International Research Journal of Natural and Applied Sciences
ISSN: (2349-4077)
Impact Factor 5.46 Volume 6, Issue 6, June 2019
Website- www.aarf.asia, Email : editor@aarf.asia , editoraarf@gmail.com

# Urban Expansion and its impact on Urban Heat Island (UHI) Effect

Vijay Shanker Pandey[++]

[++] *Freelance GIS and Remote Sensing Consultant, Gorakhpur, Uttar-Pradesh, India*

## Abstract

The urban heat island (UHI) refers to the phenomenon of higher atmospheric and surface temperatures occurring in urban areas than in the surrounding rural areas. Urban expansion is accompanied with a change in land surface characteristics that influences the urban thermal environment. It has been observed that spread of urban landscape and replacement of open land and vegetation cover within the city by built up structures may further intensify the UHI effect that will exacerbate the health impacts of the higher temperatures that are already common in urban areas.In such scenario, it seems that planning the urban growth so as to bring down the adverse impacts of urbanization is what is required rather than to consider the adverse impacts as inherent, inevitable and hence accepted price of urbanization. LANDSAT imageries of November 1990 and December 2014for Allahabad were used to compare the change in land cover of and the impact of such change on the thermal environment of the city.Supervised fuzzy technique of land cover classification was used to generate membership value of different land covers within each pixel for the two images while mono-window algorithm was used to generate Land Surface Temperature (LST) for the two images. Land cover classification indicated that there had been a substantial increase in urban built area along the urban fringe as well as a high degree of urban infilling had taken place throughout the city right from the core to the fringe in the north east. Image of LST for 1990 and 2014 indicated that temperatures within the city have increased by 4 $^0$C to 6 $^0$C indicating phenomenal increase in UHI effect during the period. Rapid and unplanned urbanization characterized by ignorance for land cover change and its impact on thermal environment were the major cause behind intensification of UHI effect in the city.

[++]**Corresponding author:**
Vijay Shanker Pandey - Tel: +91-8826644115
Email Id: vspandey@gmail.com

***Key Word:*** *LANDSAT-8, Land cover, urban expansion, Land Surface Temperature, Landscape Index*

**Abbreviations**:

| | |
|---|---|
| UHI | Urban Heat Island |
| LST | Land Surface Temperature |

## Introduction

The Urban Heat Island (UHI) is designated as an urban space within which surface temperatures are higher than those of the surrounding rural landscape (Pinho andOrgaz2000; Shenlai X 2009). Urban expansion is accompanied by a phenomenal alteration of the land cover, as natural vegetation is removed and replaced by non-evaporating, non-transpiring surfaces, (Park 1986; Eliasson 1996; Montavezet al. 2000)which is one of the major cause of UHI effect (Oke 1982; Quattrochi et al. 2000). The other important cause for UHI formation is the direct release of anthropogenic heat released by human activities that includes heat escaping from cars, homes from within the city (Magee et al 1999). Ideally, an UHI is the difference in temperature recorded within a city from which is subtracted the temperature that would be measured at that same location without the presence of the city. As such measurement is not possible; the UHI intensity can be calculated by taking the temperature difference between an urban location and any nearby rural location with similar geographic features (Magee et al 1999).Urban areas have marked effects on environmental conditions at both local and global scales (Herold et al. 2003; Liu and Lathrop 2002) including climate change (Grimm et al. 2000). The effect of urban expansion is particularly significant as the global urban population is projected to almost double by 2050 (UN 2008)which is expected to bring about unprecedented changes in urban micro-climate. As the UHI typically exhibit a positive relationship with urban population size, the urban climate, particularly the heat island effect is expected to intensify further(Yamashita 1996).

The conversion of rural landscape into urban areas through development is currently occurring at an unprecedented rate that has a marked effect on the natural functioning of ecosystems (Turner 1994). Alteration of the earth's land cover in the process of urban expansion has be dramatic as large areas of natural vegetation have been removed and replaced by impervious surfaces, such as metal, asphalt, and concrete. Impervious surfaces are surfaces where water cannot infiltrate and are associated with transportation and building rooftops. The amount of impervious surfaces is related to population size and degree of urbanization (Stankowski 1972). It is an important indicator of environmental quality (Arnold and Gibbons 1996) and hence analysis of the relationship betweenthe LST and percent impervious surface area in anurbanized environment provides an alternative for studies ofurban expansion and related surface UHI phenomena. Previousstudies have shown that the higher the urban intensity or imperviousness,usually the higher the LST(Oke 1976; Weng2001). One of the prominent out-come of urban expansion is increase in intensity of

UHI effect that has numerous environmental, social and economic consequences (Bristow and Mullens 1995). Urban expansion is accompanied with a change in land surface characteristics that influences the UHI as the city spreads along its fringe and open lands are replaced by buildings within the city itself. It has been observed that conversion of new area into urban landscape adds to the areal extent of UHI while urban infilling tends to further intensify the UHI effect.

The UHI effect has been the subject of numerous studies in recent decades as it is exhibited and documented in many major cities around the world (Wang et al. 1990; Taha 1997; Kim and Baik 2004;Kikegawa et al. 2003; Huang et al. 2005;Giridharan 2004). An understanding of an UHI is central to urban micro-climatology and human environment interactions as UHI causes environmental discomfort and has many adverse affect on health (Voogt 2002; Huang et al. 2005). Higher urban temperatures also mean increased consumption of energy, mostly for air conditioning(Akbari et al. 2001; Assimakopoulos et al. 2007; Kolokotroni et al. 2007) and as power plants burn more fossil fuels, they drive up the pollution level that further leads to degradation of green spaces (Driscoll 1985; Myer 1991).It has been suggested that the impact of urbanization and land cover change on surface climate is not negligible as compared to atmospheric greenhouse effect (Kalnayet al. 2003; Zhouet al. 2004). In most cities around the world, the effect of urbanization on local climate, especially on outdoor temperature is alarming (Oke 1982; Rosenfeld et al. 1995; Sailor 1995; Taha 1997; Atkinson 2003; Giridharan et al. 2004) and is considered one of major problems in twenty first century. Out of the growing concern and response related to UHI effect, the relationship between urban land cover and UHI effect has been investigated extensively but the impact of urban expansion which includes urban infilling within the city besides the spread of urban areas along the urban fringe has received limited attention. The present work intends to identify areas of urban infilling and expansion and analyze their impact on UHI effect in Allahabad City.

