

Spatio-temporal relation of Urban Density and Surface urban heat island index

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Abstract: Over the decades, an unprecedented growth in urban areas has impacted cities population and its local climate. The urban built-up densification has increased local temperature of cities in comparison to its surrounding areas covered majorly with open land and vegetation. It gives rise to urban heat island effect, but it does not affect the entire city in a homogeneous manner and depends upon its urban density. For incorporating spatial non-homogeneity, a non-linear mathematical function is required to understand the spatio-temporal change in built-up urban density and urban heat island effect in cities. An inverse s-shape function is used in this study explaining city expansion around the central business district and its relation to the surface urban heat island index. The temporal change in inverse s-shape function signifies urban expansion and is validated via urban sprawl matrices. Also, urban density and surface urban heat island index exhibits a high degree of fitness between the values 0.95-0.98. This study helps in understanding spatial -change in urban heat island effect and urban density and can be used in future for vulnerability assessment studies of cities against extreme events.

Keywords: Surface urban heat island index, urban land density, land surface temperature, urban development

1. Introduction

Over the years, extensive increase in urbanization has become one of the reasons for change in local climatic conditions in cities. As per the IPCC, 2021 (AR6) report, it is projected that in the next two decades an increase of 1.5-degree Celsius in temperature can be observed globally. The increase in temperature along with the growing urbanization has not only affected the future but the current conditions of population living in the cities facing high levels of air-pollution, heat island effect and extreme weather conditions.

How urbanization is a cause of concern for increasing the effect of urban heat island in cities? Majorly, Urban areas are covered with impervious surfaces having high heat capacity such as cement, concrete, asphalt for the development of roads, buildings, and pavements replacing vegetation cover and slowing the process of evaporation. These materials instead of reflecting back, absorb the solar radiations and relatively increase the temperature within the city in comparison to the cities' hinterland (dominated by soil, vegetation). Apart from increase in impervious areas, other major causes of concern are anthropogenic activities such as transportation vehicles and industries radiating greenhouse gasses into the atmosphere. It affects the weather conditions and local climate of the city and results in urban heat island effect (UHI). It arises due to the difference in heat absorption property by built-up materials and natural soil, vegetation. It is defined as the positive temperature difference between an urban area and its nearby remote area, and is one of the most widely known consequences of urbanization on local climate (Souch and Grimmond, 2006).

The process of urbanization involves densification (infill growth), leapfrog growth (development occurring far away from the city) and edge growth in the periphery of the city. These processes impact and generate urban heat

island effect. The relation needs to be studied by a mathematical function, which describes the process. The UHI effect is caused by the difference in air temperature in urban areas and its nearby vegetation/open land cover. Traditionally, air temperature's in-situ weather station data (Voogt, 2007) are used. But due to non -availability of station data across the city, the remote sensing satellite data is useful. The land surface temperature measured using the thermal sensors are used as a replacement of air temperature data.

Numerous studies have suggested the existence of relationships between land cover and land surface temperature (Zhou, 2011). Analysis of city-wise increase in urbanization and its annual LST values are discussed using a general regression model. In (Bonafoni, S) urban density- LST relation is established using a quadratic equation for day time MODIS data. For quantifying the effect of urban heat islands, Surface Urban Heat Island (SUHI) index is used and it is defined as the difference in land surface temperature between the urban areas and its surroundings (Rao, 1972). An urban land density function is formulated in (Jiao, 2015), denoting it by inverse S-shape Rule. The function is used for both mono and polycentric cities and it is described for major cities of China. For evaluating purposes, the function and its behavior on urban expansion is studied in this paper and its relation with SUHI index is discussed.

In this study, we established a mathematical spatial temporal relation between the processes of urbanization and surface urban heat island index. A non-linear relation using the s-inverse function is used to satisfy the process. Spatially, it is a function of distance from the cities' central business district to its periphery. The value and parameter of the function is evaluated temporally for the selected time period of study. For analyzing, we use data for a decade from 2011 to 2021 of Indian remote sensing

satellite Resourcesat-2 and MODIS night time LST for deriving urban areas and SUHI index respectively.

