

SPATIOTEMPORAL VARIATIONS IN THE IMPACTS OF URBAN LAND USE TYPES ON URBAN HEAT ISLAND EFFECTS: THE CASE OF RIYADH, SAUDI ARABIA

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ABSTRACT:

Urban heat island (UHI) effect is considered to be one of the key indicators of the impacts of urbanization and the climate changes on the environment. Thus, the growing interest in studying the impacts of urbanization on changes in land surface temperature (LST). The literature on LST indicates the need for more studies on the relationship between changes in LST and land use types, especially in the arid environment. This paper examines the spatial and temporal changes in land surface temperature influenced by land use/land cover types in Riyadh, Saudi Arabia. Multi-temporal Landsat images of the study area, 1985, 1995, 2002 and 2015, were processed to derive land surface temperatures. UHI index was computed for the different land use/land cover types (high-density residential, medium-density residential, low-density residential, industrial, vegetation, and desert) in the study area. The results indicate a trend of rising temperatures in all the land use types in the study area. This is probably due to climate change. The industrial area has the highest temperatures among the land use types. The lowest temperatures are found in the vegetation area as expected. There is a need to implement mitigating measures to reduce the effects of rising temperatures in the study area.

1. INTRODUCTION

The level of urban growth and spatial expansion, especially in the developing countries, has been unprecedented. The global urban spatial extent has been increasing at a rate higher than urban population growth rate (Seto et al., 2011). The global urban extent that increased by 58,00 km² from 1970 to 2000 is expected to most likely increase by 1.5 million km² in 2030 (Seto et al., 2011). A recent study by Li et al. (in press) posited that global urban extent could increase by 1.2 million km² from 2010 to 2050. The rapid expansion of urban land use has impacts on climate (Seto and Shepherd, 2009; Mishra et al., 2015), flood risk (Muis et al., 2015), biodiversity (Grimm et al., 2008), carbon emissions (Houghton et al., 2012) and energy use (Santamouris et al., 2015; Güneralp et al., 2017). The impacts pose challenges to cities in their drives towards achieving urban sustainability and meeting the sustainable development goals (SDG).

One of the impacts of rapid urbanization and urban expansion is urban heat island (UHI). Urban heat island is attracting growing attention due to its implication for climate change and urban sustainability. It is an occurrence whereby an urban area has a higher temperature than its surroundings (Voogt and Oke, 2003). The urban heat island effects are caused by the anthropogenic features and activities of urban areas. Urban natural surfaces are changed to impervious surfaces, buildings and road network during the process of urbanization and spatial expansion. The variations in the surface materials, land use and morphology of urban areas influence local temperatures and make urban areas warmer than the surrounding non-urbanized areas. It is important to monitor urban heat island effects to implement mitigating measures. However, the conventional way of monitoring through ground measurements is limited in

spatial coverage. Historical weather data are obtained mainly from airports and weather stations that might be located on the outskirts of cities. It might not be feasible to obtain data with adequate spatial coverage through ground measurements due to the required sampling (Li et al., 2013). The development of thermal remote sensing has provided opportunities for getting data at varying spatial resolution and coverage.

Satellite-derived thermal data have been used to study UHI parameters and the relationship between UHI and urban physical components (Voogt and Oke, 2003; Weng, 2009; Ngie et al., 2014). Yue et al. (2007) and Zhang et al. (2009) examined the relationship between satellite-derived land surface temperature (LST) and normalized difference vegetation index (NDVI), a measure of vegetation abundance. Studies by Zhou et al. (2011), Lu et al. (2015), Gage and Cooper (2017), Odindi et al. (2017) and Berger et al. (2017) highlighted the relationship between LST and land use/land cover. Gage and Cooper (2017) and Berger et al. (2017) included vertical structure in their analysis to study the effect of the height of structures on surface temperature. Bechtel (2012) and Jiang and Weng (2017) estimated UHI parameters from land surface temperature. Though the need for more studies on the estimation of UHI parameters had been emphasized by Weng (2003), the studies on the relationship between LST and urban land use/land cover still prevail. Time series and statistical analysis and modelling (Fu and Weng, 2016; Li et al., 2017; Tran et al., 2017) have been used to better understand the influence of the characteristics of urban surfaces on UHI.

In Saudi Arabia, particularly Riyadh, the studies on UHI are limited despite the rapid spatial expansion of the major cities (Aina et al., 2008; Rahman, 2016; Alqurashi et al., 2016a;2016b) and some documented environmental impacts

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(Aina et al., 2014; Alqurashi and Kumar, 2016). The studies by Lim et al. (2007) and (2011), Hereher (2016) and Aina et al. (2017) were based on Madinah, Qassim, Makkah area and Yanbu. The studies on Riyadh were based either on single year analysis or old satellite data (at least five years old) (Alghamdi and Moore, 2015; Lazzarini et al., 2015). Thus, this study aims at examining the effects of variations in land use/land cover types on urban heat island effects in Riyadh.

2. MATERIALS AND METHODS

2.1 Study Area

Riyadh is the capital of Saudi Arabia and the largest city with a global city status (Short, 2017). According to a government estimate in 2016, the population of the city is about 6.5 million and the population growth rate is about 4% (<http://www.ariyadh.com/Eng>). The number of housing units in Riyadh is 1.2 million (<http://www.ariyadh.com/Eng>). It is located close to the centre of Saudi Arabia, away from the two coasts at the west and east of the country (Figure 1). Riyadh climate is dry and the temperature varies from 11 degrees Celsius in winter to 42 degrees Celsius in summer (<http://www.ariyadh.com/Eng>). Though recent efforts have been made to establish public transport in Riyadh, the city's transportation has been automobile-dependent. This has implications for greenhouse gas emission and urban climate.

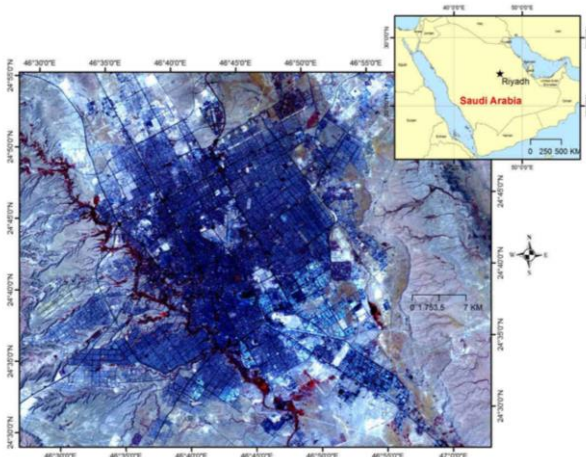


Figure 1. Location and spatial extent of Riyadh

2.2 Landsat and urban density data acquisition

The study used multi-temporal Landsat data downloaded from the USGS website (<https://earthexplorer.usgs.gov>). The years and the sensors of the data downloaded are shown below (Table 1). The study area is located at the edge of two Landsat scenes, so two images were downloaded for each year.

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

Table 1. Details of the downloaded satellite data

An urban density map of Riyadh was extracted from an official document (ADA, 2003) and Google Earth was used to confirm the density of the identified residential density areas (High,

Medium and Low). The confirmation was carried out by checking the closeness/compactness and height of the buildings. The assumption is that high-density areas will have high buildings that are close to one another while low-density areas will have low buildings that have spacious surroundings. Other land use/land cover types such as industrial, vegetation and desert were identified by using Google Earth only. Samples (50 points per land use/land cover) were taken to analyse the effect of land use land cover on UHI (a total of 300 points).

2.3 LST estimation and data analysis

The first step in estimating LST is to convert the pixel values of the dataset to at-sensor spectral radiance (L_λ) by using Eq. 1.

$$L_\lambda = \text{Gain} * \text{DN} + \text{Bias} \quad (1)$$

where L_λ = at-sensor radiance
Gain = slope of the radiance (Table 2)
Bias = intercept of the radiance (Table 2)
DN = digital number (pixel values)

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

Table 2. DN conversion coefficients (Source: Chander et al., 2009)

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

$$\text{LST} = K_2 / \ln(K_1 / L_\lambda + 1) \quad (2)$$

where LST = LST at-satellite brightness (Ye et al., 2017)
 K_1 = calibration constants (Table 3)
 K_2 = calibration constants (Table 3)
 L_λ = at-sensor radiance from Eq. 1

Sensor	K_1 ($\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$)	K_2 (K)
TM	607.76	1260.56
ETM+	666.09	1282.71
TIRS	774.8853	1321.0789

Table 3. Thermal band calibration constants (Source: Chander et al., 2009)

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

After the derivation of the LST, the sample points (300) were used to extract the LST values for the different land use/land cover types. The statistics (mean and standard deviation) of the values were computed for the different land use/land cover types. One way analysis of variance (ANOVA) was performed to determine if the differences observed in the LST values were significant.