As our cities will continue to grow, it is required that the adverse impacts of anthropogenic modification of environment in and around our urban centers be curtailed rather than to consider those adverse impacts as inherent, inevitable and hence accepted price of urbanization.Many UHI analyses treat the quantitative description of land cover type as an end in itself and fail to correlate the variation in intensity of the UHI with different components of land cover due to highly heterogeneous urban land cover (Karl et al. 1988; Magee et al. 1999; Pinho and Orgaz 2000; Streutker 2002;Potchterand Sofer2006).It has been observed that simply comparing the temperature within an urban area to that in the surrounding rural area is not adequate in itself. Sustainable urban design and planning requires identification of land cover change at the fringe areas as well as within the city. To identify urban expansion and associated change in land cover LANDSAT imageriesof the study area for November 1990 and December 2014 have been used. Supervised fuzzy technique of land cover classification was used to generate membership value of different land covers within each pixel for the two images while mono-window algorithm was used to generate LST for the two images. The membership image of settlements from the two images was compared so that addition of built up surface within the city in form of urban infilling and transformation of urban fringe areas to urban landscape was identified. Information relating to thermal environment generated from the two images were also compared so that change in intensity of temperature was identified which was subsequently used to establish relationship between change in urban land cover and its impact on UHI effect.

## Method and materials

### Study area

Allahabad, located between $24^0$ 15’N -$24^0$ 30’N and $81^0$30’E-$81^0$ 45’E is one of the oldest urban center in middle Ganga plains of northern India (Fig.1). The city covers an area of 120 $km^2$ and has a population just over one million. Allahabad lies on flat alluvial plain that is bordered in North and East by river Ganges while river Yamuna forms its Southern border. Since 1950 the city had experienced enormous growth in population size and areal extent and at present stretches well beyond the rivers that once formed its natural boundary. Since last two decades, the city has witnessed a trend for infilling of open land within the citydue to which the city presents an ideal opportunity to study the impact of urban infilling and expansion. The methodology worked out in assessment of impact of urban expansion on UHI’seffect in Allahabad city can be applied for monitoring, planning and management of UHI’s in other cities of the Ganga plains as well.

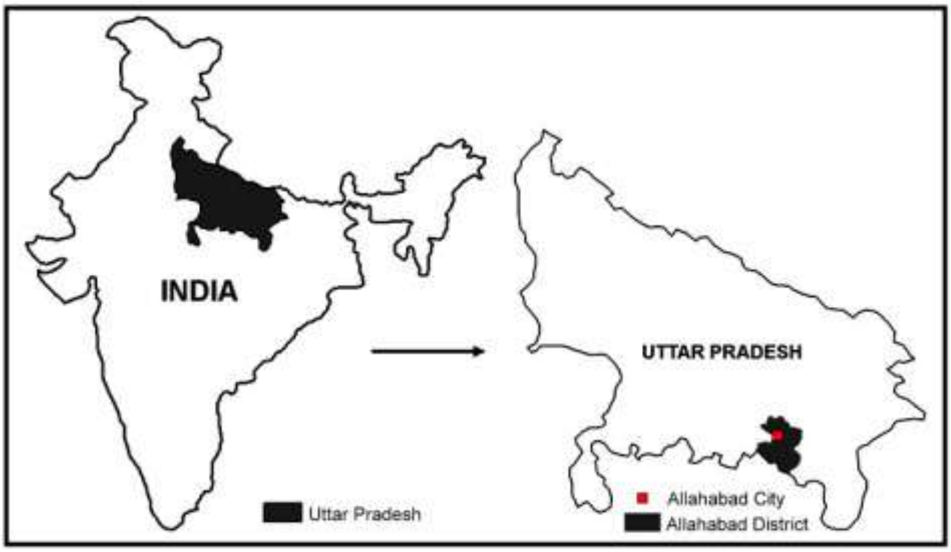


**Fig.1**Location of Allahabad City

**Data**

UHI had long been studied by ground-based observations but it had proved difficult to monitor and measure UHI solely with in-situ instruments as such observations lacked simultaneity and even large number of observations required interpolation and estimation. Temperature measurements from satellites, on the other hand, have higher spatial coverage and can be carried on simultaneously over a large area. Satellite thermal data can effectively depict the patterns of the thermal environment of extensive urban areas(Streutker 2002)and with the advent of thermal remote sensing technology, remote observation of UHIhad became possible and hadalso provided new avenues for the observation of UHI (Voogt and Oke2003). Multi-sensor datasets, higher resolution and new processing techniques, had improved the accuracy of satellite thermal sensing, allowing new applications to studies focusing on urban climatology (Los et al. 1997; Christopher 2002; David 2003). In recent years, with the advance of the study on algorithm and the improvement of sensor, remotely sensed data is being used extensively in the field of urban climate and UHI(Aniello et al. 1995;Dousset and Gourmelon 2003; and Lo and Quattrochi 2003). Landsat Thematic Mapper (TM) and LANDSAT-8 thermal infrared (TIR) data with 120 m and 60 m spatial resolutions, respectively, had also been used for micro level studies of UHI (Chen et al. 2002; Weng 2001, 2003).To identify different land covers that form basis for detecting urban expansion and to quantitatively measure the LST, LANDSAT imageries(Path 143/Row042)acquired on mid morning of 17 November 1990 and 09 December 2014 were analyzed.Although the mid-morning timing of the LANDSAT- 8overpass was not ideal for analysis of the UHI, it was feasible without major loss of information.The imageries were acquired through the USGS Earth Resource Observation Systems Data Center, which had corrected the radiometric and geometrical distortions of the imageries. The LANDSAT imageries were further rectified to a common Universal Transverse Mercator coordinate system based on 1:24,000 scale topographic maps, and were resampled using the nearest neighbor algorithm with a pixel size of 30 m by 30 m for all bands including the thermal band. The resultant RMSE was kept less than 0.5 pixel.