2. Study Area

Ahmedabad city is in the center of Gujarat, located in the western part of India. Geographically, the city covers an area of 720 sq. km and is located on the banks of Sabarmati river. The river divides the city into two as, eastern and western part of Ahmedabad. The former consists of dense building structures with narrow roads and industries emitting greenhouse gasses. West of the Sabarmati river, the urban development is relatively dispersed with sparse vegetation. The Central Business District (CBD) of the city is along the ashram road with 119 ha. of area connecting the western and eastern part of Ahmedabad. The study area is shown in figure 1 and figure 2 show the CBD point of the city used for analysis.



Figure 1. The study area of Ahmedabad.



Figure 2. CBD point in Ahmedabad city.

3. Dataset Used

Resourcesat-2 LISS IV Dataset:

Indian Remote Sensing satellite data from Resourcesat-2 with LISS IV sensor is used for extracting urban areas for the period 2011 through 2021. The sensor has the capability of 5m ground spatial resolution with three spectral bands of red, green and near infrared. In this study, the data is used for October month for delineating urban

areas for maintaining the common reference of calculating annual urban growth of the city. For all the analysis purposes, the satellite images were georeferenced with the base year of 2011 as reference.

MODIS LST Dataset:

The land surface temperature for the period (2011-2021) is obtained from MODIS land surface temperature night time data. The night time data is used because temperature differences between the urban surfaces and surrounding rural areas are usually larger at night than during the day. The effect of urban heat island effect on cities is studied using mean annual data. The data product MCD11A2 with 1 km spatial resolution, gives an average LST value over the period of every 8 days. In total it gives 48 images annually which signifies the mean LST pattern of a year. In total, 10 years of data is used and 480 images of land surface temperature are used for generating SUHI for studying the UHI effect.

4. Methodology

The spatial-temporal relation between urbanization process and surface urban heat island index are needed to be established for cities. For understanding the pattern, the city is partitioned in concentric rings around the central business district CBD point as shown in figure 3. The urban density is calculated for each ring by the ratio of urban area in a particular ring to the total area of that ring. Similarly, for Surface Urban heat island index, the mean value of each of the buffer rings is used. Below, the process is explained about urban areas extraction, density calculation and surface urban heat island index and its mathematical relation.

Urban areas extraction and growth analysis

The urban area consists of impervious surfaces and urban vegetation areas, which are dominated by built-up environments. When using remote sensing images, urban land is defined by impervious surface area (Arnold & Gibbons, 1996) which includes pavement and roofs that are closely associated with built-up areas. In this study, we define urban land as impervious surfaces and the rest vegetated, open land and other land cover classes under non-impervious surfaces.

The IRS Resourcesat-2 LISS IV data is used for extracting urban areas from deep learning artificial intelligence approaches proposed in (Rastogi et al., 2020). The model is trained for 20 cities of India with heterogeneous terrain and climatic conditions. It is developed for mapping urban areas for smart cities of India. The proposed UNet-AP model is used for extracting urban areas from remote sensing data. The average accuracy assessment for the obtained urban area is 95.62% as evaluated against the ground truth data from stratified random sampling method. The average kappa coefficient value is 0.85 for all the year.

Urban areas for Ahmedabad are extracted for each year from 2011 to 2021 and the yearly growth is shown in figure 3. A total increase of built-up area from 221.58 sq. km in

2011 to 253.91sq. km in 2021 is calculated, with a total increase of 14.62%.