In addition, a UHI index was calculated for the different land use/land cover using SUHI – Surface Urban Heat Island, as shown in Eq. 3 (Voogt and Oke, 2003; Lazzarini et al., 2015).

$$\text{SUHI} = \text{LST}^{(\text{URB})} - \text{LST}^{(\text{SUB})} \quad (3)$$

where $\text{LST}^{(\text{URB})}$ = LST of urban area (Land use types)
 $\text{LST}^{(\text{SUB})}$ = LST of suburban area (Desert)

3. RESULTS AND DISCUSSION

3.1 Satellite-derived LST

The result of the LST from 1985 to 2015 (Figure 2) shows no prominent trend of increasing maximum temperature. However, the minimum temperature starts its increasing trend from 1995 to 2015. The highest minimum temperature shown is 32°C in 2015 while the lowest temperature is 15°C in 1995.

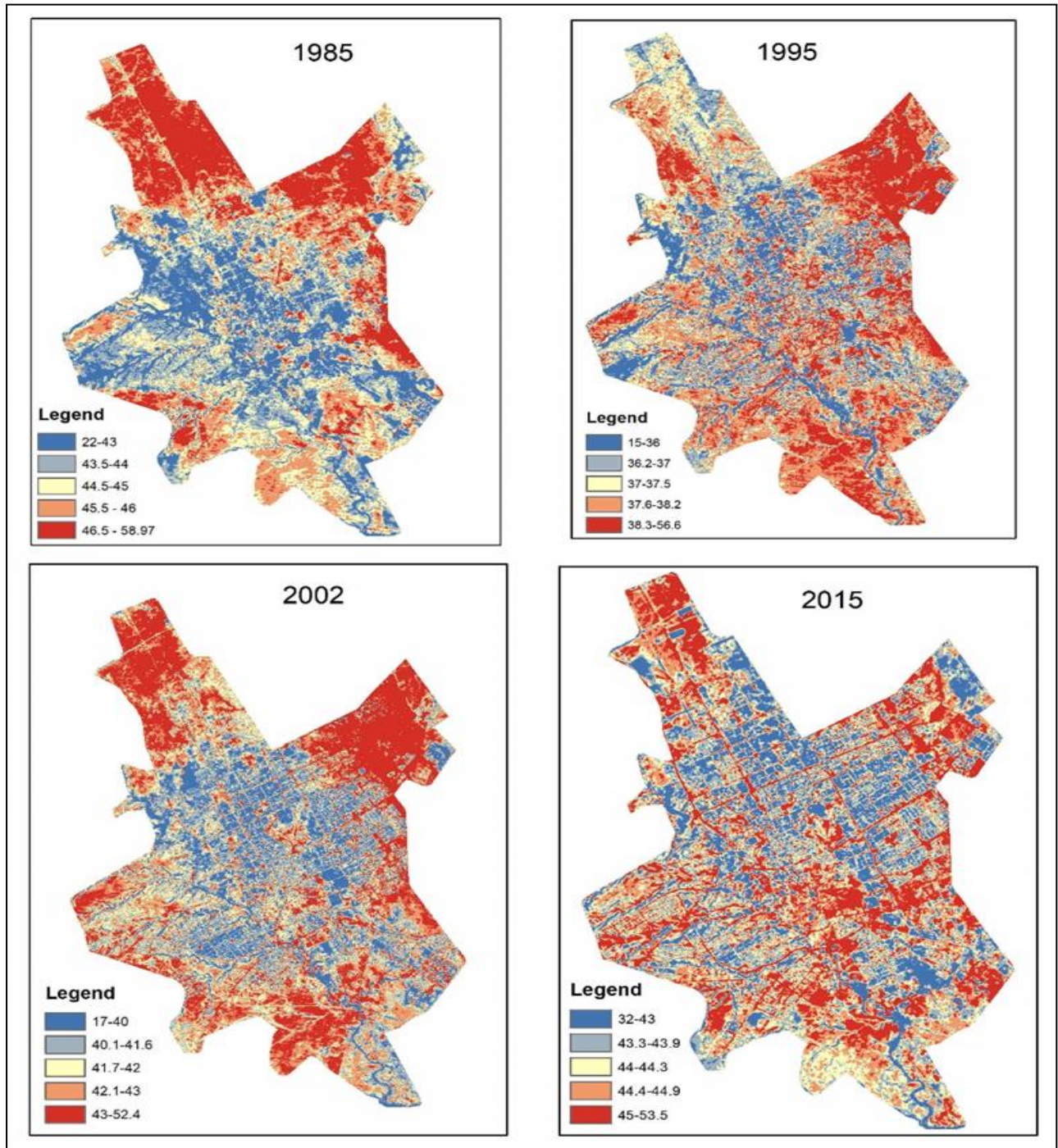


Figure 2. LST dynamics in Riyadh from 1985 to 2015

High temperature values can be seen along the transportation network. The 2015 image (Figure 2) shows the most prominent high temperatures along transport corridors. This is most likely due to the increasing number of vehicles plying Riyadh roads.

3.2 LST and land use types

The results of the statistical analysis are shown below (Table 4 and 5). They show that the desert is generally warmer than the other land use/land cover types. This buttresses the findings of the previous studies by Alghamdi and Moore (2015) on Riyadh and Aina et al. (2017) on Yanbu. The LST means in 1995 are lower than the means of other years. This might probably due to an increase in the vegetation cover from 1985 to 1995. Aina et al. (2008) and Alghamdi and Moore (2015) highlighted that the vegetation cover in Riyadh increased from 1985 to 1998 and thereafter started decreasing. However, changes in the vegetation cover of the built-up area might not account for the decrease in desert temperatures in 1995. The results indicate a trend of increasing temperatures in all the land use/land cover types from 1995 to 2015. The result of the one-way analysis of variance indicates significant differences in the LST of the land use land cover types at 0.01 level.

Land use type	1985		1995	
	Mean	Standard Deviation	Mean	Standard Deviation
Desert	45.58	3.28	37.84	1.23
High density	42.34	0.73	37.36	1.18