**Land Cover classification**

Urban land cover represents one of the most challenging areas for remote sensing analysis due to the high spatial and spectral diversity of surface materials (Maktav et al. 2005). Land cover classes are mapped from remotely sensed data through digital image classification where all pixels are categorized into land cover classes (Lillesand et al. 2008). As the spatial resolution interacts with the heterogeneous urban land cover a special problem of mixed pixels is created, where several land cover types are contained in one pixel. Mixed pixels have been recognized as a major problem affecting the effective use of remotely sensed data in urban land cover classification and change detection (Fisher 1997). Traditional classifiers are per-pixel based, and cannot effectively handle the mixed pixel problem (Cracknell 1998). Use of high spatial resolution image data does not lead to high accuracy of classification (Clapham2003) and as per-pixel based classification loses both spatial resolution and statistical information; supervised fuzzy approach for land cover classification had been applied in the present study. Thapa and Murayama (2009) have shown that classification results can be improved using fuzzy supervised approach as it considers that each pixel might belong to several different classes without definite boundaries. The fuzzy supervised classification approach works using a membership function, where a pixel's value is determined by whether it is closer to one class than another (Jensen 2005; Wang 1990).

Homogeneous sample pixels were identified as training pixels in the image that were used as representative samples for each land cover category to train algorithm and to locate similar pixels in the image. In all four major land cover type were identified and five to ten region of interest were prepared that were used as signatures of training samples for different land covers. The ground reference data were used to prepare the training signatures. For supervised fuzzy classification of satellite data, PARBAT software had been used and for identification of different land covers, region of interest had been created using ENVI software. The fuzziness parameter was set between 1.5 and 2.0 as proposed by Zhang and Foody(2001). Fuzziness parameter with value 2.0 along with Euclidean distance was taken as it forms an ideal combination for lower resolution data like LANDSAT (Gopal and Woodcock, 1994). The membership value in fuzzy classified data pixels gives their degree of affinity with the centroid of the optimal class. Membership μ of the $i^{th}$ object to the $c^{th}$ cluster of n number of classes in ordinary fuzzy c-means, with d the distance measure used for similarity, and the fuzzy exponent q determines the amount of fuzziness, is defined as:

$$\mu^{ic} = \frac{(d_{ic})^{\frac{-2}{q-1}}}{\sum_{c'=0}^{n}(d_{ic'})^{\frac{-2}{q-1}}}$$

In the supervised fuzzy c-means, the class centroid is determined from the training data. Output of the supervised fuzzy classification had been used for further analysis.Land covers in Allahabad city for 1990 are depicted in Fig. 2 and for 2014 in Fig. 3 where as the membership images for settlements are shown in Fig. 4 and Fig. 5 for 1990 and 2014 respectively.

