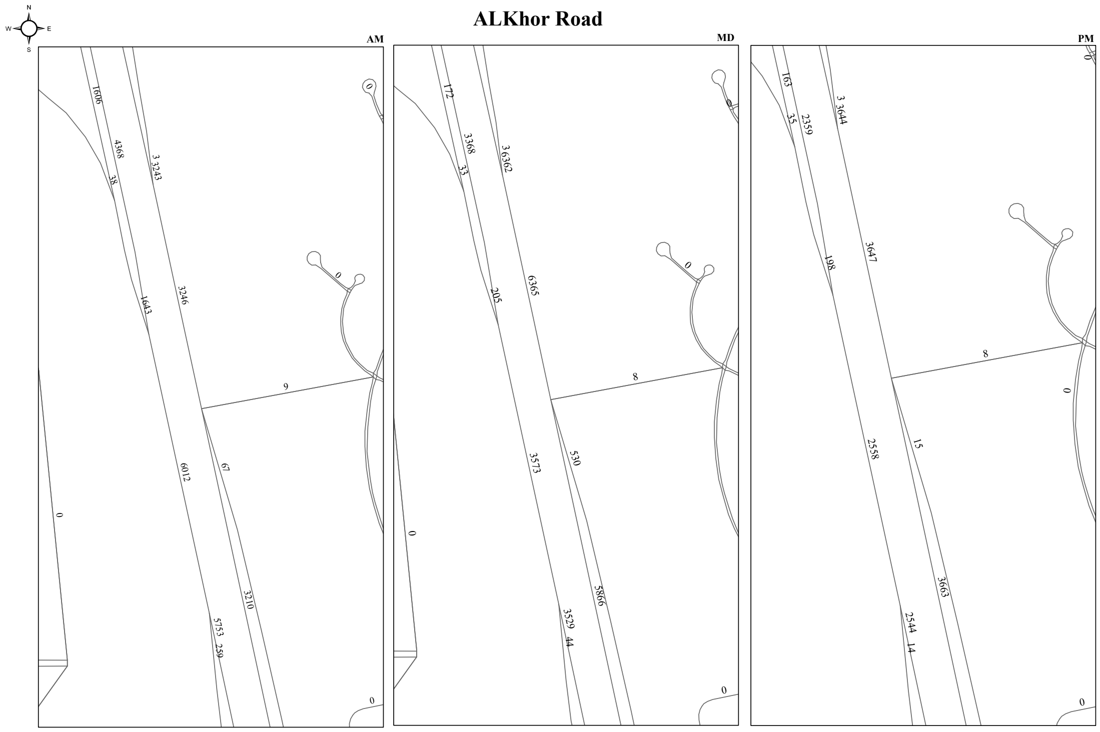

Figure 54. Al-Khor Road traffic volume (Source: Ministry of Transport and Communications).

The data show that a substantial number of cars enter Doha each day from other Qatari cities. On all roads, the heaviest traffic can be seen during the morning rush hour; traffic generally starts to decrease by midday, and the decline continues into the evening rush hour period. These patterns are illustrated in Figure 55.

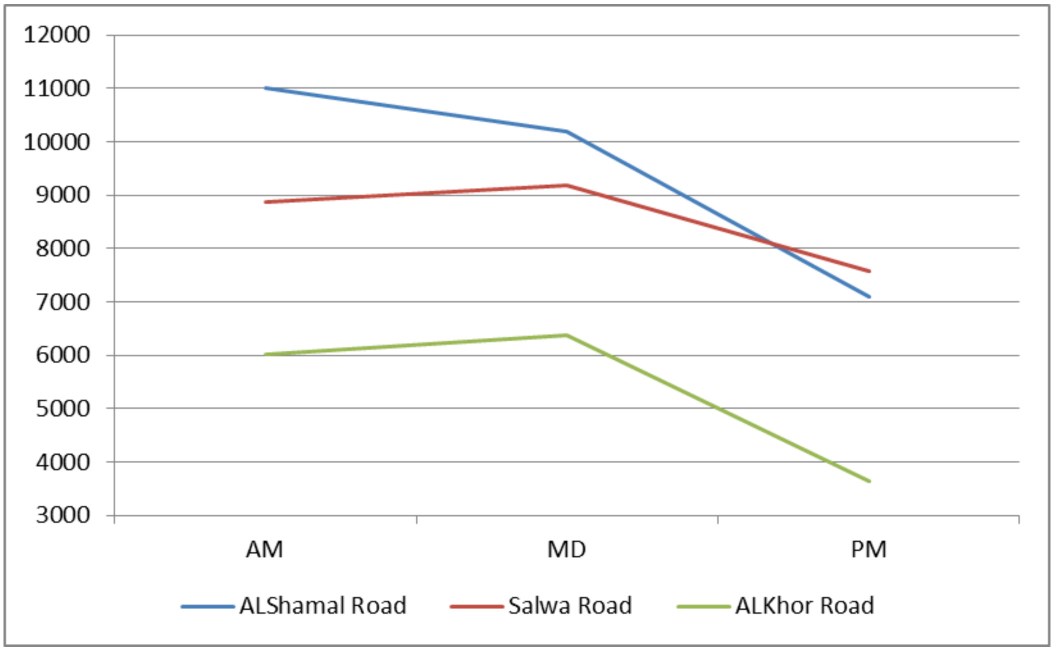

Figure 55. Variation in traffic volume across rush hour periods on Al-Shamal, Salwa and Al-Khor Roads (Source: Author).

In general, motorized vehicles such as cars increase the heat island effect in Doha and play a major role in heat formation and movement in the city. The public transportation system in Doha is relatively underdeveloped as yet, making it much less convenient for many residents than the use of private vehicles. The road network has continued to grow in recent times, but a metro system is currently under construction. The implementation of this system is predicted to reduce the city's daily traffic volume by around 190,000 cars, as well as reducing CO2 emissions by approximately 162 tons per day, according to Rail Qatar (Rail Qatar, 2016). Reduction in car volume will be attempted through the implementation of new parking fees and the construction of shaded walking pathways, but making lesser use of private cars will likely be challenging for many people.

The design aspects of a city can play a major role in mitigating the UHI and motivating people to walk or use public transportation systems, therefore reducing dependence on private cars. The following are field measurements, which can help us to understand better the connection between traffic volume and the UHI effect in Doha.

4.5 Impact of Traffic Volume on Land Surface Temperature

Determining clearly the link between traffic volume and the surface temperatures of Doha’s roads is a difficult and complex problem, because many factors are likely to influence surface temperatures in various areas. To help understand the relationship between traffic volume and surface temperatures, the former has been calculated for both directions on selected roads, as traffic jams are known to affect surface temperatures. Figure 56 shows the traffic volume of a number of streets in Doha.

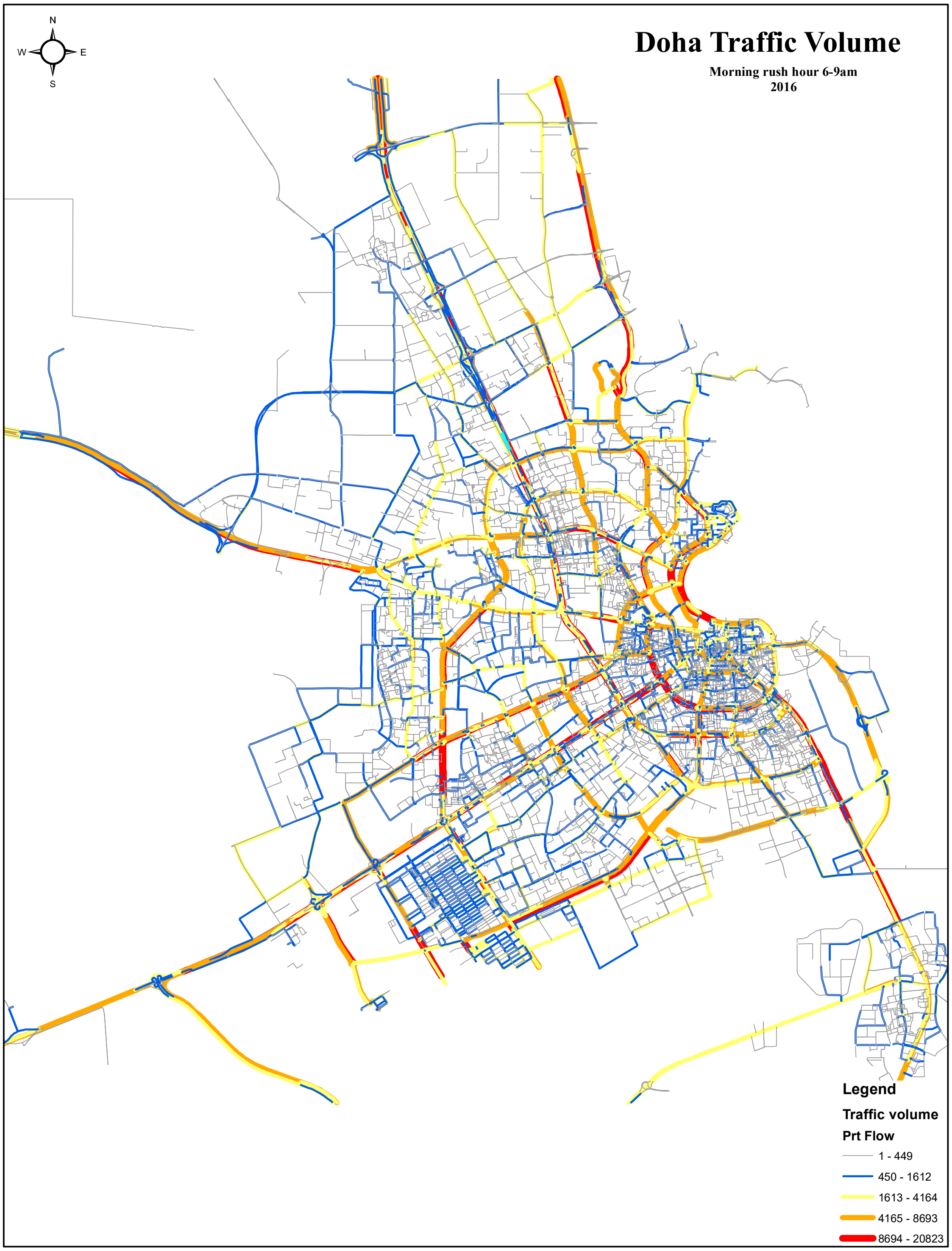

Figure 56. Bidirectional traffic volume on Doha roads (Source: Ministry of Transpiration and Communication).

