Mapping Urban Heat Island Effect in Comparison with the Land Use, Land Cover of Lahore District

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Abstract

As the population in urban areas around the world grows each year, cities struggling to cope with the increased urban migration expand at varying rates. This urban sprawl comes with the expansion and exacerbation of the Surface Urban Heat Islands (SUHI) of cities. The connection between land-use/land-cover (LULC) and the Land Surface Temperature (LST) is the focus of this study, more specifically which of the LULC practices prevalent in Pakistani cities are particularly contributing to the formation, expansion and intensification of SUHIs is the question this study aims to answer.

LST of the district of Lahore was calculated using Landsat images more than a decade apart. The LULC types were also mapped using supervised classification techniques, while the training areas for the classification were gathered using random sampling technique during a survey of the study area. Using the resultant LST & LULC maps of the city and superimposing the boundaries of several new satellite towns of the city, the temporal changes in LST and LULC were compared.

The built-up surface area within the city district in 2011 showed 25% increase since 2000, this caused the SUHI to expand as well. Previous studies pertaining to the issue of LST in Pakistani cities have shown the fact that with the growth of the cities the SUHIs have also grown, this study goes a step further and identifies the specific land use activities and land cover types that have contributed to the expansion as well as intensification of the SUHI. Among the identified LULC classes, the Sand/Vacant land class consistently turned out to the warmest of LULCs found in the study area. Further focus on individual neighborhoods of the city show that the rise and fall of the Sand/Vacant Land LULC type also accompanies the rise and fall of the average LST of the area. The average LST of the entire target district showed a rise of 0.73 ℃ in 2011.

The study concludes that the ever increasing encroachment of the city's newly developed suburbs over the countryside have accompanied an overall warming of the district's average LST over the past decade and that letting the land lie vacant for years after clearing the agricultural fields for future urban development is a practice that has undesirable environmental effects. Adding more environmental factors and increasing the temporal span of the study would help ascertain a causal relationship between UHI and LULC practices.

Key Words: Surface Urban Heat Island, Land Surface Temperature, Urban Climate.

Introduction

Human beings have been living in cities for millennia, the first of these are believed to have sprung up in Mesopotamia and the Indus Valley Civilization. Today settled areas are generally divided into the categories of urban and rural. Living in cities has its pros & cons, the very purpose of developing cities included greater economic activity with markets and business centers along with these was proximity to political power, better health, education, transportation and communications facilities. As cities grew so did their problems, to sustain growth not only did the stress on natural resources in the surrounding areas increase but also increased the degree of planning and management that was required to keep those cities running.

Pollution, being among the problems associated with urbanization, is of many sorts. Pollutants can pertain to many kinds of environments in different states i.e. it can be solid, liquid, gas and even energy. The activities that human beings perform in their daily lives waste energy and this wasted energy can sometimes cause unwanted effects. The effect here we are most concerned about is that of excess heat. When cities are built changes are made to the existing environment, these changes affect

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the energy balance of the entire environment by altering the transfer and storage of energy. This gives rise to the phenomenon called the Urban Heat Island (UHI). "The surface urban heat island (SUHI) effect is defined as the increased surface temperatures in urban areas in contrast to cooler surrounding rural areas," according to Sobrino et al., (2013).

Like many metropolises of the world, the city of Lahore has experienced massive growth in terms of its geographical size & population in recent years. The status of being the administrative, financial & cultural center of the region has led to consistent expansion of the city, to accommodate the ever increasing population most prominently due to the rural-urban migration.

Apart from the inherent side effects of unchecked expansion like congestion, rise in crime, weak administration etc. there are other disadvantages too. One such drawback is the alteration of the urban climate due to growth and intensification of the Surface UHI, especially when this growth comes at the expense of agricultural land. The disappearance of vast areas of green fields is not only a loss of aesthetics but also increases food insecurity and more importantly, for our concern, the loss of the cooler vegetative land cover. This would lead to an expansion of the SUHI of the city as the countryside recedes. The crowding of the city center(s) would in all likelihood also lead to the intensification of the SUHI, in areas of dense urban development.

It'd be desirable to ascertain the presence and extent of the SUHI for the city of Lahore during the course of this study. The relationship between the identified LULC classes & the observed LST will also be assessed. Specific areas of the city that may have gone through noticeable changes over the time period under observation will be identified and finally to make recommendations for the remedy of any undesired changes in the SUHI of the city.

Land Surface Temperature (LST)

Many human activities associated with urbanization, like vehicular traffic, fossil fuel burning, energy generation etc. generate heat as a by-product which becomes a cause of heat pollution. This increase in heat exchanges between the built environments is further exacerbated by the different nature of man-made structures, which have lower albedo and higher heat storage capacities than soil and vegetation and are more impervious to moisture than natural surfaces (Oke, 1982). This means that buildings and other urban structures tend to be warmer than the air temperature, unlike their rural surroundings (Bertz&Berdahl, 1992); this is how an Urban Heat Island (UHI) is formed.

Several factors like the Earth's energy balance, thermal properties of the target surface along with the amount of exposure to sunlight and cloud cover affect the Land Surface Temperature (LST). It is a key factor affecting most physical, chemical, and biological processes of the Earth (Becker & Li, 1990). Before estimating the LST the spectral radiance needs to be calculated, this is done by transforming the Digital Number (DN) values of the individual pixels of the satellite image into spectral radiance by using the sensor calibration data for the specific satellite (Markham & Barker, 1986). For regional or local scale study of LST Landsat(TM) TIR images are considered sufficient (Larson & Carnahan, 1997), but for studies spanning larger areas, data from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA AVHRR) satellite sensor is recommended by Gallo et al. (1993) and by Gallo & Owen (2002). In fact data from remote sensing satellites is preferred over point measurements on the ground for the LST calculation over large surface areas (Dash et al., 2002)

Data and Methodology

Landsat TM images were acquired for the dates, 28th&^{27th} of April 2000 & 2011 respectively, so that the images used are from the same season 11 years apart. The local time of satellite overhead pass was 10:00 AM (approximately). The average atmospheric temperatures observed for both days in Lahore were 31.5 ℃ and 31.4 ℃ respectively.