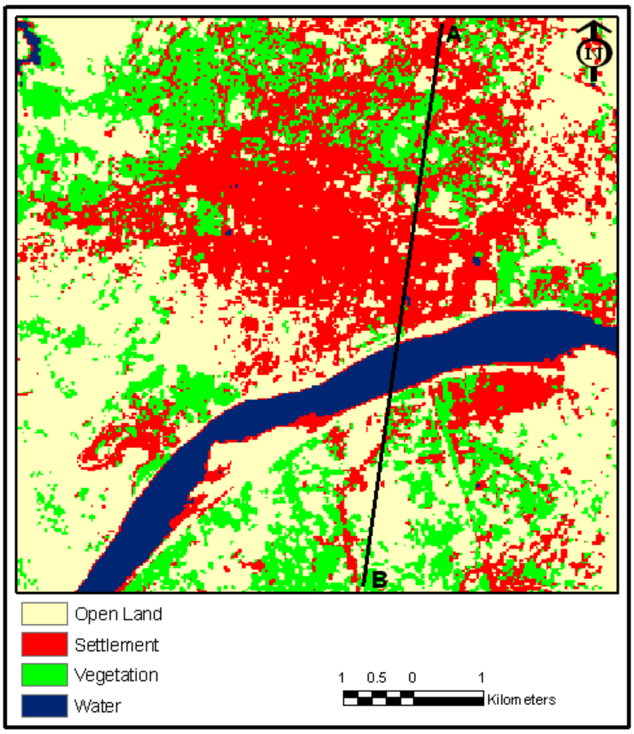


**Fig.2**Land cover, Allahabad City (1990)

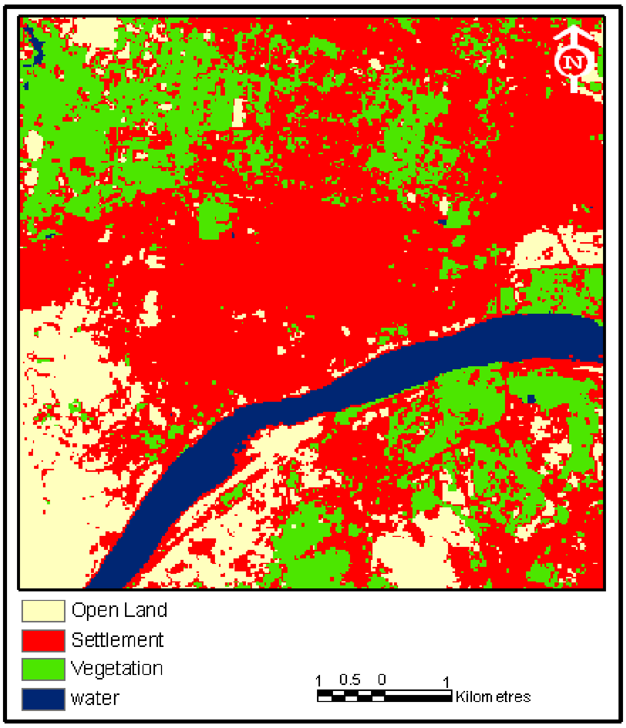


**Fig.3**Land cover, Allahabad City (2014)

Land cover maps generated for 1990 (Fig. 2) and 2014(Fig. 3) imageries indicated that there had been a substantial increase in urban area during the period. Open areas in the Western fringe of the city had registered significant increase in area under settlements while the other major area of urban expansion had been the South Eastern corner of the city across the river. Areas along the urban fringe to the North East of the city had also registered significant expansion. It is interesting to note that the patches of open land within the central core of the city had also been replaced by built up surface indicating urban infilling in the central core of the city. To quantify the degree of urban infilling, membership image of settlement had been generated using supervised fuzzy technique for classificationthat gives percentage of built up land cover in each pixel. Comparing the membership images for settlement for 1990 (Fig. 4) and for 2014 (Fig. 5) it is evident that a high degree of urban infilling had taken place even in areas of high density of built up surface as the extent of bright areas that indicate high percentage of settlements had increased significantly in the central part as well as the in the fringe areas to North East of the city.

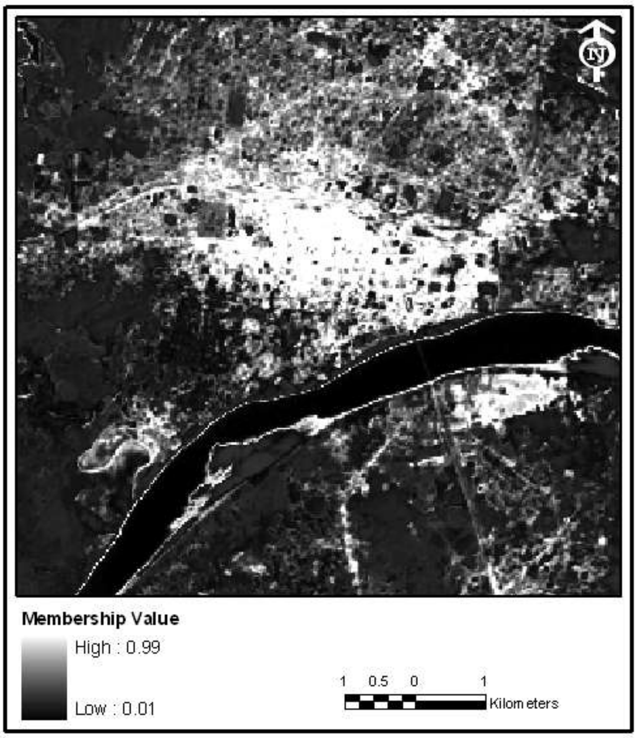

**Fig.4**Membership image for Settlements, Allahabad (1990)

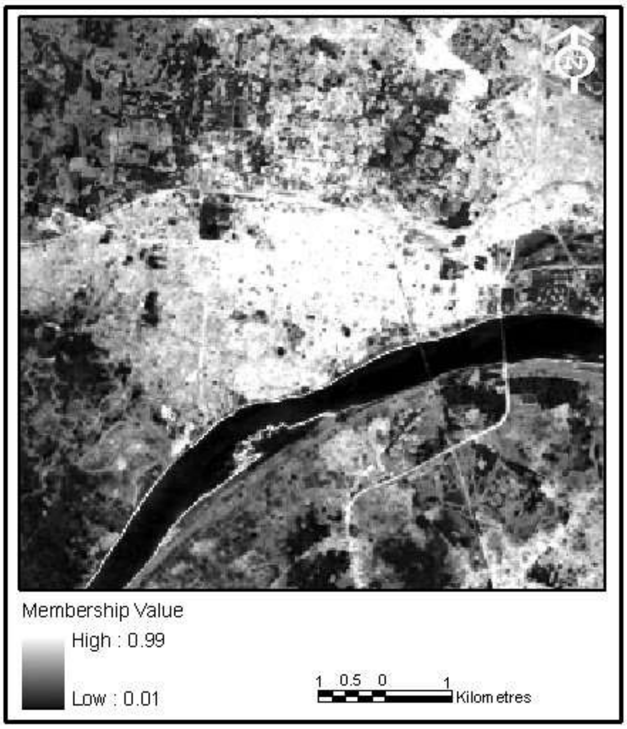


**Fig.5**Membership image for Settlement, Allahabad (2014)

**Land Surface Temperature Generation**

Estimating LST at sensor Brightness temperature was derived from LANDSAT band 6 (with an effective wavelength of 11.457μm). The Land Surface emissivity was derived by NDVI technique proposed byJime´nez-Mun˜oz and Sobrino (2003); Kant and Badrinath (1998) using derived NDVI (NDVI = NIR – R / NIR + R) and vegetation cover ($p_v$) image. Using this information, LST had been derived with help of Mono – window Algorithm as proposed by Qin et al. (2000).