Medium density	45.63	1.83	37.62	1.07
Low density	43.62	1.07	37.64	1.03
Industrial	40.47	3.78	36.13	3.48
Vegetation	43.33	4.54	35.25	3.08

Table 4. Mean and standard deviation of LST by land use types in 1985 and 1995.

Land use type	2002		2015	
	Mean	Standard Deviation	Mean	Standard Deviation
Desert	44.15	1.78	45.22	1.25
High density	42.05	0.95	44.39	0.51
Medium density	42.97	1.76	43.46	0.67
Low density	40.82	1.19	43.60	0.86
Industrial	40.98	3.73	45.14	1.97
Vegetation	40.19	4.53	40.30	2.90

Table 5. Mean and standard deviation of LST by land use types in 2002 and 2015.

3.3 SUHI analysis

The SUHI analysis shows that the desert is warmer than the other land use/land cover types (Table 6). Almost all the SUHI results are negative except the SUHI of medium density in 1985 (Table 6). The results are in line with the findings of Alghamdi and Moore (2015) but conflicts with the findings of Lazzarini et al. (2015). Lazzarini et al. (2015) claimed that the built-up area of Riyadh has positive SUHI compared with the suburbs (the desert area). The SUHI values of high-density, low-density, and industrial areas show an increasing trend from 1985 to 2015 to indicate that their values are nearing the desert values (Table 6).

On the other hand, the SUHI values of vegetation and medium density areas show a reducing trend (Table 6).

SUHI	1985	1995	2002	2015
High density	-3.25	-0.482474	-2.10	-0.82
Medium density	0.05	-0.21653	-1.18	-1.76
Low density	-1.96	-0.200666	-3.34	-1.61
Industrial	-5.11	-1.711856	-3.18	-0.08
Vegetation	-2.25	-2.59453	-3.97	-4.92

Table 6. SUHI values of different land use types (1985 – 2015)

4. CONCLUSIONS

The study has shown the changes in the LST values of the different land use types in Riyadh. The trends of some of the indices require attention. There is a need for further study to derive the LST rather than using the at-satellite brightness. Also, population data of the study area can be used to analyse the exposure of the populace to high temperatures.

Different mitigation measures should be introduced to abate the negative trends. The recent initiative to design road centrelines with greenery might be useful in reducing UHI effects in Riyadh.

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