Atmospheric temperatures for the corresponding dates were obtained from the websites of the National Climate Data Center of the National Oceanic & Atmospheric Administration of the USA and the World Meteorological Organization (WMO). The daily mean atmospheric temperature readings for both of the days under consideration were also confirmed using temperature records from the Pakistan Meteorological Department. Accurate district boundary for Lahore was obtained through the Urban Unit Lahore.

LULC Classification

The Land-cover and Land-use maps for the study area were developed by performing supervised classification of Landsat TM images for two specific days 11 years apart. LULC types were broadly identified as:

Table 1: LULC classes defined.

LULC Class	Description
High Density Built Up	Consisting mostly of low rise but highly dense built up areas with sparse open space and vegetative cover in between. Areas with plots typically less than 10 marlas (250 Sq. yards) and having most structures of two storeys or more were included. For eg. Ichhra, walled city &Baghbanpura etc.
Low Density Built Up	Consisting of the rest of settlements and urban structures. The building materials for both the Built-up classes includes bricks, cement, concrete asphalt etc.
Fallow Land	By the end of the month of April wheat crop is harvested and most of the agricultural land is left fallow before the sowing of the next crop i.e. rice, so the exposed soil shows different spectral characteristics than barren land
Vegetation	Includes urban vegetative land-cover like grasses and trees etc. and also includes whatever vegetative land cover exists during that time of the month over agricultural fields
Sand/Vacant Land	Includes the area which lies barren year round, this also includes the land cleared up by the construction projects for developing new housing societies, lastly
Water	This class includes all the water bodies in the study area, from ponds and pools of identifiable sizes to canals and the river Ravi on whose banks Lahore is situated.

LST Calculation

Calculation of the LST of the study area was done by utilizing the thermal infrared (TIR) Band 6 of the Landsat TM. The TM thermal band has a noise level comparable to a temperature difference of 0.5 K (Gibbons &Wuckelick, 1998). It also has a spatial resolution of 120 meters.

Using surface emissivity, the brightness temperature is converted to LST using Planck's equation:

$$S_t = T / 1 + (\lambda \times T / \rho) \ln \in$$

As used by Artis& Carnahan (1982) &Weng et al. (2004), here: St is the LST, T is the surface radiation temperature, λ is the wavelength of the band used, in this case = 11.5 μm (Markham & Baker, 1985), the value of ρ used in the above equation = hc/σ = 0.01438 m K, σ here is the Stefan-Boltzmann's constant, h is the Planck's constant and c is the velocity of light. ϵ is the surface emissivity, calculated below.

To calculate T, T = K2/ ln (K1/Lλ+ 1), where K1 and K2 are pre-flight calibration constants: K1=607.76 [W m-2 srμm] and K2=1260.56 K. Lλ is the surface radiance received at the sensor:

$$L_\lambda = \left(\frac{L\max - L\min}{QCAL\max - QCAL\min} \right) \times (DN - QCAL\min) + L\min$$

WhereLmin&Lmax were be obtained from the images' auxiliary files, while QCALmin=1 &QCALMax=255.

Emissivity ϵ = 0.004PV + 0.986 (Sobrino et al., 2004)

Where Pv is the Proportion of Vegetation,

$$Pv = [(NDVI - NDVImin) / (NDVImax - NDVImin)]^2,$$

Normalized Difference Vegetation Index (NDVI) was calculated using atmospherically corrected images of the bands, visible (0.63-0.69μm) and near-infrared (0.76-0.9μm) of the Landsat TM.

This method of calculating emissivity using atmospherically corrected data is called the Normalized Difference Vegetation Index Thresholds Method (NDVITHM) (Sobrino et al., 2011). The methodology used here produces a minimal LST bias of 0.9 ℃ with calibration (Hu & Jia, 2010).

SUHI Calculation

In order to calculate the SUHI of the target area, the LST images obtained for both the years (April, 2000 and 2011) through the preceding procedure were used. For each of the resultant images the following formula was used to calculate the SUHI value for each year:

SUHI = (LST)Urban - (LST)Rural (Tiangco et al., 2008)

Here LST Urban is the average value of LST for the area considered urban and LST Rural is the average LST value for the entire area considered rural inside the district of Lahore.

Results& Discussion

The LULC images thus generated for each of the two acquired images follow:

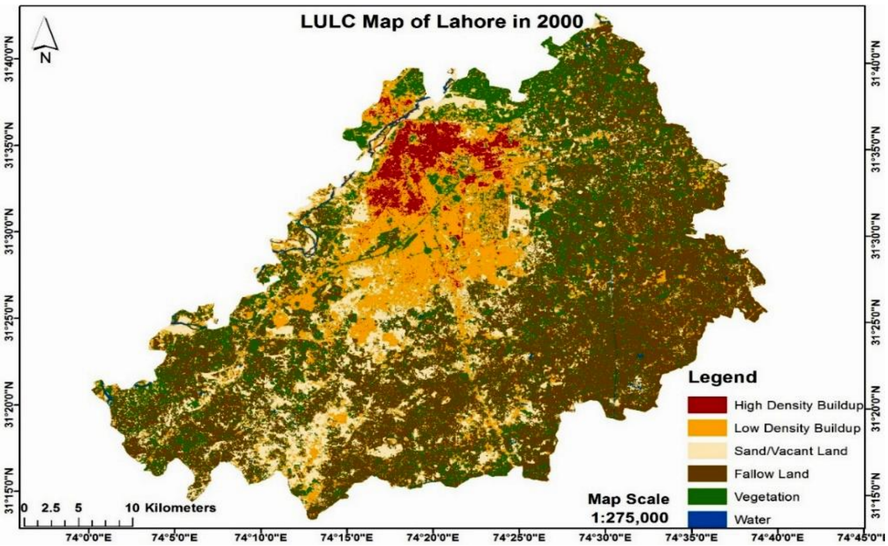

Figure 1:LULC map of district Lahore by supervised classification in 2000.