Algorithm for LST estimation:

$$\boldsymbol{T_6 = [a_6(1 - C_6 - D_6) + (b_6(1 - C_6 - D_6) + C_6 + D_6)T_6 - D_6T_6]C_6}$$

Where:

$a_6$and$b_6$ are the coefficients. For the possible temperature range *0 – 70$^0$C (273 – 343 K)* in most cases,

$a_6$ = -67.355351

$b_6$ = 0.458606

$C = \varepsilon\tau$

$D = (1 - \tau)[1 = (1 - \varepsilon)\tau]$

ε = Land surface emissivity

τ = Total atmospheric transmissivity

$T_{sensor}$ = ($T_6$) at sensor brightness temperature

$\boldsymbol{T_a}$= Mean atmospheric temperature

$T_a$= 16.0110 + 0.92621 $T_o$

$T_o$= near surface air temperature

τ = 0.974290 – 0.08007w (high$T_o$)

τ = 0.982007 – 0.09611w (low$T_o$)

w = atmospheric water vapor content for the range 0.4 – 1.6 gm/cm$^2$

Value of Land surface emissivity had been taken from derived emissivity image. The computation of LST from band 6 data is depended on determination of atmospheric transmittance $\tau_6$ and effective mean atmospheric temperature$(T_a)$.

Based on the above mentioned algorithm, LST image was generated for study area for November 1990 (Fig. 6) and December 2014 (Fig. 7). Comparing the LST map generated for November 1990 (Fig. 6) with the land cover map for November 1990 (Fig. 2) it is clear that the highest temperatures where around $26^0$C and were associated with the open land in the South Western part of the city and across the river in the South. Patches of open lands with similar high LST were also present in the Eastern and Northern parts of the city. LST over the water surface and large vegetation patches in the Northern part of the city were comparatively cool with temperatures of around $20^0$C to $22^0$C while the central core of the city had temperatures around $24^0$C to $25^0$C (Fig. 6). Thus the range of temperature over Allahabad city in 1990 was between $20^0$C to $28^0$C. LST map for Allahabad in December 2014 indicate a marked rise in temperature with the temperature range between $21^0$C to $32^0$C (Fig. 7). Large parts of central city that had temperatures around 24 to $25^0$C in 1990 had in 2014, temperature of around $27^0$C to $30^0$C proving that temperatures of urban areas had increased substantially. Temperatures over river in 2009 were around $21^0$C which was similar to what it was in 1990 ($20^0$C).Due to loss of vegetation patches in the Northern part, large parts that had temperatures similar to river in 1990 had in 2014, temperatures similar to urban areas indicating that with loss of vegetation and subsequent urbanization, areas in Northern parts of the city had become part of UHI. Open lands associated with river bed in South West and in small patches in East and North remained the hottest parts of the city (Fig. 7).