Surface temperatures are rather high in Doha's main industrial area despite a relatively low traffic volume there. This situation differs from that of the local coastal roads, whose low temperatures are largely due to the sea breeze. The map in Figure 57 highlights the industrial area and shows traffic volume.

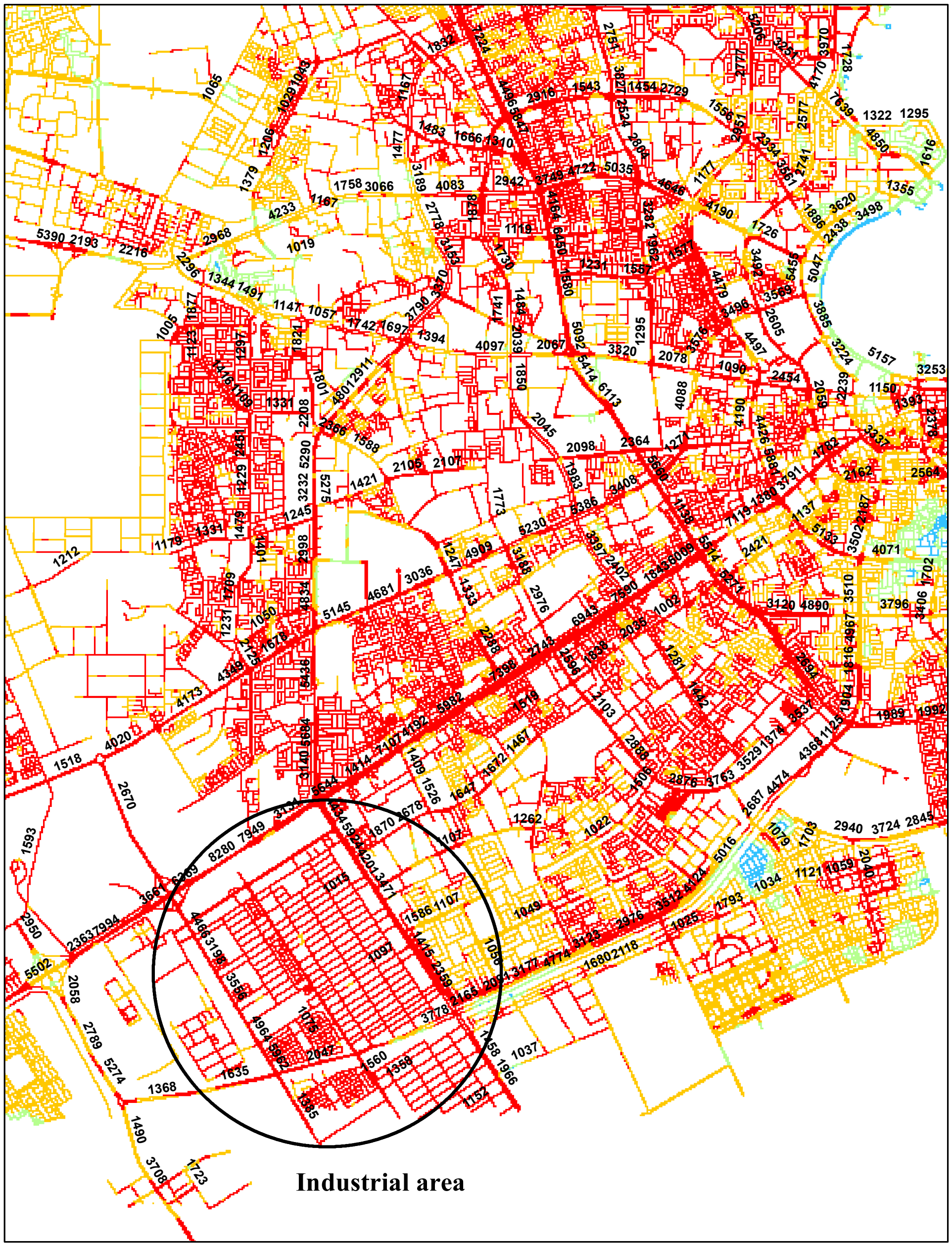

Figure 57. Doha industrial area traffic volume (Source: Ministry of Transport and Communications).

Most intersections also recorded high temperatures, even when traffic volume there was measured as low to medium. Evidently, traffic jams were responsible for increasing temperatures because of car emissions, which themselves tend to heat the nearby atmosphere. As Figure 58 shows, urban transportation contributes to heat formation in the city, with the temperature of Doha’s intersections in winter providing a useful indication of the amount of heat caused by traffic congestion. To avoid such elevated levels of traffic, the need for a greater number of accessible roads is clear, and the issue is likely to grow ever more urgent.

During the winter season, intersections along Al-Shamal and Salwa Roads recorded high temperatures, reaching as high as 40 °C. Figures 59 and 60 illustrate heat emissions along Al-Shamal and Salwa Roads, respectively. In these figures, it is clearly seen that Doha’s traffic intersections operate as heat islands, evidently due primarily to heat emission from cars.

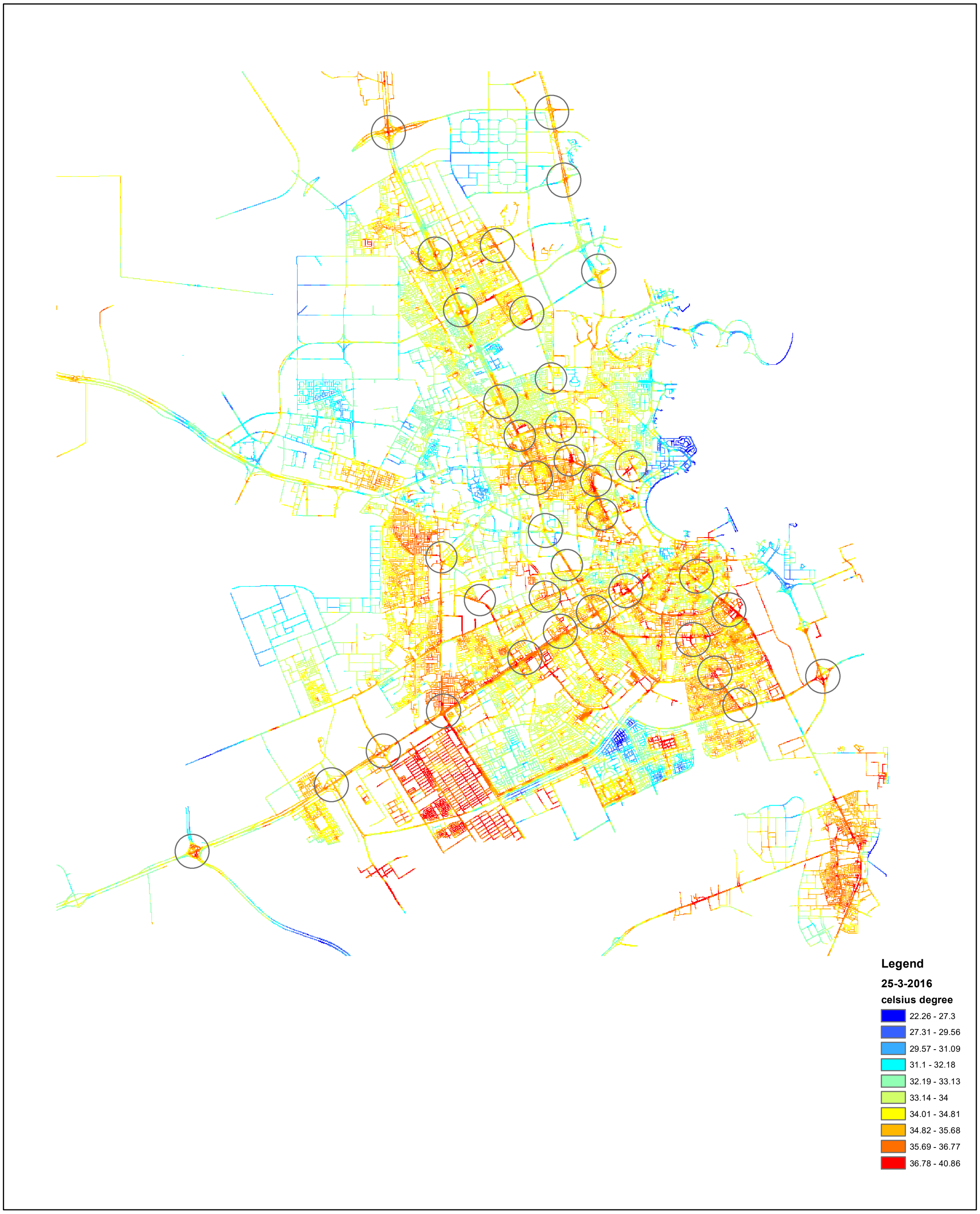

Figure 58. Doha: surface temperatures at road intersections (Source: http://glovis.usgs.gov; metadata processed by Author).

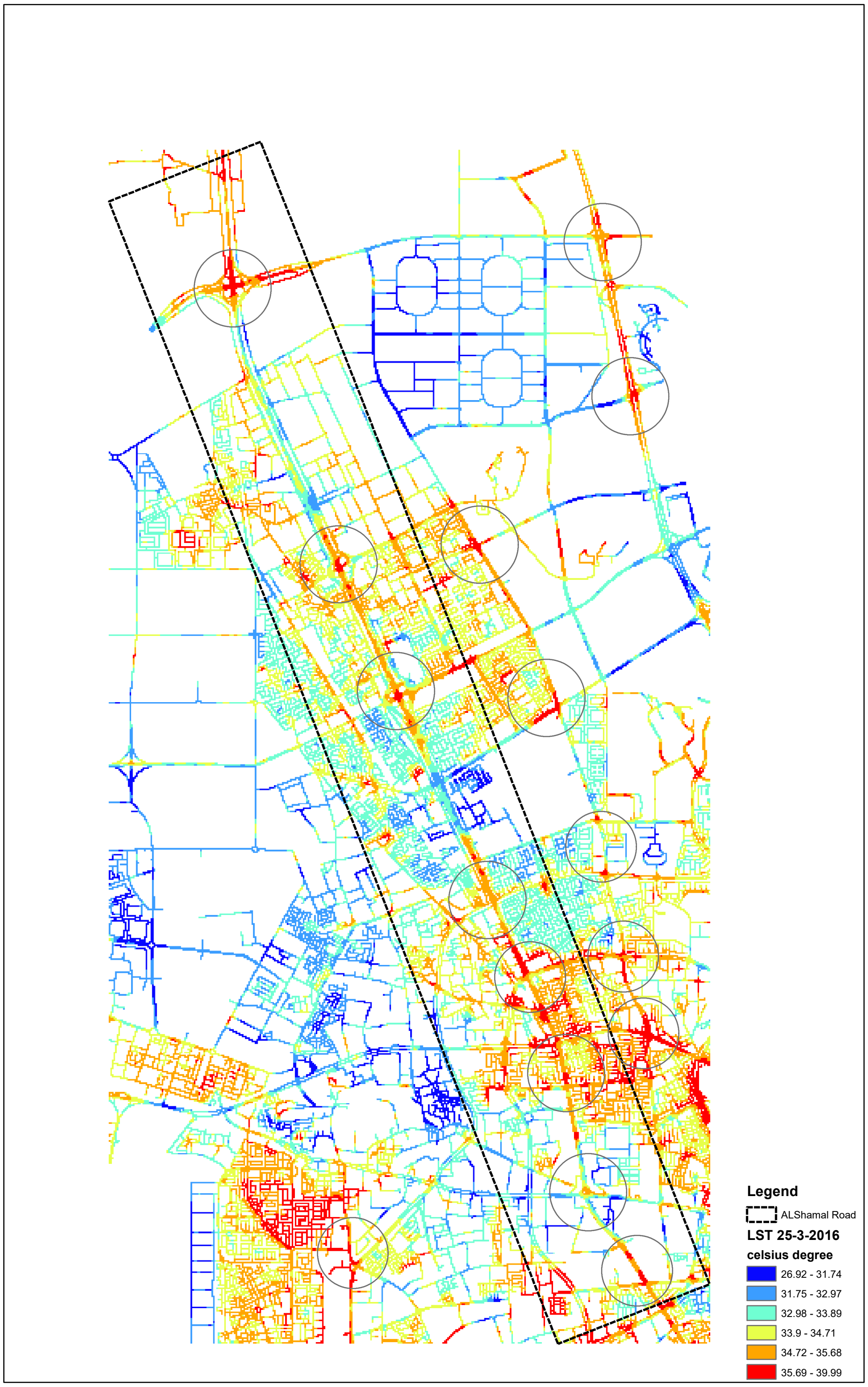

Figure 59. Al-Shamal Road: surface temperatures at intersections (Source: http://glovis.usgs.gov; metadata processed by Author).

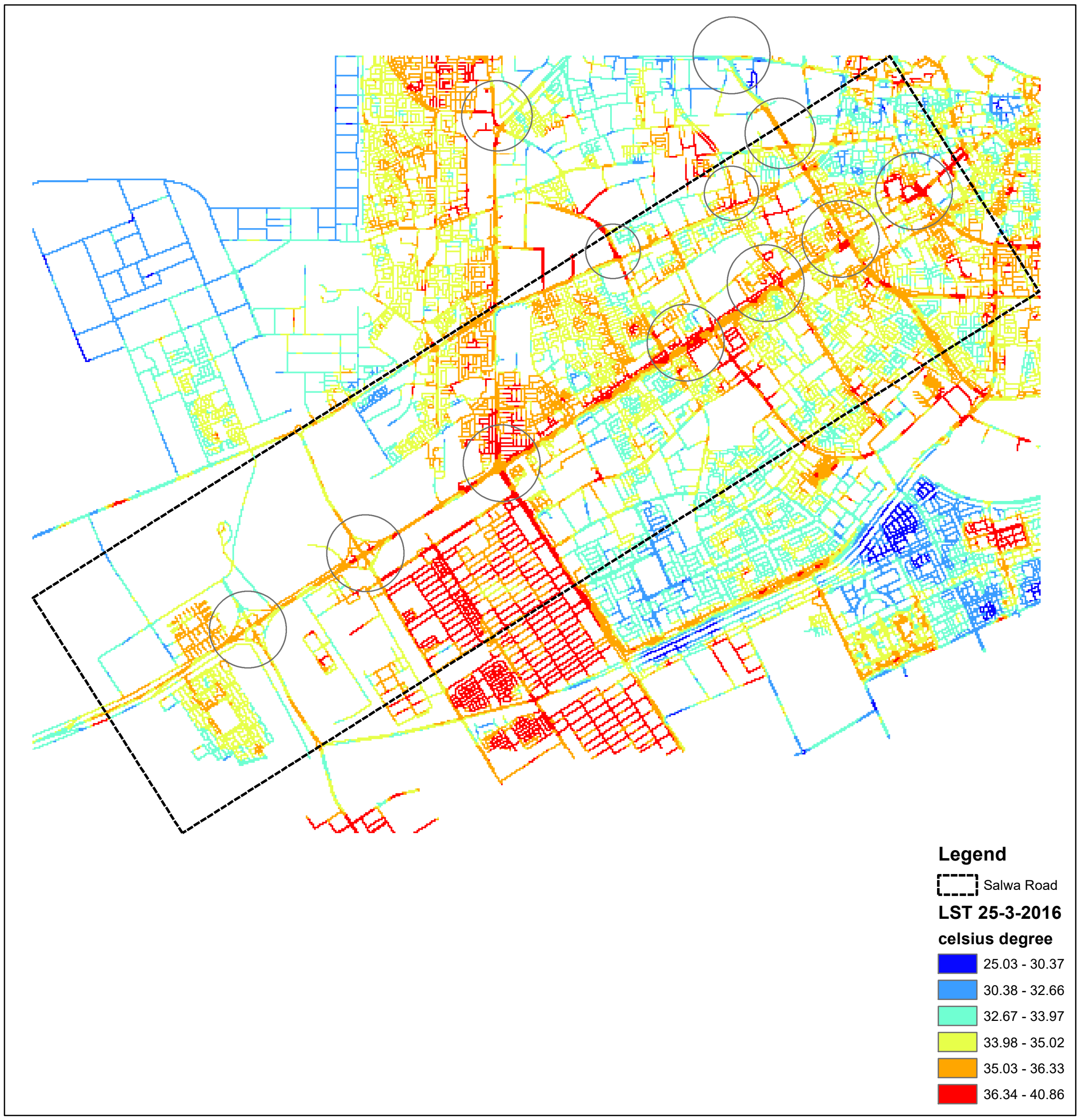

Figure 60. Salwa Road: surface temperatures at intersections (Source: http://glovis.usgs.gov; metadata processed by Author).

In order to understand the extent to which traffic contributes to heat islands, this study applied GIS data to analyze traffic volume and its correlation to surface temperatures. The goal was to investigate the possible connection between peak traffic volumes and maximum temperatures recorded in the targeted areas. The maps in Figure 61 illustrate simultaneously land surface temperatures, morning peak traffic volume, and topography on Al-Shamal, Salwa and Al-Khor roads.

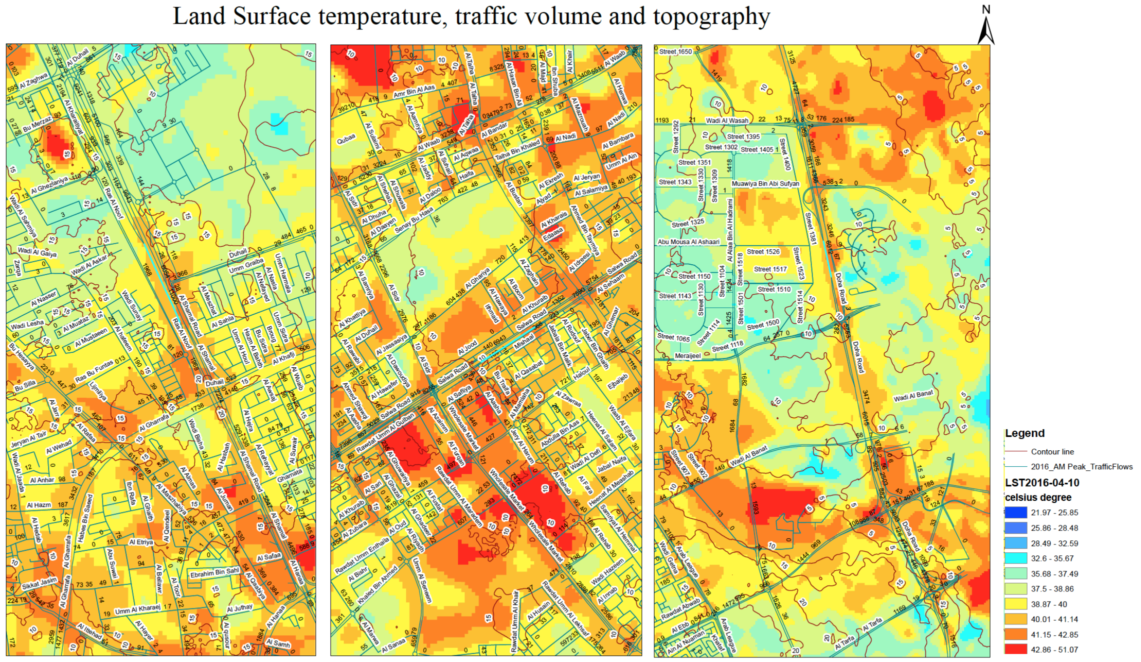

Figure 61. Land surface temperatures, traffic volume and topography (Source: http://glovis.usgs.gov; metadata processed by Author).

Increased urbanization requires the building of new transport infrastructure for the sake of accessibility, which means an expanded use of asphalt and other materials typically utilized in urban settings. The result is that urban development leads to an enhanced UHI. Surface temperatures tend to be particularly high in areas with an altitude of less than 10 meters. Moreover, all of the roads investigated here showed higher temperatures than their surrounding areas, indicating that within these small-scale regions, local topography has no significant effect on surface temperatures. The volume of cars was found to be particularly high during rush hour periods on Al-Shamal Road, which has a high traffic capacity of around 11000 cars. The result of these large traffic jams is a substantial amount of generated heat, with each car contributing its own heat to the temperature of the nearby surface. Salwa Road also showed high temperatures which extended to the surrounding areas, with a heavy traffic volume of up to 8000 cars. Much of this traffic is likely due to the many businesses and available activities on this road. Al-Khor Road also recorded high temperatures along its route, because of its traffic and paving materials. However, its surrounding areas showed relatively little influence from this heating, due to the moderating effects of sea breezes.

Analysis was also undertaken of other roads with similar locations and directions of traffic flow, but having a range of traffic volumes, ranging between 2000 and 4000 cars. This analysis revealed that the amount of increase of surface temperatures along particular sections of the roads depended on both amount of traffic (congestion) and on air temperature. The more traffic and congestion, the higher were the temperatures of surfaces paved with dark asphalt. Roads used by more than 2000 cars recorded higher temperatures than their surroundings, and this was especially true for roads characterized by heavy congestion.

In order to confirm the objectivity and validity of the research results on high ways, an investigation has been conducted on main roads, the more traffic the more urban heat island generated. Figure 62 shows roads with different traffic volumes. Between main roads, surface temperatures are notably higher within congested areas. The road shown in the leftmost part of the figure, Al-Duhail, had a traffic volume of 1136; the area surrounding this road is characterized by low urbanization. Congestion on this road at and near intersections led to an increase in recorded temperatures relative to the surroundings, reaching as high as 42 °C. The second road shown in the figure (Al-Furousiya, middle image) exhibited a low to medium traffic volume, ranging from about 2000 to 5000 cars, and showed temperatures of 38 to 41 °C. The road surface temperature was elevated in congested areas (those with 4801 to 5081 cars). The rightmost image in the figure shows Al-Areesh Road, which had a low traffic volume ranging from 991 to 1043 cars, and showed surface temperatures that were relatively high, at around 40 to 42 °C, compared to the surrounding area.

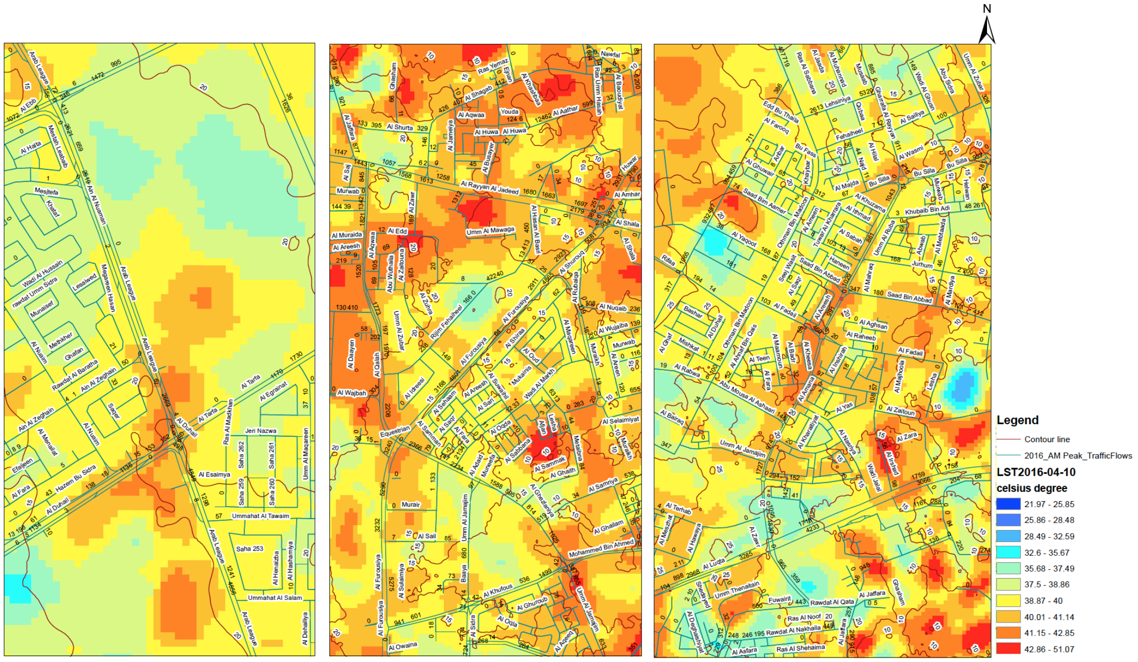

Figure 62. Land surface temperatures, traffic volume and topography of selected roads (Source: http://glovis.usgs.gov; metadata processed by Author).

GIS data provide us with the means to determine the overall link between surface temperatures and traffic volume in the selected areas, using the Exploratory Regression tool. Analysis showed a correlation of around 75% for the selected roads. This shows that there is a strong correlation between traffic and UHI effects. Figure 63 illustrates this correlation via an examination of Al-Shamal Road.

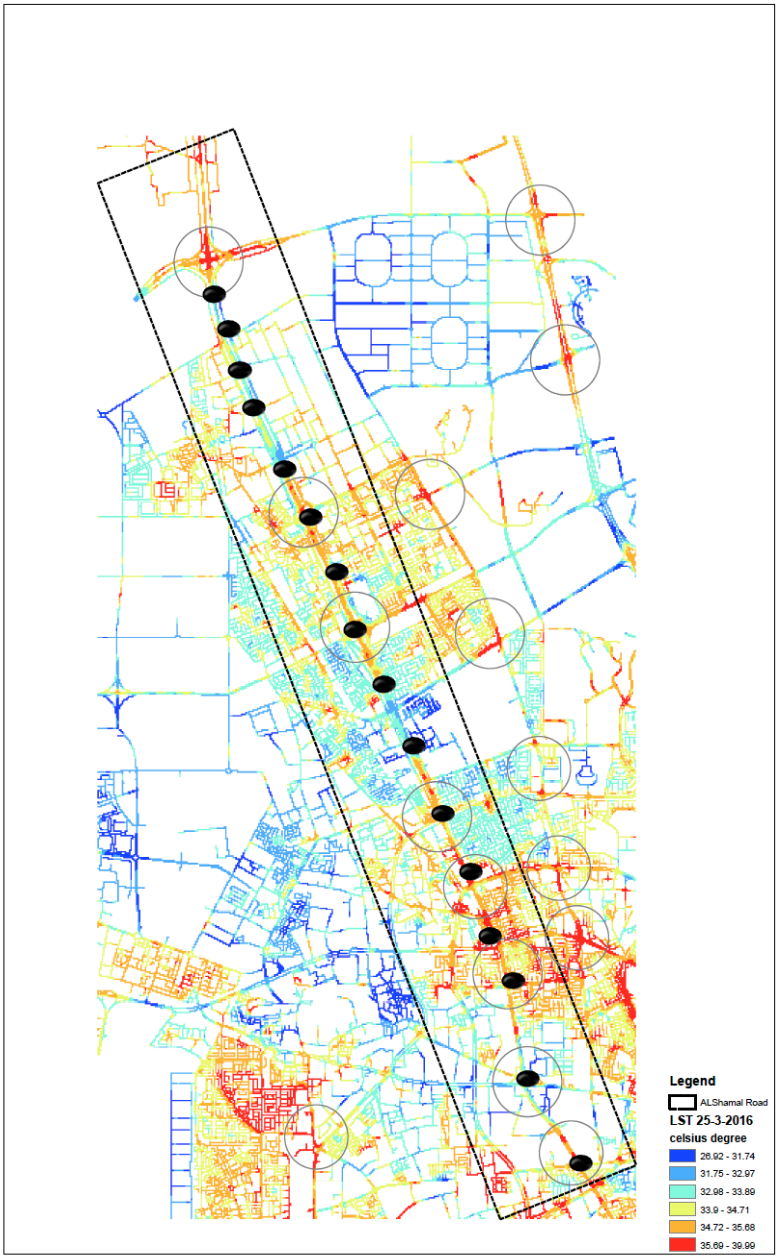

Figure 63. point location on AL-Shamal Road (Source: Author).

Random points (shows in figure 63) along the road were chosen, for each of which the land surface temperature and the traffic volume are graphed together at the same time 10am. The correlation is visually obvious in the figure 64, in that places with a higher number of vehicles tended to show higher recorded temperatures.

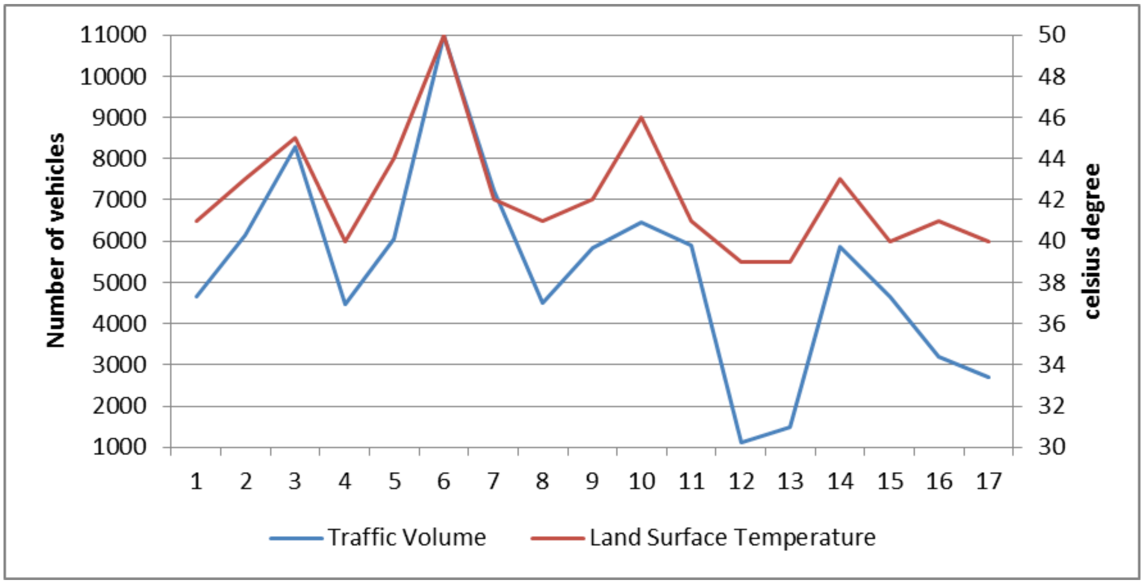

Figure 64. Correlation between land surface temperature and the traffic volume (Source: Author).

However, when expanded to include all of the roads in Doha, the correlation results were very weak, because most intersections recorded higher temperatures even with a lower traffic volume. Therefore, differences in surface temperature along a given road may be observed because of variation in traffic congestion and car flow. The present analysis has documented that traffic plays a leading role in heat formation in Doha; in other words, traffic congestion contributes to the UHI effect. Moreover, such heat influences microclimatic conditions and is reduced when there are trees along the sides or median of urban roads. Trees create shaded areas and thus enhance microclimate conditions by increasing human thermal comfort.

4.6 Traffic Dissipation to Mitigate the Amplification of the Heat Island Effect

Traffic volume is difficult but important to manage, as traffic adds to the UHI, which in turn has the effect of heating the surrounding areas. Such heating effects are weaker on stretches of the road where vehicles are able to move relatively rapidly, and lower surface temperatures are found there. However, when vehicles reach a subsequent intersection and traffic builds up, temperatures are seen to increase there. For example, on Salwa Road, as depicted in Figure 65, surface temperatures are generally high along the road but show clear increases at all of the main road exits, at which heat islands are created. The traffic volume is high along Salwa Road, at between 5000 and 7000 vehicles, while the main exits along the road have a traffic volume of around 2000 to 5000 vehicles. The heat effects caused by such large numbers of vehicles greatly influence the surrounding areas.

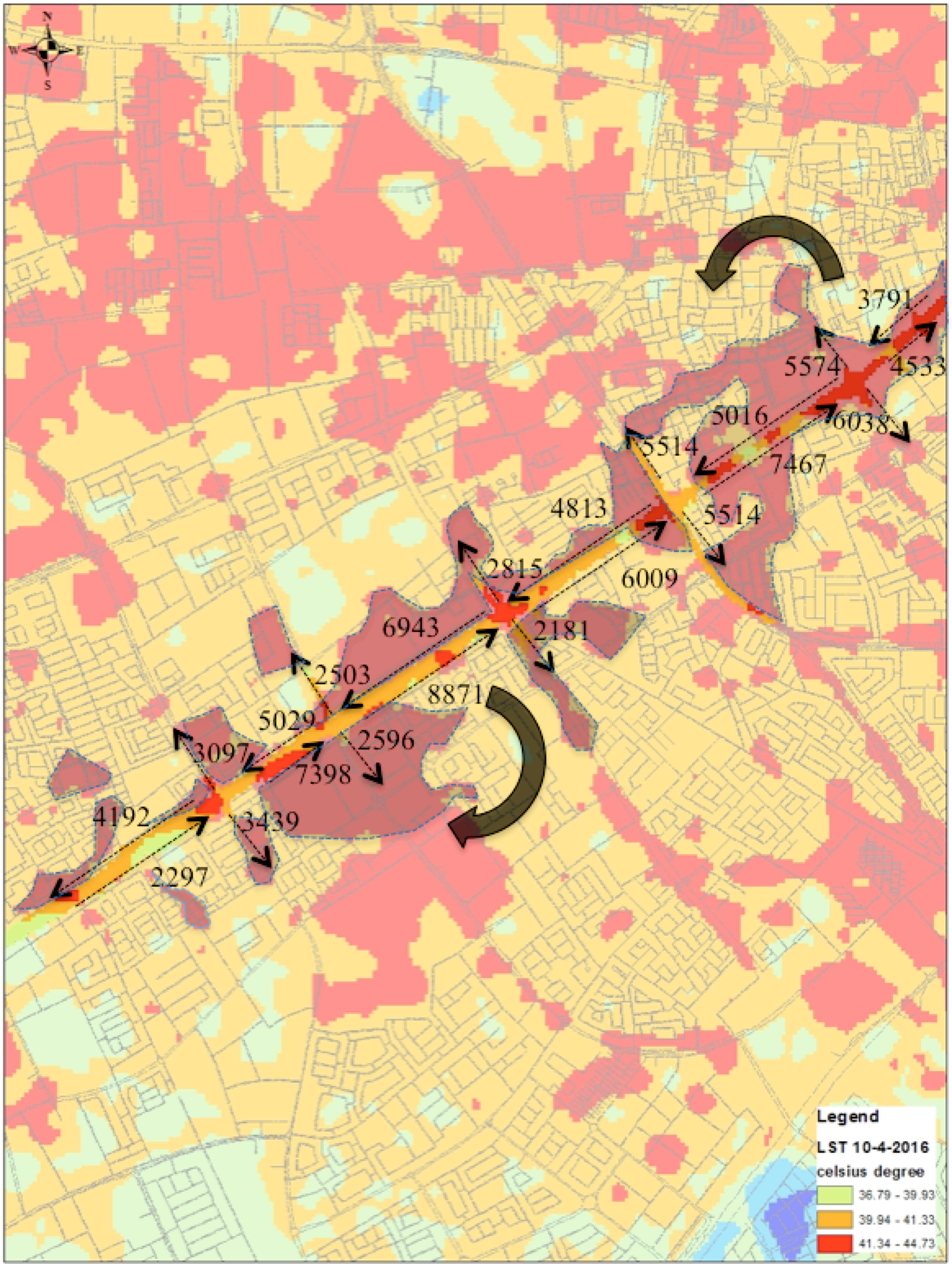

Figure 65. The role of traffic volume in increasing the surrounding surface temperature (Source: http://glovis.usgs.gov; metadata processed by Author).

On Al-Shamal Road, surface temperatures were seen to be lower after each intersection, but heat island effects were seen as the road reached urban areas. Traffic volume on some parts of the road reached as high as 5000 to 11000, but the number of cars decreased as cars departed the road, headed toward different destinations, reaching a low of about 1000 to 4000 vehicles. The heat generated by these vehicles led to higher surface temperatures on the road, which then spread to the surrounding area. These effects are shown in Figure 66. If more exits are created along heavily-trafficked roads, accessibility and connectivity to urban areas are improved, and excess heat will tend to dissipate and be absorbed by the environment.

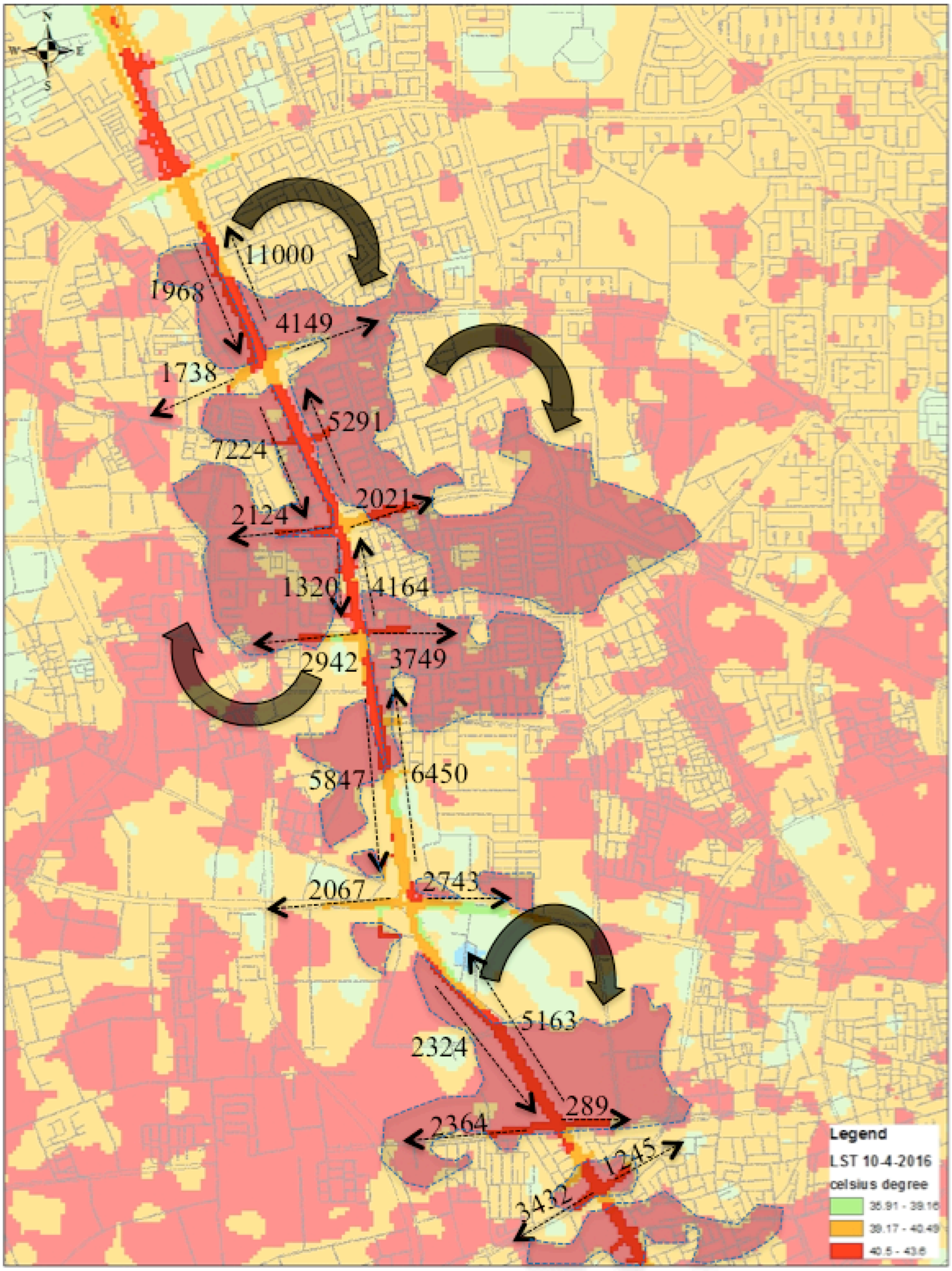

Figure 66. Al-Shamal Road: the role of traffic volume in increasing the surrounding surface temperature (Source: http://glovis.usgs.gov; metadata processed by Author).

4.7 Transforming the Intersection from Heat Island to Cool Island

Ahmed Bin Ali Street is the most active street in Doha, and recorded the highest temperatures in the summer and winter. Figure 67 shows an intersection located on this street in a very active mixed-use area, where many commercial and financial services are provided. There is also a green area along this part of the street. This mixed-use area can be considered a public attraction as it hosts schools, a hospital, shops, restaurants, petrol stations, governmental buildings, and other institutions and offices. All of these services attract people both day and night, so this part of the road is busy almost all of the time.

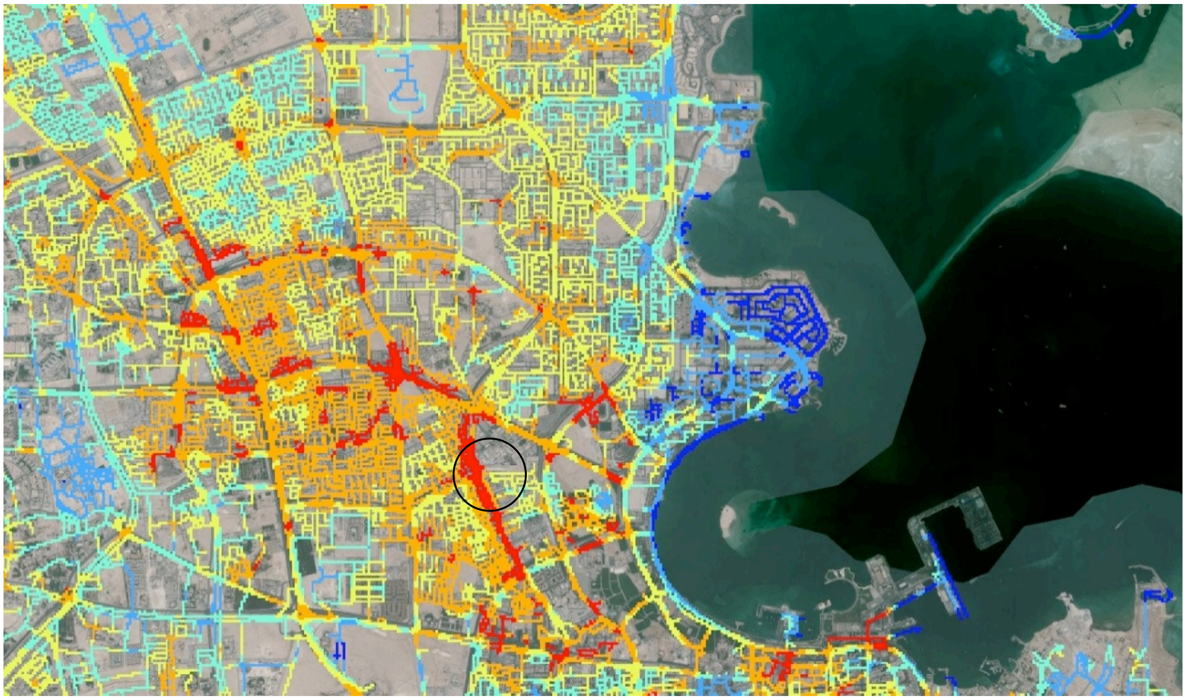

Figure 67. Intersection location (Source: Author).

Figure 68. Intersection area (Source: Google earth).

As discussed earlier, to reduce surface temperatures in places like this intersection, all of the following are critical: shaded pedestrian pathways, bicycle routes, trees, and a reduction in time cars must wait at the intersection. Figure 69 illustrates how an intersection can be transformed for the better when car-oriented streets are replaced with "green streets," leading to enhanced local thermal conditions and subsequent human comfort. Such changes are possible by altering the way in which streets are designed, incorporating narrower street lanes which slow down traffic, as well as walkways, cycle lanes, and landscaping. It is proposed that intersections like the one depicted in the figure will reduce the adverse effects of cars and enhance the quality of air, improving human comfort.

Figure 69. Intersection proposal (Source: Author).

This prototype illustrates how a number of options can be brought to bear simultaneously to reduce traffic congestion and enhance the microclimate. These options incorporate design elements such as pedestrian paths, urban furniture, lighting, suitable paving materials, and pedestrian crossings. The prototype addresses 4 main aspects:

- Vegetation
- Shade
- Accessibility
- Various mods of transportation

Reduce the effects of cars and enhance the quality of air and improving human comfort.

4.8 Chapter Summary

Population growth in Doha has been on the rise, due in part to the hosting of many mega-events in the city. Many of the newer mega-projects incorporate efforts to protect the environment, which may therefore help reduce the UHI effect in Doha. These efforts include the establishment of green areas with trees and shading devices along pathways, along with environmentally friendly transportation options.

The analysis of Landsat images has provided an overview of the UHI in Doha. The areas most affected by the UHI are Doha's airport, areas of dense industrial activity, road networks, and areas of heavy construction. This study focused in particular on the road network, which was recognized as a UHI in all of the images that were analyzed. Clearly, the overall impact of Doha's roads on the UHI has been strong. This research explored issues related to traffic volume, identifying roads with the most traffic and correlating traffic volume and surface temperatures on those roads during the morning rush hour, the time of day with the heaviest traffic. Temperature measurements obtained by satellite were confirmed to be accurate, and consistent effects of traffic volume on temperature were found. This is because these heated surfaces release heat gradually; field measurements provided a clear determination of road surface temperatures during the morning and evening rush hour periods. All of this takes place against the backdrop of overall high temperatures on the city's roads.

The analysis of land surface temperatures revealed that temperatures within the road system are usually higher than those of the surroundings, due to heat from cars and other vehicular traffic. Part of the UHI effect can be attributed to the dark paving materials that are often utilized on streets and in parking lots. Heat transmission during motorized travel adds to the heat island effect and to global warming more generally. The impact of traffic, heat from car engines, and paving materials which absorb and release warmth, all add to the heat island effect in Doha. Transfer of this heat throughout the city is also aided by the movement of cars and other vehicles.

The analysis found a correlation between traffic volume and strength of UHI effects. The city's traffic acts as an instigator of heat formation in Doha. A chief cause of this is the fact that all important sectors and government agencies are based in Doha, so that the need for commuting is high, increasing heat island effects in the city. Furthermore, most road intersections recorded high temperatures even with low to medium traffic, showing that traffic congestion adds to the UHI because of the heat produced by vehicles.

This chapter has provided a thorough overview of heat distribution effects in Doha. High traffic volume is responsible for a certain amount of heat formation, creating UHI effects to which traffic jams contribute further; all of the intersections examined here recorded higher temperatures than their surroundings. Additionally, correlation between traffic volumes and surface temperatures was found to be relatively weak, because of the much more significant contribution to heat from traffic jams. When cars move slowly or have stopped, they have more time to release heat at specific points; this heat is then absorbed by the surface of the underlying road.

Road exits from routes with more connectivity to urban areas tend to dissipate such effects of vehicles on the surroundings. The implementation of more connected and accessible roads should help mitigate UHI effects. Furthermore, by transforming the intersection form heat island to cool island by implementing pedestrian pathways and green areas.

In summary, many factors have been found to contribute to the UHI in Doha, beyond the very high air temperatures and humidity during the summer. Urban design incorporating ideas such as transit-friendly growth and the “People’s Urbanism” can be suggested as ways to help reduce the UHI. The data analysis carried out here has confirmed that motorized vehicles have a significant influence on heating Doha’s urban areas, creating a significant and adverse effect on human comfort within the city.

CHAPTER 5: DISCUSSION OF THE RESULTS

5.1 Introduction

This study tested the hypothesis that motorized transportation contributes to the UHI in Doha, and explored ways to mitigate UHI effects. The results indicated that the emission of heat from vehicles increases Doha's UHI, due largely to the fact that traffic congestion leads to higher surface temperatures on the city's roads. A number of other factors also contribute to the heat island effect, including energy consumption, especially in the summer.

Urban areas recorded relatively high temperatures, with some obvious variation based on time of year (i.e., winter temperatures were lower than those in the summer). Other relevant factors include urban materials, which variously reflect or absorb solar radiation. The primary aim of this study was to investigate whether and to what extent traffic volume contributes to UHI effects. The connection between the density of traffic and the formation of heat was analyzed using data taken from remote sensing and field measurements. As an outcome of this research, three sources were identified as having a particularly great impact on heat formation in Doha, thus acting as primary contributors to the UHI; these were:

1. Main roads in Doha are a significant source of heat.
2. Traffic jams, even those having an overall low traffic volume, enhance these effects.
3. Airflow redistributes and spreads the heat generated as a result of items (1) and (2).

These factors play a major role in increasing heat in Doha's urban areas. In short, vehicles are a key driver of heat emission and distribution in the city. To achieve a reduction of these effects, it will be necessary to implement regulations aimed at mitigating vehicles' heat production, in part by reconsidering how paving materials are incorporated into the city's roads. Design aspects must play an important role in any such effort.

This study's findings support the study hypothesis stated earlier, that the city's traffic contributes to the UHI in Doha, in that roads with more traffic in fact did tend to record higher temperatures.

5.2 Traffic Adds to UHI

This study has shown that heat from vehicles adds to the UHI which add to the local air temperature in Doha, as does the influence of traffic congestion, such as the kind found at road intersections and acting as "hot spots." A clear relationship between UHI effects and traffic volume was captured via the map analysis carried out here. Among other things, the analysis showed that land surface temperatures were higher on paved roads. Exposure to heat from vehicles' motors leads to a temperature rise in nearby surfaces, which is then transferred to the city.

Key factors that affect the city's microclimatic conditions can be summarized as follows:

1. Atmospheric: air temperature, wind and humidity all have influences on outdoor human comfort.
2. Surface: asphalt and other building materials affect the distribution of heat throughout the city.

3. Vegetation: green areas and trees create shade which enhances urban climatic conditions.
4. Building systems: energy consumption for the cooling of buildings has a significant impact on the environment, including effects linked to warming.

In addition to the factors outlined above, an adverse heating impact on the environment was seen to be due to the city's transportation system – both from the vehicles themselves, due to their heat emissions, and from asphalt, because of its tendency to absorb and re-radiate heat. This dynamic was responsible for large-scale heat formation in Doha. Moreover, the findings revealed that road intersections recorded relatively high temperatures, due to traffic congestion, even when traffic volume was low. Roads with high traffic volumes also showed high temperatures, with relevant factors affecting heating including traffic speed and road width. Grote has stated that the main factors affecting the amount of heat and other emissions from traffic include the size of road intersections, distance, prevailing traffic speed, and vehicles' size (Grote, 2016).

Microclimatic conditions in the city are thus affected by the factors mentioned above, the net effect of which can be a reduction in human comfort due to the resultant outdoor thermal conditions. The urban fabric also affects climate. Inappropriate road designs tend to lead to an unfavorable urban environment (Farr, 2008), including decreased outdoor human comfort. Reducing the amount of motorized vehicles on the roads, such as by deliberately limiting the allowed number of cars, can reduce the amount of heat emanating from traffic. In addition, design aspects can play a major role in reducing negative impacts on the environment.

5.3 Surface and Air Temperatures

The surface has an indirect effect on air temperatures, and vegetation and parks function as cool areas. Urban areas typically have warmer air temperatures than their surroundings. Air temperature is affected by both general atmospheric conditions and local surface temperatures.

5.4 Urban Design and UCI

UHI effects and pollution cause health problems. To mitigate the risk of such health hazards and other negative aspects of city life, many solutions are available, including green roofs and green areas, more parking spaces, and mixed-use urban centers that encourage walking. These are but some of the ways to reduce a city's Land Surface Temperature (LST).

In the relevant literature, many ways of reducing the temperature of urban areas are discussed. Targhi and Van Dessel (2015) argued that urban design must take into account the importance of thermal comfort in urban outdoor spaces. For example, pedestrian paths designed for the use of the community will tend to reduce the need for vehicles (Targhi, 2015).

The creation of UCIs can be achieved by designing compact urban areas, and offering more green areas and water elements. Building forms, human activities, and energy consumption also affect the local urban climate. Additionally, many of the world's cities (e.g., London, Hong Kong, Tokyo, downtown Sacramento, California, and Buffalo, New York) have recorded higher temperatures in the absence of sustainable urban design and transit-friendly growth. Such design and growth improve connectivity within a city by increasing the number of pedestrian pathways, thus leading to a decrease in the need for cars for the sake of mobility. Smart growth supports the design of compact urban areas that reduce the need for commuting and offer numerous pedestrian pathways. Access should be provided to multiple modes of transportation, linked to pedestrian pathways, to encourage more walking by the public (Wey, 2014).

The implementation of regulations concerning city development can help to manage urban growth. For example, many activities taking place in urban areas produce excessive heat. If such activities are relocated outside urban areas, the result is more livable urban spaces. Lessons can be learned from the traditional design of historic cities in efforts to transform a city from one with dominating UHI effects to one more balanced through the presence of UCIs.

Such initiatives can form part of an approach to urban design which reduces a city's negative impact on the environment. In order for this to be feasible, it is necessary to reduce the number of people who commute regularly by car. In addition, green areas, green corridors and green infrastructure enhance the microclimate and human comfort by providing shade from trees. Furthermore, these areas act as tools for mitigating UHI effects.

5.5 Transit-Friendly Design and Growth

Combining transit mechanisms and urban design is important for the sake of managing a city's transportation and congestion. If carried out successfully, it can help a community to reduce traffic on the streets. The key point here is that this is not about increasing street widths to accommodate more cars, but rather to offer a variety of transport options with people-friendly design in order to reduce traffic. There are many practices that have been implemented successfully in other countries in order to reduce the number of private cars and the total number of vehicles by implementing regulations such as high parking fees. The historic city of Fez has a hot arid climate and is characterized by compact urban design; a reduction in the number of cars entering the city was accomplished by narrowing the city’s roads. This has had multiple benefits including a smaller impact of traffic on the environment, improved microclimatic conditions including a more comfortable outdoor climate, and a reduction in net energy consumption.

Another example of a successful experience in decreasing the number of cars in a city has been the implementation of a congestion charge in Stockholm. This measure faced problems of public acceptance before its implementation, but significant and favorable results have been observed afterwards. These include reductions in traffic congestion and air pollution from car emissions, leading to an enhancement of air quality.

It is important to establish climate-sensitive urban design policies while also enabling user-friendly urban environments. Urban planners and developers should give ample attention to climate-related issues when designing urban spaces.

5.6 Chapter Summary

In some areas of the city, traffic flow showed a weak relationship with land surface temperatures, because traffic volume is a greater contributor to the heat formation instigated by vehicles. The contribution of traffic jams to heating was seen to be quite high, with significant heat generated in congested areas adding significantly to UHI effects. This negative impact is due to heat generated by slow-moving or stopped cars being absorbed by the road surface, resulting in hot microclimatic conditions which decrease human comfort. The results also revealed that road intersections acted as hot spots in Doha, and that road networks in general exhibited high temperatures.

Dependency on cars, typically for commuting, is clearly responsible for increasing the heat on Doha's roads, especially at intersections. Many primary areas of activity (government buildings, universities, workplaces and entertainment destinations) are located in the city center of Doha, thus increasing the number of cars entering Doha. This situation is exacerbated by the lack of a developed public transport system.

In order to mitigate the health risks and other negative impacts that result from this situation, a variety of policy options should be considered, including green roofs, more parks and vegetation, and other means discussed earlier in this manuscript of reducing the city's LSTs. Urban planners and developers can play a crucial role in creating urban outdoor designs which lead to comfortable thermal conditions. This is quite feasible in compact urban areas, for example, by using shaded pathways to reduce the amount of incoming solar radiation and thereby aiding the formation of urban cool island effects.

Many new concepts in urban planning attempt to deal with environmental issues in order to reduce the negative impacts of the urban environment and enhance the quality of life for the people there. Some of these concepts include “smart growth,” which encourages people to walk and use public transportation rather than depending so much on cars. Other concepts include “transit-oriented development” (TOD), which promotes the development of compact urban areas offering a variety of transportation options that are well-designed and convenient to use.

In conclusion, the findings of this study can prove influential in reducing the UHI effect and enhancing microclimatic conditions and human comfort, especially in hot arid climates like that of Doha. This can be done by increasing the prevalence of open spaces, shaded areas and other drivers of cool island effects; decreasing traffic congestion; and supporting sustainable forms of urban transport and development.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

This thesis began with a discussion of the recent literature, in order to contextualize the research questions and methodological underpinnings of the study. This concluding chapter summarizes the theoretical and empirical value of the findings that were presented and discussed in the body of the thesis. In sum, the findings of this study offer practical guidelines for enhancing the quality of life in cities like Doha by improving outdoor thermal conditions and human comfort.

6.1 Conclusion

The UHI effect is an important phenomenon observed in many modern cities, due to which air temperatures and surface temperatures in urban areas tend to be elevated. Research has shown that UHIs have a major influence on urban environments, although the specifics of that influence can vary based on local conditions (Kolokotroni, 2006).

Study of this phenomenon is of great importance because of its negative impact on the environment in terms of increased air pollution, human disease, and general human discomfort. Within a given city, the prevalence of UHI effects is often related closely to urban form and design in that city. In general, rapid urbanization tends to increase the probability that heat islands will form, due to the materials typically used in urban settings as well as a lack of suitable urban design and building forms. Dark material absorbs heat and can reach temperatures of up to 59 °C. Urban surfaces also tend to allow less surface evaporation than green areas and trees allow, and are characterized by increased capacity for heat storage. UHI effects can contribute a net temperature increase of up to 10 °C, relative to rural surroundings, when the effects of other environmental factors are taken into account (Tam, 2015). Such effects lead to human discomfort, high levels of energy consumption, and increased pollution, and other health hazards.

The main research questions of this study aimed to determine (1) the relationship between motorized transport and the UHI in Doha, (2) the relationship between UHI effects and the intensifying traffic problem in Doha, and (3) the areas that are affected by UHI effects in Doha, as determined from LST maps.

This study contributed to the understanding of motorized transportation and traffic on the UHI in Doha, as well as the correlation of UHI effects with traffic congestion within the city, including in areas with overall low traffic volume. These findings were the outcome of an analysis of land surface temperature (LST) maps. It was found that there is a strong relationship between traffic and UHI effects. The road network in Doha recorded high temperatures even in winter, as hotter surface temperatures and thermal inversion combined to result in warmer air. Traffic volume affected thermal inversion and heat formation, which constitute an indirect impact of increasing mobility within the city. The direct impacts of increased mobility include noise and carbon emissions, as well as the heat emissions from motorized vehicles that are a key contributor to increased UHI effects.

There are many areas affected by UHI effects, such as the airport, the industrial area, and the road network. Most large-scale construction areas also exhibited high temperatures on LST maps. The results show that the main roads in Doha (Al-Shamal, Salwa and Al-Khor Roads) had the highest traffic volumes as well as high temperatures. The road intersections in Doha with frequent traffic jams recorded high temperatures, and congested roads recorded high temperatures even if their overall traffic volume was relatively low. This is a clear indictor that motorized transportation and traffic contribute greatly to the UHI in Doha. It is also evident that such effects can be aggravated by atmospheric conditions such as air temperature, wind, and humidity.

The field measurements for Al-Khor Road showed temperatures as high as 54 °C during the summer. The high temperature of the surface produced hotter microclimatic conditions and lowered the air quality. The need for new public transport options to reduce the traffic in Doha is clear, and it is expected that the rail network currently under construction will reduce the city's traffic volume by 190,000 cars per day, leading to a daily CO2 emissions reduction of 162 tons. This should result in a marked improvement in the comfort and health of the people in Doha. Other measures can also be taken to reduce UHI effects and increasing UCIs, such as through the use of trees and shaded areas (Kong, 2014). Compact urban areas that are well-designed and make available a wide range of residential needs also reduce the need to commute and encourage people to walk. This can also reduce negative impacts on the environment and enhance quality of life. Relevant concepts that lead to transit-friendly growth and promote the "People's Urbanism" include transit-oriented development (TOD), smart growth (mobility), and New Urbanism. All of these concepts focus on improving quality of life by reducing negative impacts on the environment through the implementation of urban compact areas with a variety of modes of transportation and a high level of thermal comfort outdoors.

This study's exploration of the UHI in Doha has supported for the research hypotheses presented at the beginning of the manuscript. Many areas are affected by the UHI in Doha, and map analysis clearly shows that these include the industrial area and the airport, which are the most affected areas. This is because of heat emissions caused by energy consumption from industrial activity. Motorized transportation and heat exposure during motorized travel both contribute greatly to the UHI. It is important to reduce the impact of UHI effects and high energy consumption for the sake of human comfort in the city, and develop sustainable urban areas by creating “green streets” and shading in car-oriented regions.

6.2 Recommendations

The results of this study show clearly that controlling and managing the heat emitted by cars in the center of Doha is crucial. In addition, the following steps should be taken:

- Development of compact (mixed use) urban centers offering all necessary residential services.
- Decentralization of government buildings, universities and entertainment locations.
- Increasing tree plantation to produce more shaded areas.
- Expansion of pedestrian paths and jogging areas.
- Promoting the Green Movement in the city and creating green streets.
- Urban H/W should considered on design which may enhance the microclimate condition and, thus, mitigating the UHI.

Transportation options and land use distribution have a significant impact on cities. Urban connectivity and high density similarly have a strong influence on the possibilities of smart growth trajectories for cities. There are many relevant aspects of this, including social, economic, and environmental factors; all must be taken into consideration for the ultimate goal of developing healthier, more sustainable communities. It is also the case that political factors have a major impact on the development of urban areas. Positive changes can start with regulations that favor high-density urban zones with mixed-use areas that provide multiple services in nearby locations. This avoids dependency on a commuting model, in which frequent car travel from place to place is necessary to satisfy people's day-to-day needs. Such a theory of smart growth can help in the future planning of Qatari cities and municipalities. It can help urban planners design better hospitals and schools for example, and can also be useful in implement regulations concerning private cars and public transportation that will ultimately lead to enhanced microclimatic conditions in Doha.

6.3 Limitations

It is difficult to specify exactly how variables operating on large scales, such as wind direction and humidity, impact outdoor thermal conditions and human comfort. Furthermore, it is challenging to determine the precise role that traffic plays in increasing nearby air temperatures, because there are no clearly established techniques of measurement.

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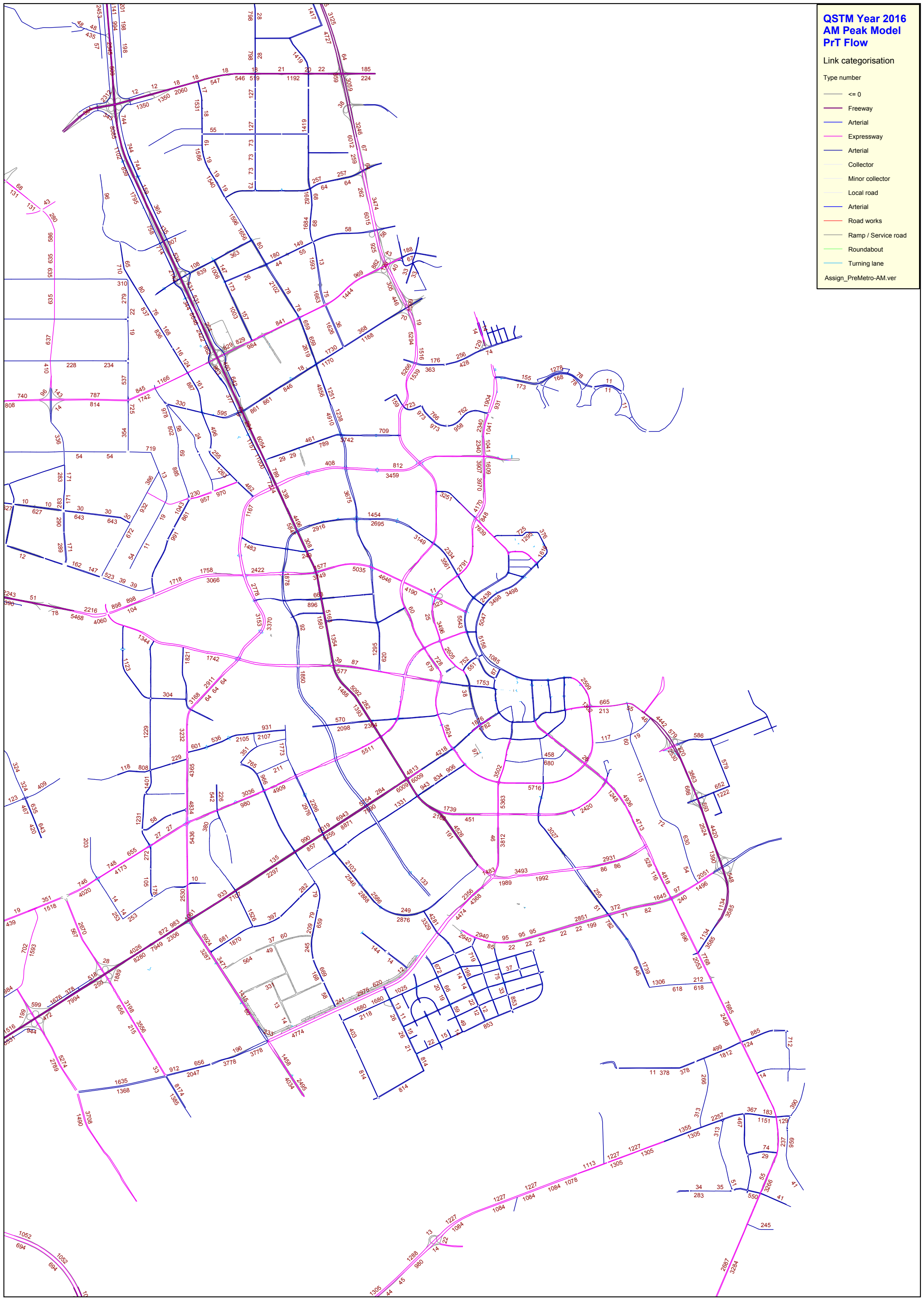
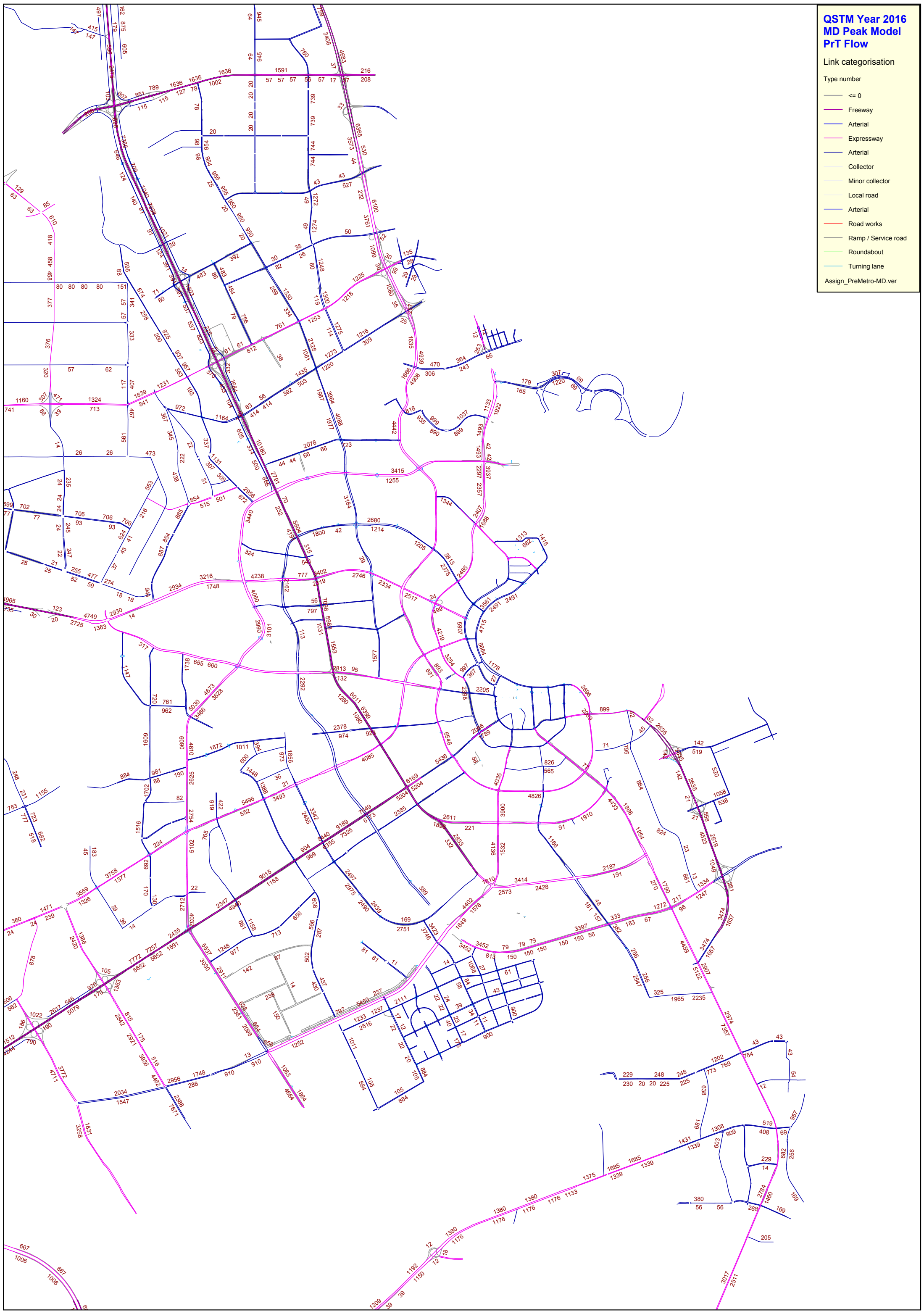
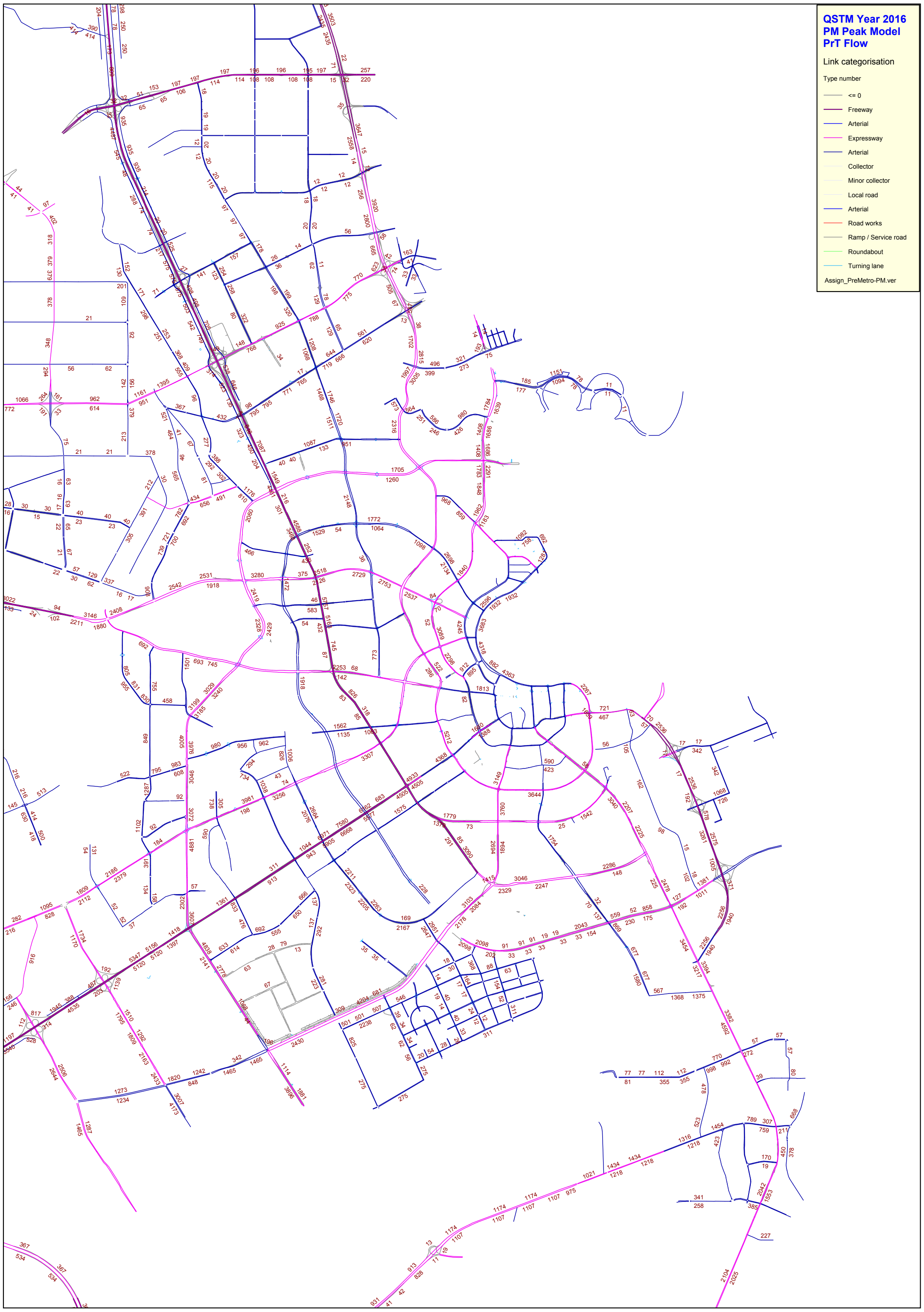
Appendix A: Data collection (Maps)



A: Morning Rush hour AM



B: Mid Day Rush hour MD



C: Evening Rush hour PM