The LULC maps show the extent and pattern of the LULC classes defined in Table 1, over the entire district of Lahore.

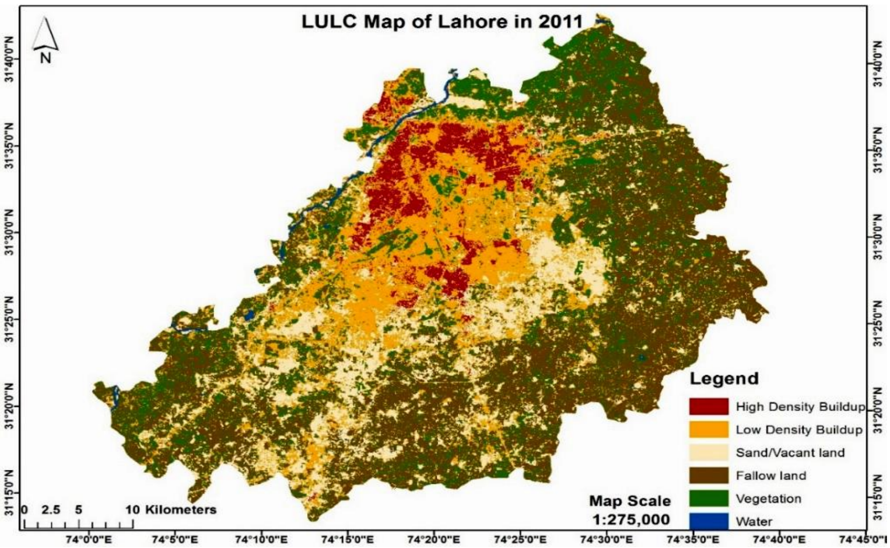

Figure 2:LULC map of district Lahore by supervised classification in 2011.

The total urban area in the district, which can be calculated as the sum of the High Density and Low Density Built-up classes shows a 25% increase between 2000 & 2011.

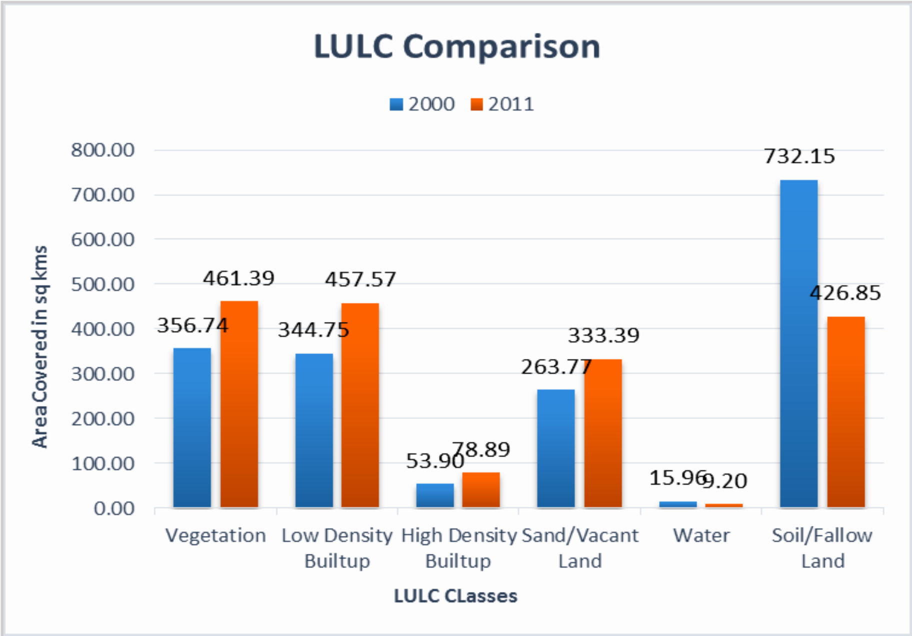

Figure 3: LULC comparison for years 2000 & 2011.

The chart above shows that LULC classes of Soil/Fallow Land and Water experienced a decrease in the area covered in 2011 compared with the image from 2000. The rest of the classes showed an increase in surface area covered for the 2011 image.

LST images for the years 2000 and 2011 follow:

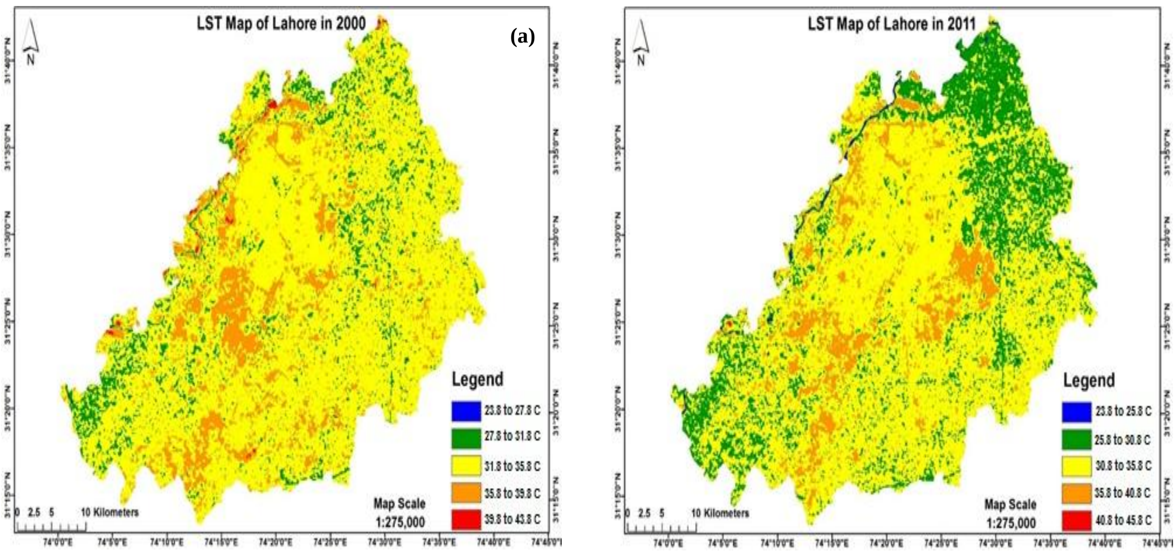

Figure 4:LST maps of Lahore in April, 2000 and April, 2011.

The average LST for the entire district in 2000 turns out to be 32.71 °C while for the image of 2011 it turns out to be 33.44 °C. This means that the average LST of the entire district was 0.73 °C higher in 2011 than 2000.

In order to see which LULC class turns out to be the warmest or the coolest, average LST for each LULC class was deduced. These are being presented in the form of bar graphs for easy interpretation.

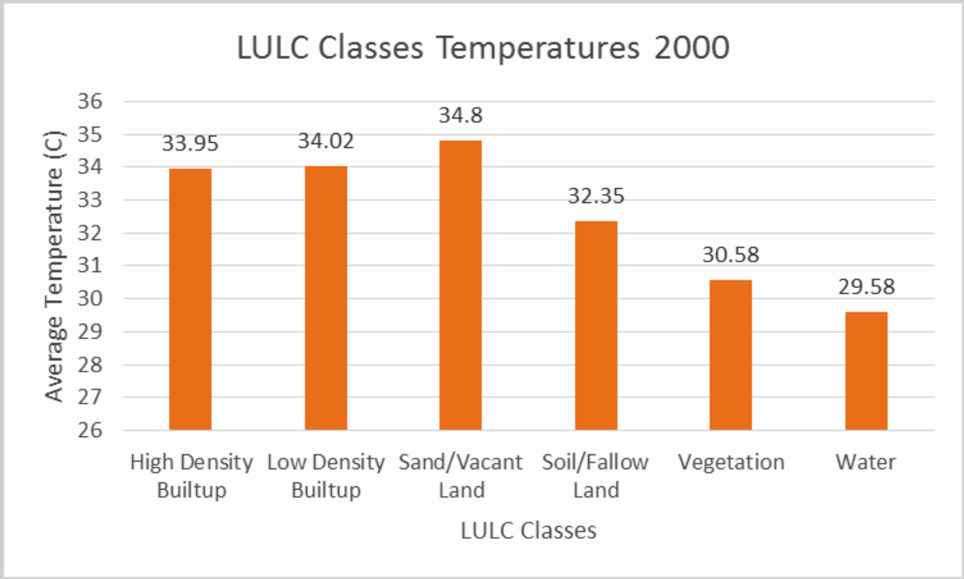

Figure 5: LULC Classes average temperatures in 2000.

The average LSTs of each of the LULC classes in 2011 are shown in the following graph:

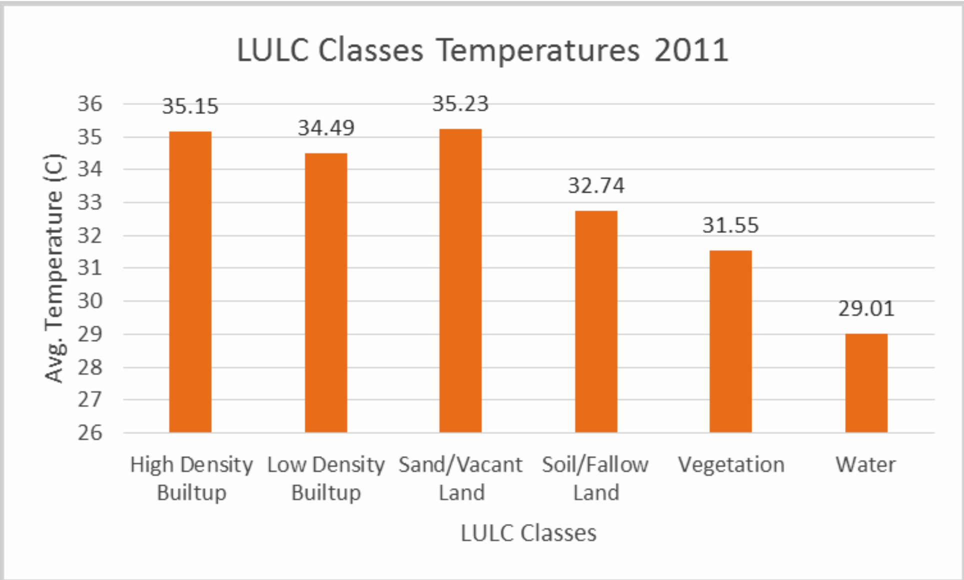

Figure 6: LULC Classes average temperatures in 2011.

The Sand/Vacant Land LULC class appears to be the warmest one followed by the High Density Builtup and the Low Density Builtup classes in the satellite image for the year 2000. This also holds true for the image for the year 2011. The coolest two LULC classes among those identified turn out to be Water and Vegetation in images from both of the observed years.

SUHI Results

Calculations performed over the satellite image from 28-04-2000 show the target area to have a positive SUHI of 1.7°C. While the same process performed for the date of 27-04-2011 returned a positive SUHI of 1.8°C. This shows that Lahore has a positive Surface Urban Heat Island during daytime through summers. This is consistent with the findings of similar studies for cities that have similar environments i.e. cities which are surrounded by mostly vegetative land cover according to Stathopoulou et al., (2009).

Like Lahore, most other cities also show a positive SUHI during both night and day time. Of the 419 cities observed by Peng et al., (2012), 92% showed a positive SUHI, the notable exceptions were cities like Jeddah & Mosul etc. which are surrounded by deserts, owing to the thermal properties of sand. Carnahan and Larson (1990) called the formation of heat sinks as opposed to heat islands by urban areas as “anomalous” and found low thermal inertia of soil, among other climatic conditions to be responsible for it while studying the city of Indianapolis (Carnahan & Larson, 1990).

Transition Zones

Apart from the LULC maps generated through supervised classification of TM images, a new category of Land Use needs to be defined here. The areas which have been earmarked for further urban expansion experience a change in land use. The land had been bought up by the private housing developers or the Lahore Development Authority (LDA), which was previously agricultural land. These lands were then gradually cleared of the agricultural fields; road & street networks were built over these with housing plots and other infrastructure for utilities. This entire process of conversion of agricultural land from rural areas into suburban towns may span years and sometimes even decades, henceforth called the “Transitional Phase”. The period during which most of the land lies vacant and barren with only empty streets mandates its categorization into a separate land use class. For the purpose of this study such areas have been identified as “Transition Zone”, as the status & conditions of these areas represent a transitional phase from rural to urban land use. The land cover present in this class has been observed to be a mix of mostly sand or exposed soil, with sparse vegetation like wild shrubs and grasses and few built structures like roads and buildings, which may be the offices and other structures constructed by the developers or some early settlers of those suburbs. This zone consists of patches rather than a contiguous piece of land due to a piecemeal development pattern of new housing societies around Lahore. The average Land Surface Temperature of the identified Transition Zone on the image from the year 2000 comes out to be 35.5 ℃. While the average LST for the total urban area of the city comes out to be 34 ℃. The average LST of the Transition Zone for the image from 2011 comes out to be 35.2 ℃. Average LST for the urban area in this image turns out to be 34.6 ℃. This shows that the Transition Zones form SUHIs of their own within the SUHIs of the city. For a clearer picture a map comparing the LST of a Transition Zone area in the east of the city between 2000 and 2011 follows:

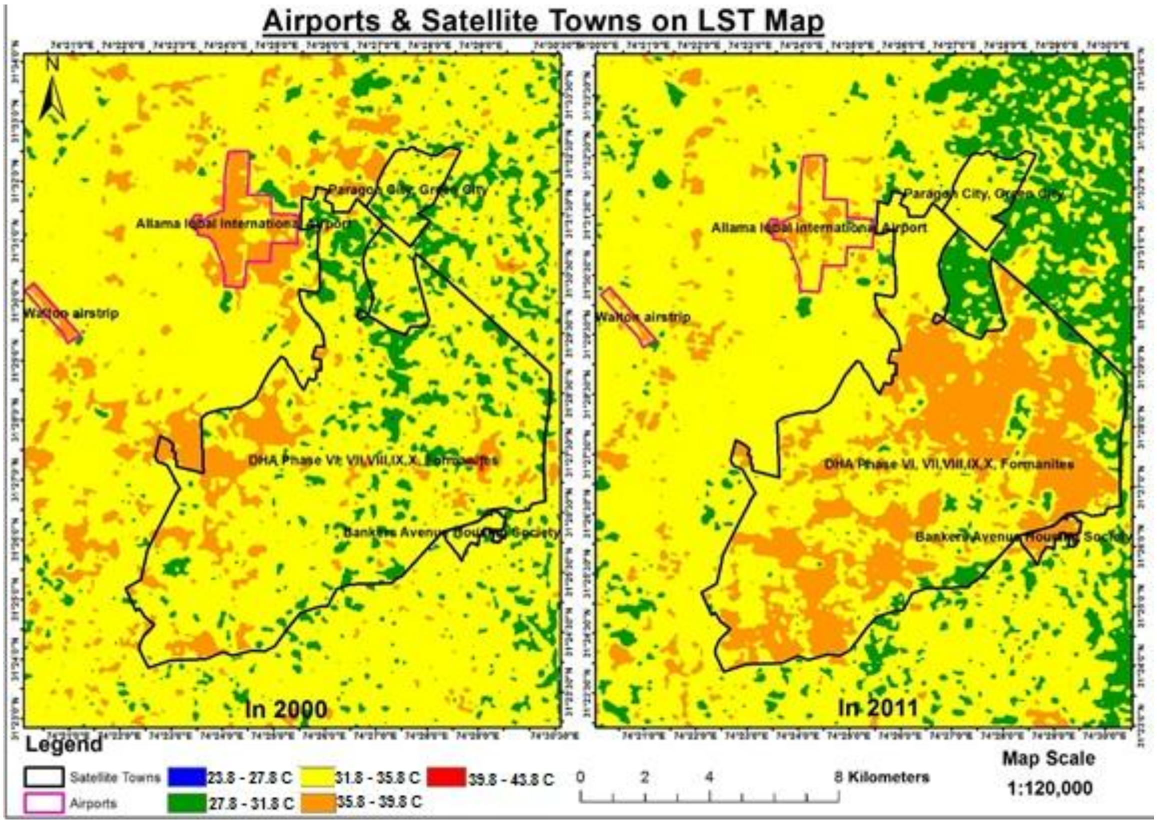

Figure 7:LST Comparison map of satellite towns in the east between 2000 & 2011.

This area was part or the rural countryside back in 2000, but by 2011 it had entered into the transitional phase. The highlighted area had an average temperature of 31.85 ℃ in the map for the year 2000. The mean temperature of this area in the 2011 map turns out to be 35.05 ℃. This means an increase of 3.2 ℃ in the mean LST of the Transition zone area in the east of Lahore was observed. The comparison between the LST classes over this area is shown in the following graph:

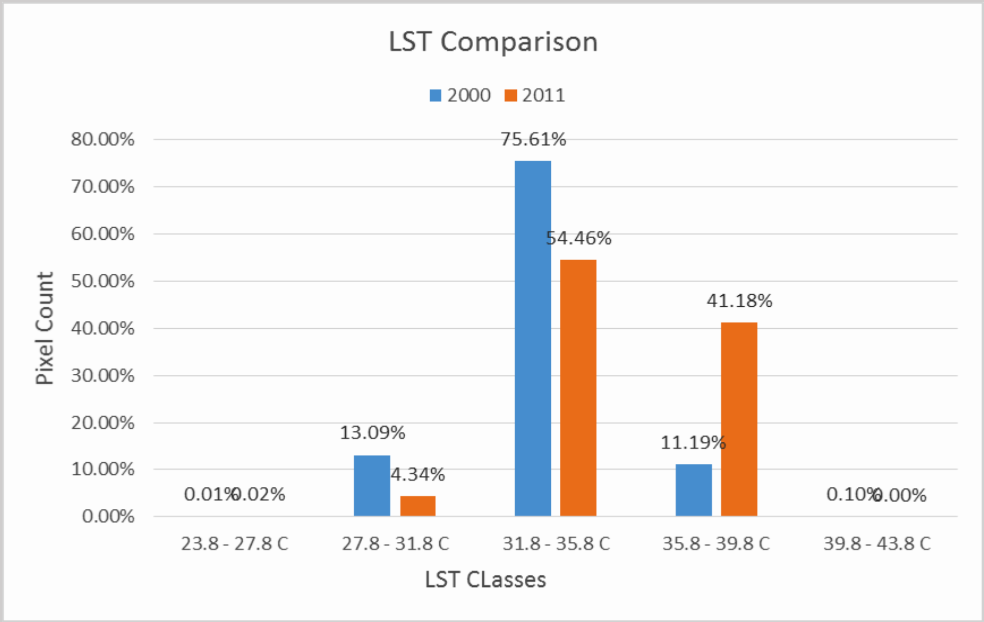

Figure 8: LST comparison for area highlighted in Fig 7.

The graph above shows a shifting of the majority of pixels towards the warmer LST classes. These changes in LST can be better understood by also observing the changes that occurred in the LULC classes between the observed years. In this area vegetation consisted 25.14% of the LULC in 2000, but as land was cleared for suburban development and the area entered the transition phase, this vegetative land cover was reduced to 8.43% by 2011. Sand/Vacant Land LULC increased in area from 14.36% to 49.11% and Low Density Builtup from 10.3 to 35.4% in 2011.

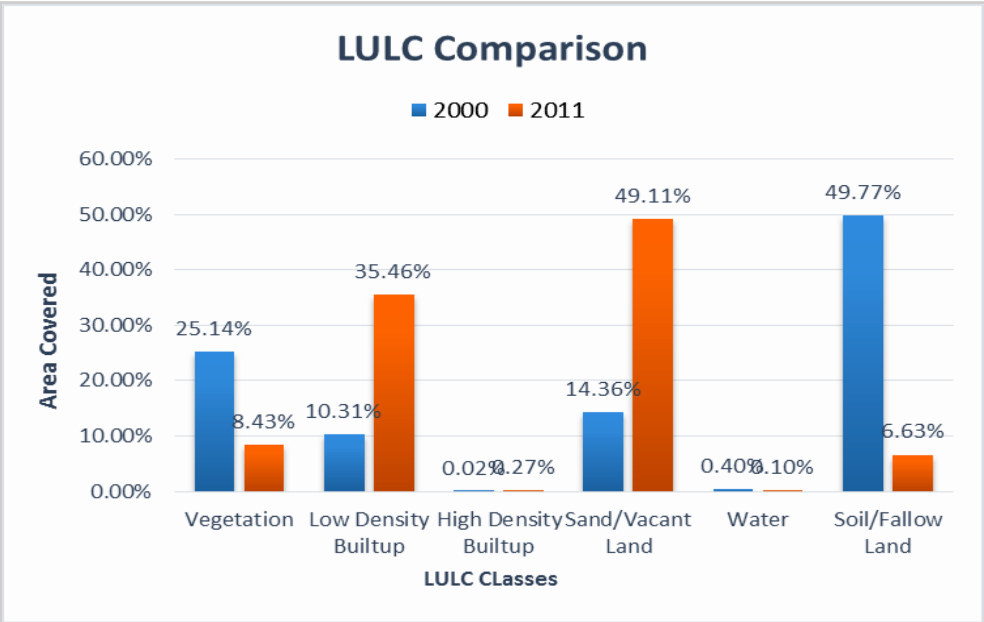

Figure 9: Comparison of area highlighted in Fig 7 for each LULC class.

Few areas of the city have also shown reduction in their mean LST between the years 2000 and 2011, these are the areas that began their transitional phase from rural to urban LULC conversion during the 1990s and had completed the transition into mostly occupied suburban areas by 2011. These would be the suburban housing schemes initiated in the 1980s and the 1990s. A case in point would be the Sabzazar town along the M2 Motorway in the south west of Lahore.

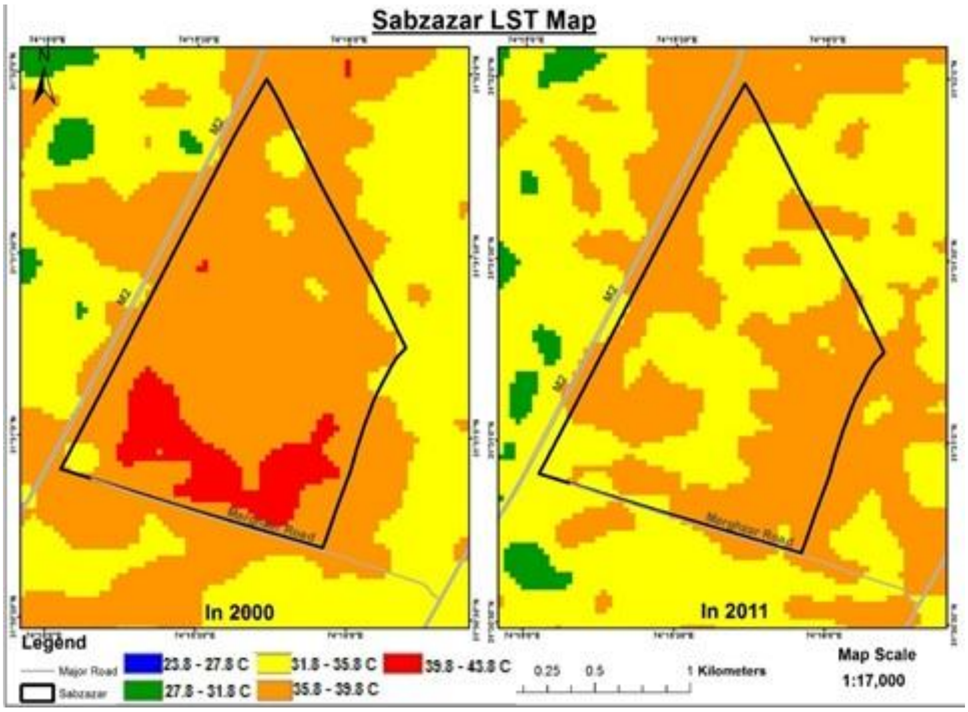

Figure 10: Sabzazar LST comparison map.

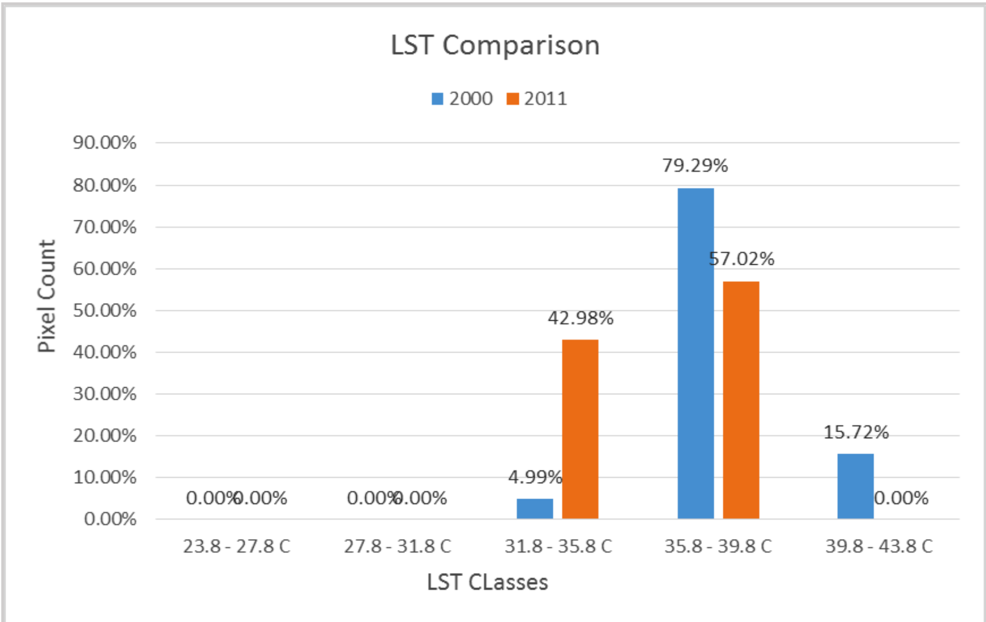

Figure 11: Sabzazar LST comparison graph.

The graph above shows the percentage of pixels belonging to the cropped image of Sabzazar town for both years 2000 & 2011. In the year 2000, 15.72% of the pixels fell in the warmest LST class of 39.8-43.8 °C while no pixels were that warm in 2011. The percentage of pixels in the warmer temperature classes is reduced in the year 2011 as compared to the image of the year 2000. The following graph compares the LULC between the two years for the same Sabzazar town. The mean temperature of the entire town came down to 35.9 ℃ in 2011 from37.8 ℃ in 2000. In other words the entire town of Sabzazar was on average 1.92 ℃ cooler in 2011 than the year 2000.