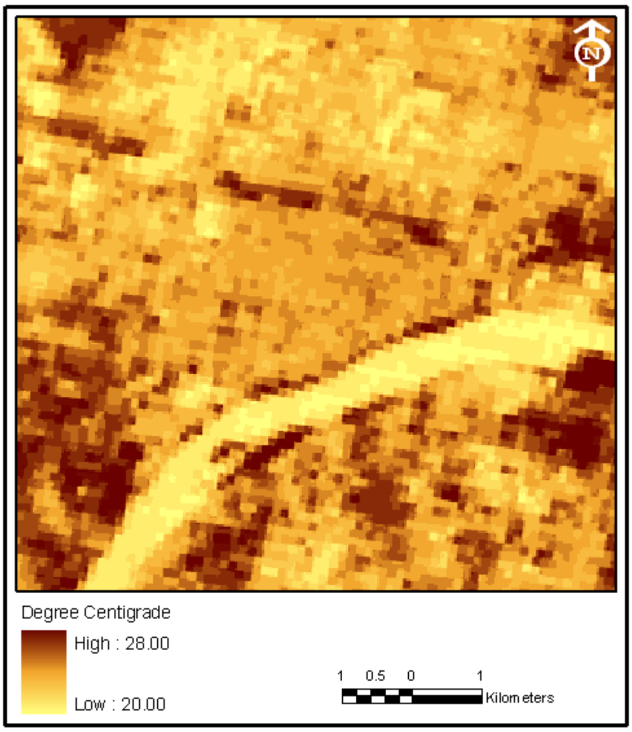


**Fig.6**Land surface Temperature, Allahabad (1990)

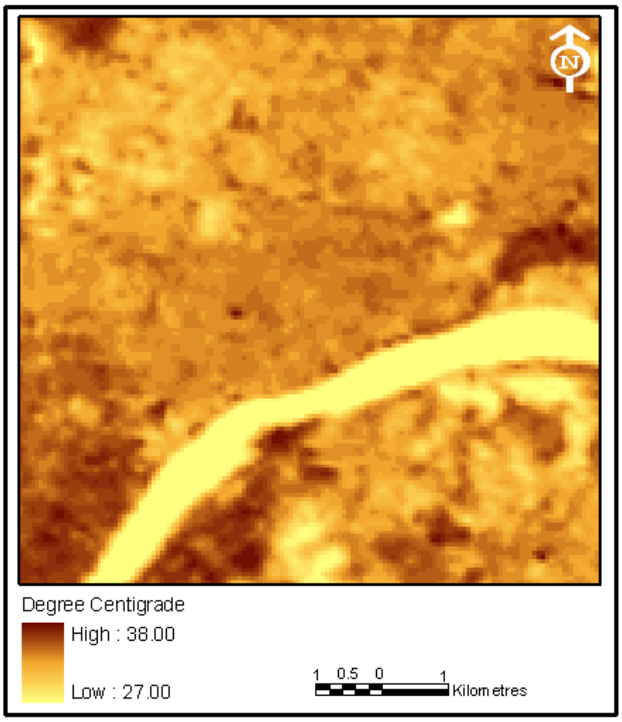


**Fig.7**Land surface Temperature, Allahabad (2014)

**Results and discussions**

Directly comparing the temperature maps of 1990 and 2014 had not been attempted at, as that required to ensure that the weather conditions over the study area were exactly the same on the two dates when the satellite data was acquired. To compare the temperature of November 1990 and December 2014, the LST over water bodies that was lowest and almost similar in both LST generated maps was used as it provided an ideal location on basis of which intensity of temperature over city could be calculated and compared between 1990 and 2014. Initially the average temperature over river was observed to be 20 $^0$C in 1990 and 21$^0$Cin 2014.The average value of temperature over river for 1990 and 2014 were subtracted from the respective LST image that gave the intensity by which other parts of the city were hotter as compared to the river in 1990 and 2014.Subtracting 20$^0$C from the entire LST image of 1990 provided the intensity of UHI over Allahabad city that ranged between 0$^0$C to 6.5$^0$C (Fig. 8). Large vegetation patches in the northern part of the city had similar cooling effect as was observed over river water while open lands associated with sand on the either side of the river were hottest and had temperature around 5 $^0$C to 6.5$^0$C higher. Temperatures over the central core of the city were 3$^0$C to 4$^0$C higher than the river waters indicating a pronounced heating effect due to urbanization. Intensity of heat island over Allahabad city in 2014(Fig. 9) indicated a marked increase as parts of the city were up to 11$^0$C hotter than the river waters. Patches of high temperature as observed in the central part of the city in 1990 had coalesced into a prominent UHI over city that had temperatures over 6$^0$C to 7$^0$C higher than the river waters. Comparing the land cover maps of 1990 (Fig. 2) and 2014 (Fig. 3) and the heat intensity maps for the two years, it is clear that the change in land cover with associated loss in vegetation cover had played a major role in increasing the intensity of UHI over Allahabad city.

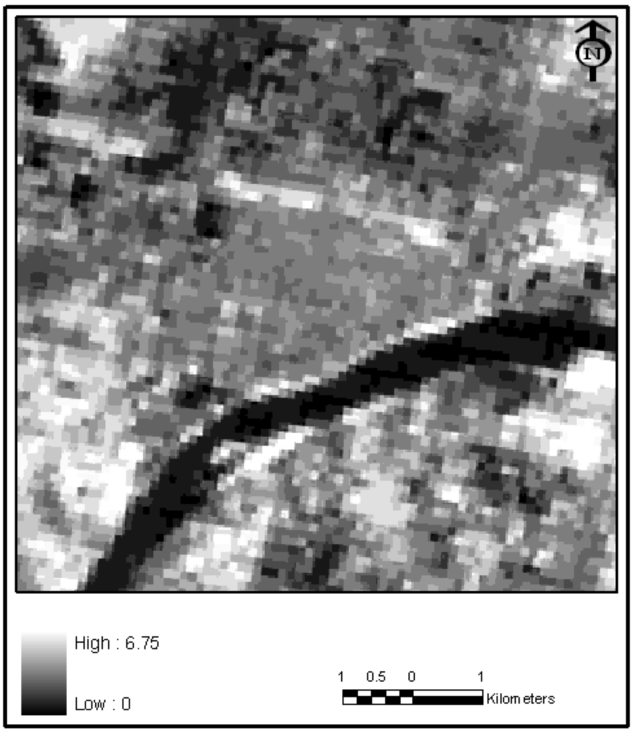


**Fig.8**Intensity of Urban Heat Island, Allahabad (1990)


**Fig.9**Intensity of Urban Heat Island, Allahabad (2014)

As stated earlier, transformation of open land and area under vegetation cover into built up surface within the city is accompanied withurban expansion along the fringe. As the city expands along its fringe the thermal environment of the new areas is modified and gradually they become part of already present UHI in the already urbanized part of the city. Within the city as open areas are replaced by built up surface, the already present UHI tends to intensify further making the urban thermal environment even worse.To analyze the impact of urban infilling on heat island effect, a line ‘AB’ (Fig. 2) is selected that runs from the northern edge of the city to the southern part passing through the central core of the city and the river. A profile is generated along line ‘AB’ on the membership imagesfor settlement for 1990 and 2014which when plotted as graph (Fig. 10a ) indicates the measure of urban infilling that had taken place within the city between 1990 and 2014. To analyze the impact of urban infilling on thermal environment of the city, another profile was generated along line ‘AB’ on the images for heat island intensity for 1990 (Fig. 8) and 2014 (Fig. 9) and plotted on a graph (Fig. 10b). Comparing the two graphs for change in membership value for settlements (Fig. 10a) and change in intensity (Fig. 10b), it is evident that substantial urban infilling has taken place not only at the fringes but also in the central core of the city. Impact of urban infilling is reflected by increase in intensity of UHI as the difference in temperature between river water (Pixel 150 to 175 on Fig. 10b) and intensity of UHI for 2014 has increased by $2^0$C to $4^0$C as compared to intensity of UHI for 1990. The only area where there was no change in intensity in temperature between 1990 and 2014was over river water.Similar temperatures over river water in 1990 and 2014 while a marked increase in other parts prove that urban expansion had led to phenomenal rise in temperatures within the city.