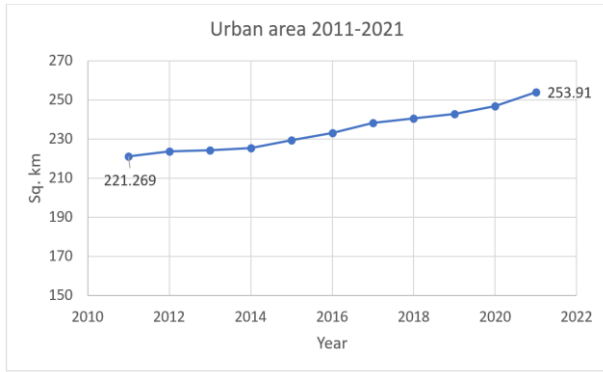


Figure 3. Increase in urban areas from 2011 to 2021.

The urban development in Ahmedabad in a decade is associated with infill development that increases the compactness of the urban core, leapfrog development which results in several small isolated patches away from the urban core and the outer extended growth in the city periphery indicated by largest patch index (LPI).

The number of built-up patches in landscape is denoted by NP. It indicates the level of fragmentation in the landscape. For Ahmedabad, the number of patches has been increased by 33%, indicating high dispersed growth surrounded by other land use from 2011 to 2021. The LPI measures how much urban area the largest contagious patch of built-up area occupies and is calculated using FRAGSTATs fragmentation analysis tool. In a decade, Ahmedabad Largest patch index has increased from 3.84% It indicates that in More urban growth is being driven by Ahmedabad's urban core, however this is not significantly large as fragmented growth is dominant.

The urban growth for Ahmedabad city from 2011 to 2021 and the concentric ring-based partition around CBD at each 1 km distance, is shown in figure 3. It is used for calculating urban density and SUHI index in each of the rings.

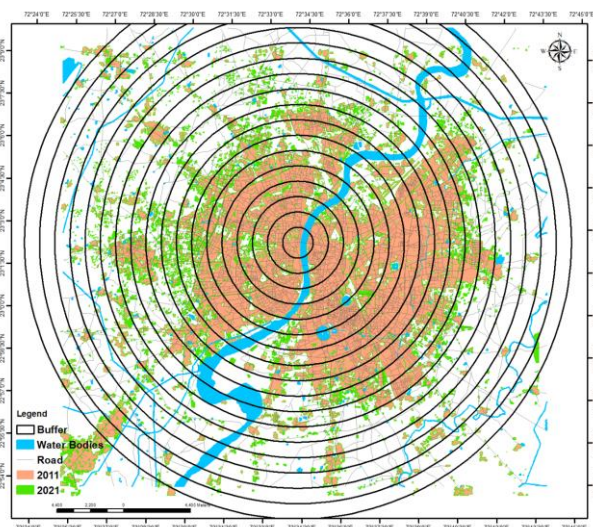


Figure 4. Concentric ring-based partition around CBD at each 1 km distance and increase in urban areas from 2011 to 2021.

Urban Land Density Computation

For computing Urban land density, a standardized approach is used for partitioning the city into concentric rings for defining the spatial extent of a city and the urban land density (ULD). Therefore, the city of Ahmedabad was divided into a number of concentric circles (Figure 4), each 1-km wide, that spread outward from the city's central business area. as described by AUDA. During the period of study, the urban land density of i^{th} ring is the ratio of urban area in i^{th} ring by the total land area of i^{th} ring.

$$ULD (i) = \frac{\text{urban areas in the ring } (i)}{\text{total area of the ring } (i)}$$

Surface Urban Heat Island Index (SUHI)

The surface urban heat island index is calculated as the difference of LST value of urban areas and its nearby non-urban areas majorly covered with vegetation/open land. Mean surface UHI intensity is calculated for each concentric ring. The annual night-time SUHI index is shown in figure 5. A significant positive change in SUHI value can be seen in 2021. The central core part of the city in 2021 has a difference of 3.4 degrees from neighboring non-urban areas. The new area under the box (Figure 5) is becoming the emerging center of high value of SUHI index. This could be due to increase in settlement and compactness within the region. Ahmedabad is emerging as a new center for development away from the city center, which could be new spot for high SUHI in the projected future.

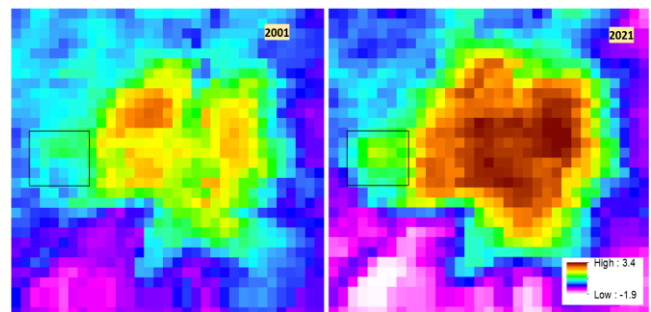


Figure 5. Night-time SUHI index for 2011 and 2021.

Inverse S-Shape Function

An inverse S-shape function is used to model urban density as a function of distance from cities' center, (Jiao, 2015) it is expressed as,

$$f(r) = \frac{1-c}{1+e^{\alpha(\frac{2r}{D})-1}} + c$$

where: f is denoted as the urban density, r is the calculated distance from the city center; c is a constant background value of urban built-up density in the city's periphery; α represents the slope of the density function; D is the calculated radius of the main urban area.

5. Results and Discussion

The study focuses on identifying the spatial temporal function for urban density and surface urban heat island index for signifying its non-stationary spatial behavior of urban local climate in a city. For calculating urban density concentric rings at a distance of 1km are generated for each year from 2011 to 2021. The urban density from the city center to the periphery does not decrease linearly. It exhibits a distinct inverse s-shape, signifying high density in the city center, and decreasing towards the periphery to the suburban areas. The analysis in concentrated rings around the CBD indicates that up to 4 km of high-density, compact urban fabric are observed. From 6 to 12 km urban areas mixed with other land classes are spread and in between 12 to 14 km area the extended urban cover with high percent of other land cover is built. After 16 to 18 km distance a new region has emerged in the past decade, which in 2011 was highly dominated by non-urban areas and is now continuously increasing in its urban density in 2021, shown in figure 6.

A mathematical function called inverse-s function is fitted for the urban density curve for temporal data. Each of the urban density curves is fitted using a modified sigmoid function via a non-linear least square method. The increase in parameter value yearly is not significant due to only 1.4% annual increase in urban areas, hence the significant change in value of α , D, c parameter of the inverse s-function equation for 2011 and 2021, is shown in table 1, defining the urban sprawl and compactness in the city. High value of parameter D indicates the urban expansion of the city. When D increases with time for Ahmedabad, it signifies its overall expansion of the urban area and it is also validated by the results of urban growth done in this study, where cities' large patch index is increased by 3%. The decrease in c value describes more fragmented growth in the periphery of the city dominated with other land cover and as discussed above section number of patches has increased by 33%. The process of urban expansion can be clearly described by the inverse s- function.

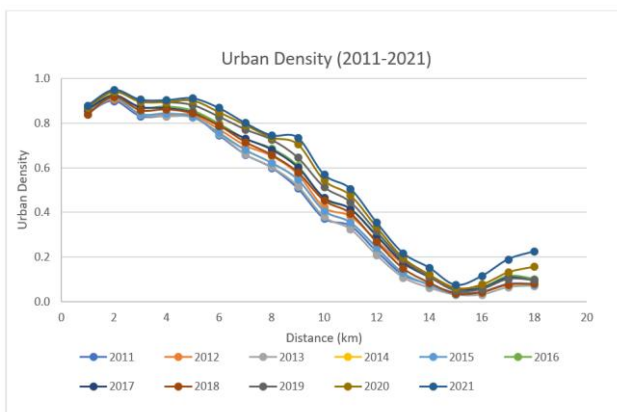


Figure 6. Urban Density for the city from 2011 till 2021.

Table1. Parameters for urban land density curves

Year	α	D	c
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2011	3.199	17.447	2.31e-15
2021	4.012	20.051	1.39e-18

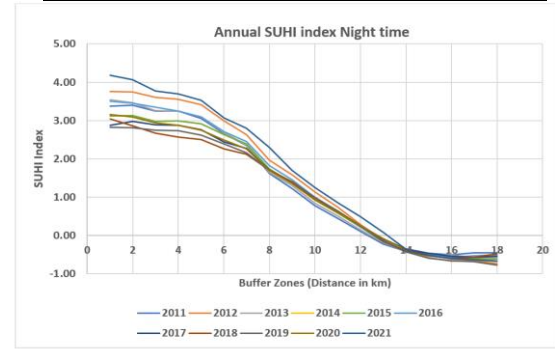


Figure 7. Annual SUHI index for night-time from 2011 till 2021.

The surface urban heat island index for night time over the concentric rings from 2011 till 2021 is analyzed. From figure 7, an increase of 1.5 degrees is seen at the city center. The SUHI value in the mixed urban and other land cover region has a maximum increase of approx. ~1 degree. The overall cover is showing a decreasing trend till the cities periphery and becomes constant for extended growth of urban areas dominated by other land cover.

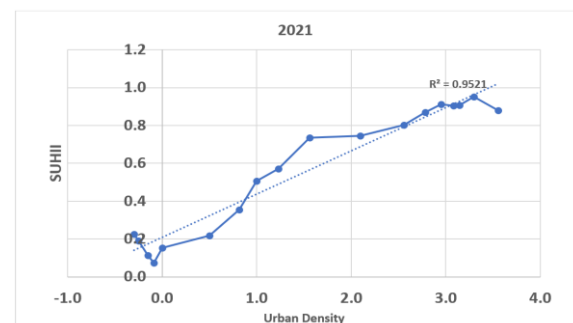
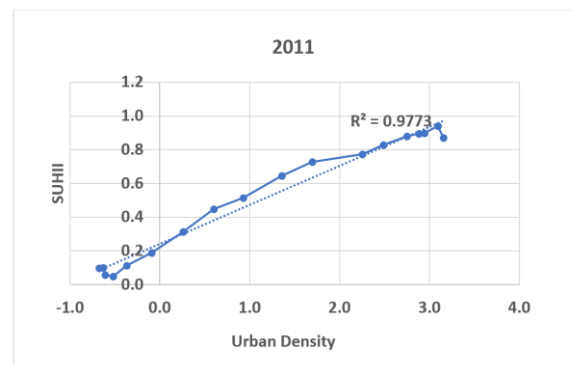


Figure 8. High degree of fitness established between urban density and SUHI index from 2011 till 2021.

To establish the relation between the urban density and SUHI index, we statistically inferred it via fitting linear regression model, the degree of fitness r^2 ranges from 0.95 to 0.99 for each year from 2011 till 2021. For demonstration, in figure 8, its relation is shown for 2011 and 2021. The very high r^2 values confirm the relation between urban density and surface urban heat island index. In figure 8, the values with negative SUHI indicate the region in the outskirts of the city dominated by land use other than urban. The number of such regions has decreased in 2021, indicating an increase in density and SUHI index for those regions.

Conclusion

In study, urban expansion of Ahmedabad city is studied from 2011 to 2021. The relation of urban expansion and densification with increasing surface urban heat island is established using a mathematical function called inverse-s- function. The urban density and SUHI does not decrease linearly, but in a non-linear fashion. With high value of degree of fitness, these two are highly correlated and can be expressed by function inverse-s function, its parameter indicates when evaluated for temporal urban expansion data indicates extended growth and densification. In future, these functions when combined with other work for identifying vulnerable regions of the city against extreme heat wave regions. Also, this work can be extended by adding one more dimension, i.e. by including height information for evaluating the volumetric effect of urban areas with SUHI index.

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