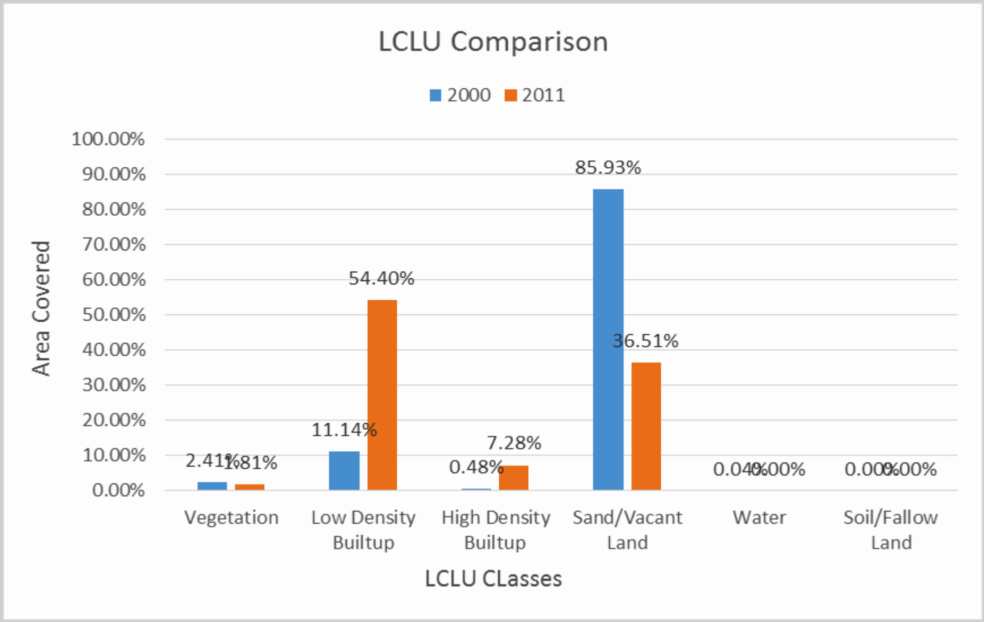

Figure 12: Sabzazar LULC change comparison between 2000 & 2011.

In 2011 due to conversion of this land into a mostly occupied suburb of the city, the vegetative and Sand/Vacant Land LULC classes witnessed a decline in percentage area while the Low and High Density Builtup classes increased in pixel count.

Conclusion

The findings of this study lead us to conclude that over the last decade the city of Lahore has witnessed rapid urban sprawl. The built-up surface area (High Density Built-up + Low Density Built-up LULC) within the city district in 2011 turned out to be 25% larger in than what it was in 2000. The average LST for the entire district in 2000 turns out to be 32.71℃ while for the image of 2011 it turns out to be 33.44 ℃, showing mean LST rise of 0.73 ℃ in 2011 compared to what it was in 2000. The city also has a positive SUHI during summers.

Sand/Vacant Land LULC type was found to be the warmest one followed by the High Density Built-up class among the LULC classes identified in the study. LST on average experienced a rise in areas where a transition from agricultural land with predominantly Vegetation & Soil/Fallow Land LULC types to Sand/Vacant Land LULC takes place. Similarareas when finally developed into Suburban towns experienced a relative cooling down of average LST, because the areas falling under Sand/Vacant land LULC class then were converted into Low Density Built-up areas. However if the development is not properly planned or if with time the built-up density of these areas increases then the rise in the High Density Built-up class also accompanies the rise in average LSTs once again.

The SUHI of Lahore or a city of similar growth pattern does not appear as a nuclear structure with a single core coinciding with the city’s Central Business District (CBD) or even with the densely populated older quarters of the city. The SUHI of Lahore seems to be warmest at its boundaries due to the development of newer housing colonies and the boundaries of the SUHI roll outwards as the city expands.

Remote Sensing data proved invaluable for the calculation of the SUHI in this study since this technique offers the ability to gather data over a large area simultaneously. In urban areas spanning several hundred square kilometers it may not be feasible to gather LST measurements across the entire area in large enough numbers simultaneously through a ground survey. Even if such a survey were conducted it would still yield point data which then would have to be interpolated to get area-wide coverage. Satellite images provide us with the capability of wide-area coverage, simultaneously and also eliminate problems of accessibility. The tradeoff of using satellite data is that it is only possible to measure the LSTs of horizontal surfaces, that's why the term SUHI was used during this study. Satellite data offer a unique ability of mapping land cover and SUHI cost effectively, at a regional scale and with suitable accuracy.

Recommendations

The warmest LULC type turns out to be the Sand/Vacant Land class and the prevalent way with which newer residential areas are developed turn agricultural land into Vacant tracts of land that lies unutilized for decades.It would thus be recommended to the city planners, developers and policy makers to attempt to restrict the creation and expansion of this LULC type in and around the cities. Cities with vegetative land covers in their surroundings must not be allowed to expand at the expense of the greener countryside unless it becomes inevitable. Even if expansion becomes an inevitable necessity, it must be designed and executed smartly. The government may regulate developers of housing schemes to either resort to stepwise conversion of agricultural land allotted to them and only move onto clearing agricultural fields once the previously cleared parts have been occupied or employ horticulture to cover the land in transition with greenery until it may be required to build upon.

The complete transition period of a suburb of the city of Lahore typically lasts well over a decade, therefore using a time span of 20 years or more between satellite images of the same area might show us some satellite towns completing their entire transition from a mostly rural area into a suburban town that is mostly developed & settled. Increasing the time span to a couple of decades or more for this study would then provide us with the complete transitional cycle of LST as well as LULC of a particular part of city undergoing a rural to urban conversion. This might help us identify a more certain causal relationship between the LULC classes and the LST.

Researchers may delve deeper into the SUHI phenomenon, with satellite data of higher temporal and spatial resolutions and also incorporate atmospheric data if possible. A relationship between urban activities and their resultant pollutants and the SUHI would be interesting to observe. A deeper insight into the mechanisms governing the formation and expansion of the UHI may help us to be able to control or mitigate its undesirable effects on urban living.

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