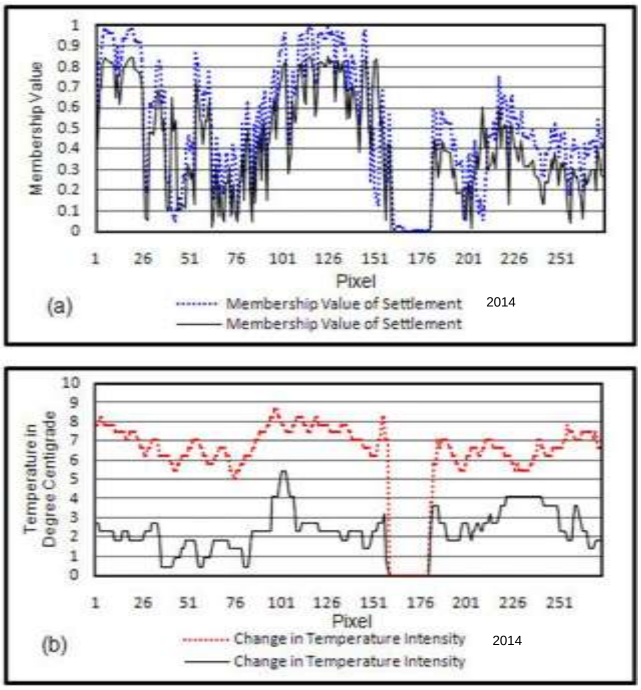


**Fig.10**(a) Comparison of membership value for settlements, (b) Comparison of Urban Heat Island Intensity, Allahabad

## Conclusions

It was observed that land cover and LST information can be derived from remotely sensed data, which provides a powerful way to monitor urban environment. Problem in classification of land cover due to mixed pixels could be handled using supervised fuzzy technique for classification of and different land covers. Presence of a major river in close proximity of urban core of Allahabad city provided an ideal condition to compare intensity of UHI effect for two images separated by a gap of 19 years. Land cover classification for the LANDSAT imageries from 1990 and 2014 indicated that there had been a substantial increase in urban built area along the urban fringe during the period.Membership imagesfor settlement indicatedthat a high degree of urban infilling had taken place throughout the city right from the core to the fringe in the north east. Image for LST for 1990 and 2014 indicated that although the temperatures over river water has remained almost constant, temperatures within the city have increased by $4^0$C to $6^0$C indicating phenomenal increase in UHI effect. The major cause behind increase in UHI effect was attributed to conversion of open land to built-up surfaces which otherwise should have been replaced by vegetation cover as it had been a cooling factor along with water surface.Thus land cover change due to urban expansion not only modifies the heat balance within the city but also has a negative effect on landscape aesthetics, energy efficiency, and human health and quality of life as pointed out by McPherson et al.(1997) and Yueetal.(2007). Study of the impact of sand associated open land along the flood plains of rivers on UHI effect is recommended as the areas with highest LST were associated with open lands close to the river.

## Acknowledgement

The authors would like to convey their thanks to USGS for providing with the LANDSAT imageries. Prof. R. P. Mishra is gratefully acknowledged for providing many good ideas in this work. Many thanks are given to all the reviewers for their constructive comments and suggestions.

## References


1. Akbari H, Pomerantz M, Taha H (2001) Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol. Energy 70:295-310
2. Aniello C, Morgan K, Busbey A, Newland L (1995) Mapping micro-urban heat islands using Landsat TM and a GIS. Computers and Geosciences:965-969
3. Arnold C, Gibbons C (1996) Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association 62:243-258
4. Assimakopoulos M, Mihalakakou G, Flocas H (2007) Simulating the thermal behavior of a building during summer period in the urban environment. Renew Energy 32:1805-1816
5. Atkinson B (2003) Numerical modelling of urban heat-island intensity. Boundary Layer Meteorology 109:285-310
6. Bristow R, Mullens J (1995) Environmental geography education: urban heat islands. In: Geography and Regional Planning. Westfield
7. Chen Y, Li X (2002) A study on urban thermal field in summer based on satellite remote sensing. Remote Sensing for Land and Resources 4:55-59
8. Christopher S (2002) Multi-temporal analysis of urban reflectance. Remote Sensing of Environment 81:427-442
9. Clapham WBJ (2003) Continuum based classification of remotely sensed imagery to describe urban sprawl on a watershed scale. Remote Sensing of Environment 86:322-340
10. Cracknell AP (1998) Synergy in remote sensing-what's in a pixel? International Journal of Remote Sensing 19:2025-2047
11. David R (2003) Satellite-measured growth of the urban heat island of Houston, Texas. Remote Sensing of Environment 85:282-289
12. Dousset B, Gourmelon F (2003) Satellite multi-sensor data analysis of urban surface temperatures and land-cover. ISPRS Journal of Photogrammetry and Remote Sensing 58:43-54
13. Driscoll D (1985) Human health - Handbook of applied meteorology, Vol. Wiley Interscience, New York
14. Eliasson I (1996) Urban nocturnal temperatures, street geometry and land-use. Atmospheric Environment 30:379-392
15. Fisher P (1997) The pixel: a snare and a delusion. International Journal of Remote Sensing 18:679-685
16. Giridharan R, Ganesan S, Lau S (2004) Daytime urban heat-island effect in high rise and high density residential developments in Hong Kong. Energy and Buildings 36:525-534
17. Gopal S, Woodcock C (1994) Theory and methods for accuracy assessment of thematic maps using fuzzy sets. Photogrammetric Engineering and Remote Sensing 60:181-188
18. Grimm N, Grove J, Pickett S, Redman C (2000) Integrated approaches to long-term studies of urban ecological systems. Bioscience 50:571-584

19. Huang H, Ooka R, Kato S (2005) Urban thermal environment measurements and numerical simulation for an actual complex urban area covering a large district heating and cooling system in summer. Atmospheric Environment 39:6362-6375
20. Jensen J (2005) Introductory digital image processing: A remote sensing perspective, Vol. Prentice Hall, Upper saddle river, NJ
21. Jime´nez-Mun˜oz J, Sobrino J (2003) A generalized single-channel method for retrieving land surface temperature from remote sensing data. Journal of Geophysical Research 108:4688-4697
22. Kalnay E, Cai M, Li H (2006) Estimation of the impact of land-surface forcing on temperature trends in eastern United States. Journal of Geophysical Research 111:1-13
23. Kant Y, Badrinath K (1998) A method for estimating the land surface temperature from satellite data using emissivity derived from vegetation index. Current Science 75:139-145
24. Karl T, Diaz H, Kukla G (1988) Urbanization: Its detection and effect in the United States climate record. Journal of Climate 1:1099-1123
25. Kikegawa Y, Genchi Y, Yoshikado H, Kondo H (2003) Development of a numerical simulation system toward comprehensive assessments of urban warming countermeasures including their impacts upon the urban buildings, energy demands. Applied Energy:449-466
26. Kim YH, Baik JJ (2004) Daily maximum urban heat island intensity in large cities of Korea. Theoretical and applied climatology 79:151-164
27. Kolokotroni M, Zhang Y, Watkins R (2007) The Landon heat island and building cooling design. Sol. Energy 81:102-110
28. Lillesand T, Kiefer R, Chipman J (2008) Remote sensing and image interpretation, Vol. John Willey & sons, New York
29. Liu X, Lathrop RJ (2002) Urban change detection based on an artificial neural network. International Journal of Remote Sensing 23:2513-2518
30. Lo C, Quattrochi D (2003) Land-use and land-cover change, urban heat island phenomenon, and health implications: a remote sensing approach. Photogrammetric Engineering and Remote Sensing:1053-1063
31. Los C, Quattrochi D, Luvall J (1997) Application of high resolution thermal remote sensing and GIS to assess the urban heat island effect. International Journal of Remote Sensing 18:287-304
32. Magee N, Curtis J, Wendler G (1999) The urban heat island effect at Fairbanks Alaska. Theor. App. Climatology 64:39-47
33. Maktav D, Erbek F, Jurgens C (2005) Remote sensing of urban areas. International Journal of Remote Sensing 26:655-659
34. McPherson E, Nowak D, Heisler G, Grimmond S, Souch C, Grant R, Rowntree R (1997) Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. Urban Ecosystems 1:49-61
35. Montavez J, Rodriguez A, Jimenez J (2000) A study of urban heat-island of Granada. International Journal of Climatology 20:899-911
36. Montavez J, Rodriguez A, Jimenez J (2000) A study of urban heat-island of Granada. International Journal of Climatology 20:899-911
37. Myer W (1991) Urban heat islands and urban health: early American perspective. Prof. Geog. 43:38-48

38. Oke T (1976) City size and the urban heat island. Atmospheric Environment 7:769-779
39. Oke T (1982) The energetic basis of urban heat island. Journal of Meteorological Society 108:1-24
40. Park H (1986) Features of the heat island in Seoul and its surrounding cities. Atmospheric Environment 20
41. Pinho O, Orgaz MM (2000) The urban heat island in a small city in coastal Portugal. International Journal of Biometeorology 44:198-203
42. Potchter O, Sofer M (2006) The urban heat island of a city in an arid zone: the case of Eilat, Israel. Theoretical and Applied Climatology 85:81-88
43. Qin Z, Karnieli A, Berliner P (2000) A mono window algorithm for retrieving land surface temperature from LANDSAT TM and its application to Israel-Egypt border region. International Journal of Remote Sensing 22:3719-3746
44. Quattrochi D, Rickman D, Estes M, Caymon C, Howell B, Luvall J (2000) A Decision support information system for urban landscape management using thermal infrared data. Photogrammetric Engineering and Remote sensing 66:1195-1207
45. Rosenfeld A, Akbari H, Bretz S, Fishman B, Kurn D, Sailor D, Taha H (1995) Mitigation of urban heat-islands: materials, utility, programs, updates. Energy and Buildings 22:255-265
46. Sailor D (1995) Simulated urban climate response to modifications in surface albedo and vegetation cover. Journal of Applied Meteorology 34:1694-1704
47. Shenali X (2009) An approach to analyzing the intensity of the daytime surface urban heat island effect at a local scale. Environment Monitoring Assessment 151:289-300
48. Stanowski S (1972) Population density as an indirect indicator of urban and suburban land-surface modifications, United States Geological Survey
49. Streutker D (2002) A remote sensing study of the urban heat island of Houston, Texas. International Journal of Remote Sensing 23:2595-2608
50. Taha H (1997) Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin. Atmospheric Environment 31:1667-1676
51. Thapa R, Murayama Y (2009) Urban mapping accuracy & image classification: A comparison of multiple approaches in Tsukuba city, Japan. Applied Geography 29:135-144
52. Turner B (1994) Local faces, global flows: the role of land use and land cover in global environmental change. Land Degradation and Development 5:71-78
53. United N (2008) United Nation urbanization: a global perspective. Proceedings of the expert group meeting on population distribution, urbanization, internal migration and development Report of the meeting, New York
54. Voogt J, Oke T (2003) Thermal remote sensing of urban climates. Remote Sensing of Environment 86:370-384
55. Wang W, Zeng Z, Karl T (1990) Urban heat-island in China. Geophysical Research letters 17:2377-2380
56. Weng Q (2001) A remote sensing GIS evaluation of urban expansion and its impact on surface temperature in the Zhujiang delta, China. International Journal of Remote Sensing 22:1999-2014
57. Weng Q (2003) Fractal analysis of satellite detected urban heat island effect. Photogrammetric Engineering and Remote Sensing 69:555-566

58. Yamashita S (1996) Detailed structure of heat island phenomena from moving observation from electric tram-cars in metropolitan Tokyo. Atmospheric Environment 30:429-435
59. Yue W, Xu J, Tan W (2007) The relationship between land surface temperature and NDVI with remote sensing: application to Shanghai LANDSAT 7 ETM+ data. International Journal of Remote Sensing 28:3205-3226
60. Zhang J, Foody G (2001) Fully fuzzy supervised classification of sub-urban land cover from remotely sensed imagery: statistical and artificial neural network approaches. International Journal of Remote Sensing 22:615-628

## List of Figures: