



# Variation in the Surface Urban Heat Island effect over Srinagar city in summer and winter seasons

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## Abstract

This study aims to assess the change in land use and land cover (LULC) and its associated changes in Land Surface Temperature (LST) and Surface Urban Heat Island Intensity (SUHII) over Srinagar city in Jammu and Kashmir between 1993 and 2022 during summer and winter seasons. First, LULC maps were prepared for the years 1993 and 2022 using supervised classification technique and then it was analysed together with LST data obtained from Landsat 5 and Landsat 8 satellites for the corresponding years to detect changes in LULC pattern, LST and SUHII over the thirty-year period. It was observed that major changes took place over built-up area which increased by about 150% in 2022 compared to 1993 indicating increased urbanization of the city. In summer, LST has increased over all the classes, but the maximum increase was found over built-up areas. The increasing LST led to increase in SUHII too especially over areas that got converted to built-up or barren surfaces from vegetated surfaces or water bodies. Over such surfaces the SUHII increased by more than 4 °C. During the winter season, built-up areas exhibited marginally higher LST compared to vegetated areas in 1993, however, the SUHII over built-up areas had decreased. In 2022, persistent cold conditions resulted in marginally lower mean LST values (7.66 °C) for the built-up areas compared to the mean LST of vegetated surfaces (7.88 °C) which resulted in lower SUHII over built areas compared to vegetated surfaces. The overall LST in December 2022 was lower than the LST observed in December 1993. These results underscore the importance of vegetation in providing cooling effect in summer and in maintaining warmer temperatures during winter.

**Keywords** Urban Heat Island · Urbanisation · Land use land cover · Surface temperature · Thermal infrared (TIR)

## Introduction

The world's urban population has grown rapidly during the past five decades and is expected to increase even more rapidly in the next 50 years (Grimm et al. 2008). In 2030, 60% of people worldwide are projected to live in urban areas and by 2050 this percentage is going to touch 68% (WUP 2018). Rapid urbanization leads to transformation of the natural landscape into man-made structures which alter the local atmosphere and raise the land surface temperature relative to the open spaces nearby (Zhou et al. 2014). The large-scale changes in urban Land Use and Land Cover (LULC)

caused by the growing urban population, are leading to several environmental and ecological issues (Liu et al. 2018). The unplanned changes in the urban LULC pattern in cities of developing countries modify the thermal characteristics of the land surface (Tran et al. 2017), which increases the Surface Urban Heat Island Intensity (SUHII) across urban areas (Rizwan et al. 2008).

Urban Heat Island (UHI), one of the best-documented examples of anthropogenic modification of the Earth system (Peres et al. 2018), is the phenomena where urban areas tend to have greater air or land surface temperatures than the surrounding rural area (Howard 1818; Oke 1973). The temperature difference is typically more noticeable when winds are mild and is typically greater at night than during the day (Phelan et al. 2015). The city will appear as an "island" in the background of the rural temperature on an isotherm map of the scenario (Montávez et al. 2000). Two broad forms of UHI exist. The first is the atmospheric UHI (AUHI) measured using networks of meteorological

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stations, while the second is the surface UHI (SUHI) determined using thermal infrared (TIR) remote sensing methods (Arnfield 2003; Imhoff et al. 2010; Oke 1982). The SUHI is caused by the urban infrastructure's increased thermal heat storage and heat capacity with lower thermal inertia, reduced evapotranspiration because of the loss of vegetation, increase in impermeable surfaces and reduced aerodynamic efficiency to transfer heat away from the surface (Li et al. 2019a). The key factors affecting daytime UHI are the differences in thermal inertia between rural and urban surfaces, anthropogenic heat from urban areas, and reduced latent heat flux over urban areas, whereas anthropogenic heat regulates nighttime UHI (Wang et al. 2007). In addition to its effects on eco-environment, the SUHI can significantly impact human health (Heaviside et al. 2017) due to its direct impact on heatwave severity (Ward et al. 2016) and atmospheric pollution (Wang et al. 2018). In order to observe surface urban heat islands, Land Surface Temperature (LST) observed from TIR sensors is a unique source of information, and it has been frequently employed as an indication for UHI studies. The urban heat island intensity (UHII) is generally assessed by taking the difference of LST between an urban area and nearby rural or suburban areas (Clinton and Gong 2013; Peng et al. 2011; Zhou et al. 2014).

Changing LULC and hence LST has a major role to play in formation as well as modification of SUHI. Li et al. (2012) in their UHI study over Shanghai city showed that land surface characteristics and spatiotemporal patterns of UHI was significantly altered by LULC change. They further found that the SUHI intensity was highest during summers and lowest during winters. Among the different LULC changes, urban expansion intensifies the UHI by increasing the number as well as the distributions of hotspots while the relation between LST and individual LULC types is not consistently linear due to possible variation across different LULC types, as well as being dependent on geographical location and season (Tran et al. 2017).

In their multi-temporal study of Noida city, India using Landsat ETM and Landsat-8 data, Kikon et al. (2016) found that LST exhibited a rising trend in areas with increased built-up land, with positive correlations observed between LST and Normalized Difference Built-up Index (NDBI) and between LST and albedo, and negative correlations found between LST and Normalized Difference Vegetation Index (NDVI) and emissivity, ultimately identifying built-up land as a significant contributor to the UHI effect. Shahfahad et al. (2022) analysed the impact of land use/land cover change on SUHII and thermal comfort in Delhi, showing that the built-up area increased from 315.18 to 720.24 sq. km during 1991 to 2018, resulting in an increase of minimum, maximum, and mean SUHII by 1.26 °C, 4.6 °C, and 1.18 °C, respectively, leading to a decline in thermal comfort. While most of the UHI studies in India have been focused on mega

and metropolitan cities only a few studies have been carried on emerging cities in India. Especially urban development on the Himalayan region needs to be monitored consistently as unplanned changes can significantly affect the delicate ecosystem. One of the largest cities in the Himalayan range in India is the Srinagar city in the union territory of Jammu and Kashmir which is experiencing increase in population and rise in tourism leading to urbanisation. Pawe (2019) analysed the urbanisation and UHI effect over Srinagar city for the years 1992, 2002 and 2013 during the autumn season (October or November) using Landsat data. More recently, Ahmad et al. (2024) analysed the urban expansion of the city and reported an increase in built-up area from 34.53 km<sup>2</sup> in 2000 to 60.63 km<sup>2</sup> in 2020. Though Ahmad et al. (2024) reported higher LST over built-up areas in 2020, a temporal analysis of LST change has not been carried out in the study. The UHI effect will have larger impact during the summer and winter seasons especially in colder places such as Srinagar. During summer, UHI effect can increase the temperature of the city affecting the people who come to Srinagar to escape from the heat in other parts of India. During cold winters, the presence of heat island may provide little respite from the harsh weather and reduce the amount of artificial heating required (Priyadarsini 2009). This study aims to analyse the changes in LULC and its impact on LST and SUHII in Srinagar city during summer and winter seasons over a period of 30 years using TIR data from Landsat-5 and Landsat-8 satellites.

## Study area and datasets

Located between 33°59' to 34°12' N latitude and 74°41' and 74°57' E longitude and a mean elevation of 1585 m (a.m.s.l), Srinagar is the largest city and the summer capital of the Union Territory of Jammu and Kashmir (Fig. 1). According to Indian census, the population of the city was found to be about 12 million. The city is surrounded with steep hills in the east and northeast, low-lying paddy fields in the north, Jhelum floodplains in the south and west, and higher plateau lands in the south. River Jhelum, a major river stream of Kashmir region, which flows through the city divides the city into two parts. Dal Lake, a famous tourist spot, fed by springs and streams originating from glacier and snow melt is located at the heart of the city. Srinagar has a temperate humid subtropical climate and witnesses four distinct seasons of summer, autumn, winter and spring. While the climate during spring and autumn usually remains cool, the city experiences hot summers with temperature going as high as 38 °C and cold winters with sub-zero temperatures. The city receives an average yearly precipitation of 720 mm with an overall annual temperature of 13.5 °C. Being a major urban and administrative centre in UT of Jammu & Kashmir, Srinagar's urban area has expanded as

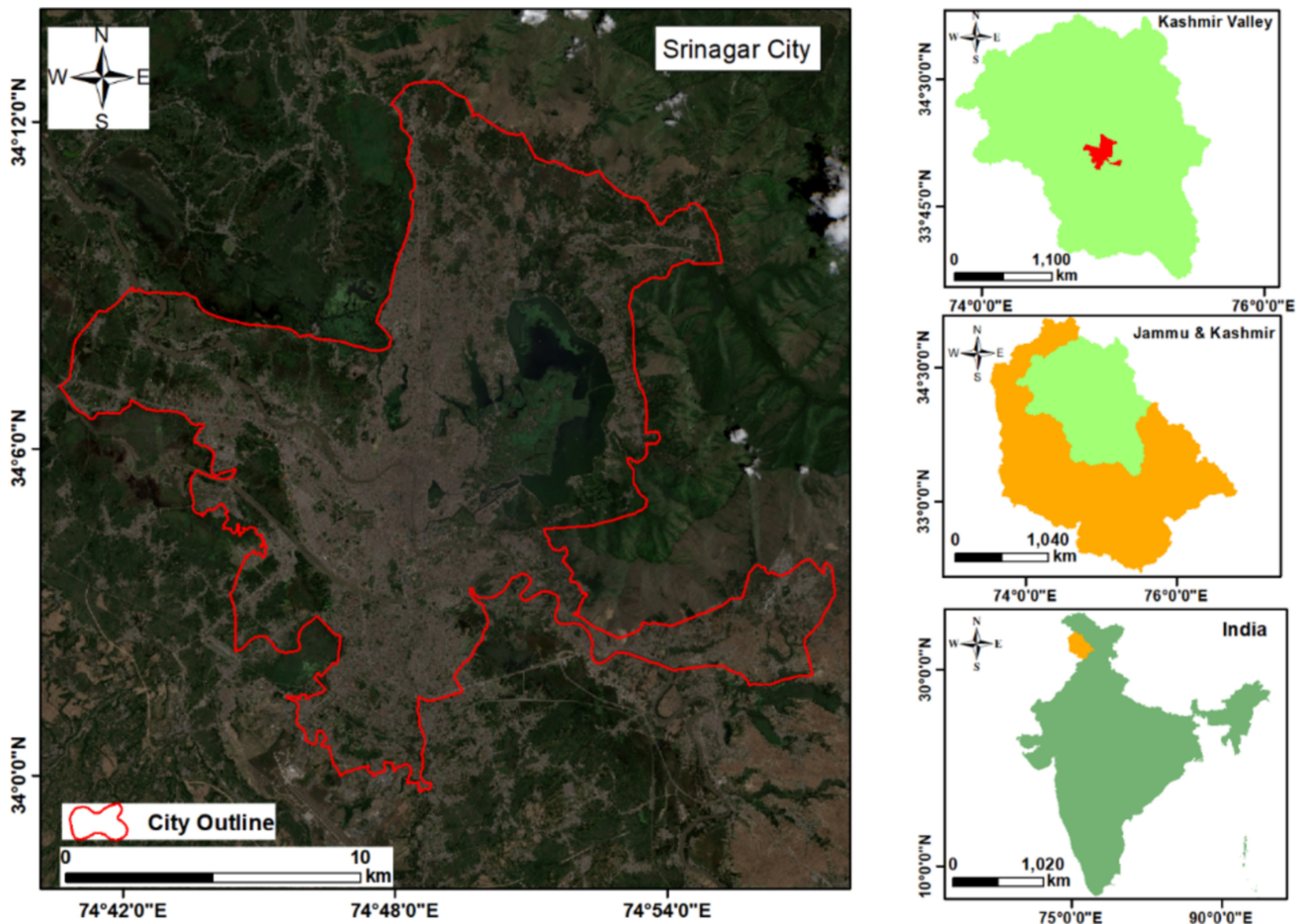


Fig. 1 Study area location

a result of extensive development of transport, tourism, infrastructure, and other related facilities which makes it is pertinent to undertake the UHI studies.

For this study, optical and TIR data acquired in 1993 and 2022 by Landsat-5 and Landsat-8 satellites respectively were downloaded (row no. 36 and path no. 149). Images acquired in the month of June (12 June 1993 and 28 June 2022) and December (5 December 1993 and 5 December 2022) corresponding to summer and winter seasons were analysed. Level-2 surface reflectance (SR) was used in the calculation of the spectral indices (NDVI and NDBI) and for LULC classification. Level-2 land surface temperature (LST) product was used for SUHI mapping. The analyses were carried out using ArcGIS and Google Earth Engine (GEE) tools.

## Methodology

### Spectral indices

Two spectral indices NDVI and NDBI were calculated for analysing their relationship with LST. NDVI is an indicator vegetation vigour (Tucker 1979) and calculated using the surface reflectance values in the Near-infrared (N) and red (R) bands. Similarly, NDBI is considered as suitable index to identify built areas (Zha et al. 2003) and estimated using the reflectance values in the shortwave infrared (S) and Near-infrared (N) bands. We have utilised the short-wave infrared band around 1.6  $\mu\text{m}$  wavelength (band 5 in



Landsat 5 and band 6 in Landsat 8) in the calculation of NDBI.

$$\text{NDVI} = \frac{N - R}{N + R} \quad (1)$$

$$\text{NDBI} = \frac{S - N}{S + N} \quad (2)$$

### LULC classification

Multispectral visualisation using False Colour Composite (FCC) images were used to create LULC maps for the year 1993 and 2022. Images acquired in June only were used for LULC classification. The entire city was divided into five major classes: built-up, agriculture, barren land, waterbodies and vegetation using supervised classification procedure with the maximum likelihood algorithm. The training sites for each class were created in a well-distributed manner through visual interpretation. Accuracy assessment of the classified maps was done by generating confusion matrix by taking random points for each class (independent of training data) and comparing them with corresponding high-resolution images available in Google Earth Pro. Using post classification techniques like image inspection and recoding, small inaccuracies in the image were corrected. The image analyst had excellent local knowledge about the city's geography which helped immensely in the visual interpretation process.

### SUHII estimation

The Landsat collection-2 level-2 LST product was used here directly to calculate SUHII. SUHII was defined here as the difference in LST of a pixel and the mean LST of vegetated surfaces within the urban boundary. This is different from the classical definition which defines SUHII as difference between LST of a pixel and LST of pixels over rural areas. This definition includes the effect of both the city and its surroundings together in SUHII estimation and may not give direct understanding of warming over a city (Martili et al. 2020). Further, the definition adopted here in this study is like the UHI definition based on the concept of local climate zones which is more relevant to urban analysis and planning (Stewart and Oke 2012; Bechtel et al. 2019). The naturally vegetated areas within the city were identified and the mean LST of the selected pixels were used as the reference LST. This reference LST was subtracted from the LST of each pixel to estimate SUHII over Srinagar city. It is to be noted that the reference LST was estimated independently for each of the summer and winter time images of 1993 and 2022 that were analysed.

## Results

### LULC pattern of Srinagar city

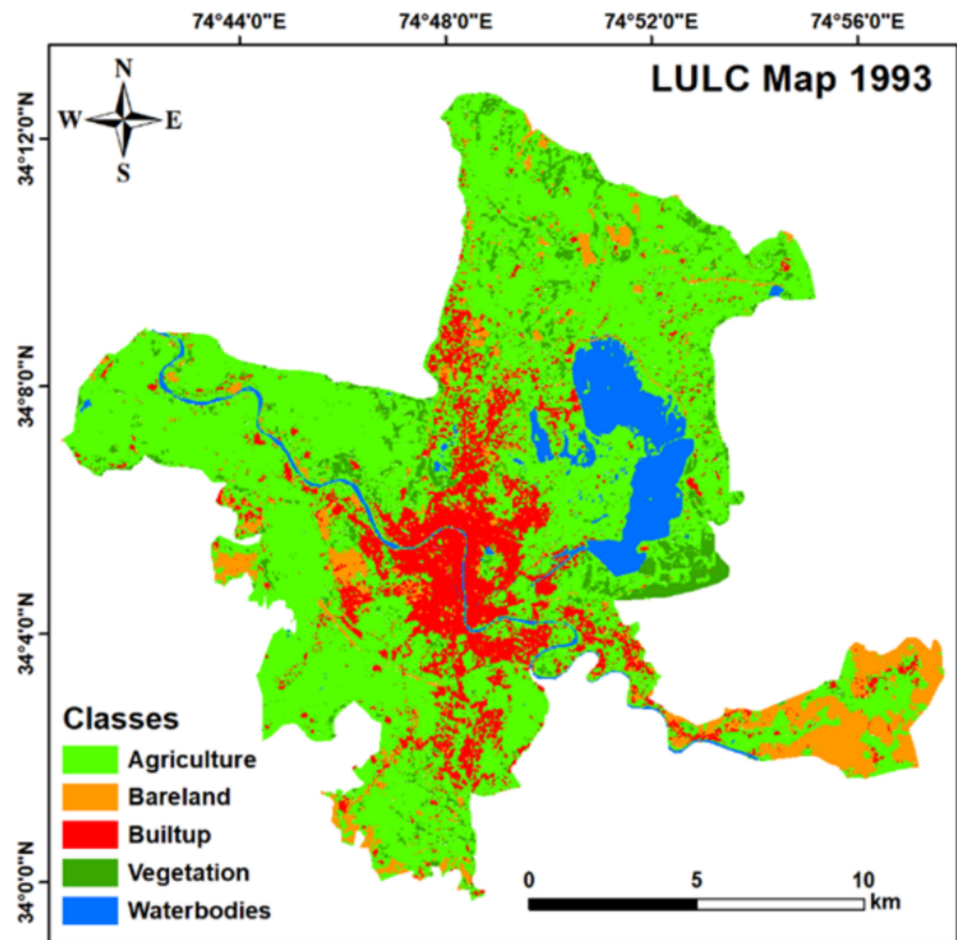
The LULC map of Srinagar city for the year 1993 is shown in Fig. 2 and the distribution of land class types in terms of area and percentage of total area is shown in Table 1. The largest land use group, representing an area of 16,100.43 hectares (65.52% of total study area) is agriculture, followed by built-up land which corresponds to 3319.17 hectares (13.51% of the total area). Pawe (2019) also reported that 11.1% of total area of Srinagar was covered with built up area in 1992 which was similar to the results obtained in this study. Ahmad et al. (2024) estimated the built-up area to cover 14% of the total area in 2000 indicating only a marginal change from the values reported in Pawe (2019) and this study. The other land cover classes barren land, water body and natural vegetation comprised of 2013.27 hectares (8.19% of the total area), 1588.03 hectares (6.46% of the total area) and 1552.77 hectares (6.32% of the total area) respectively. The 1993 LULC had an overall accuracy of 90% and a kappa coefficient of 0.84 when compared against older satellite images available in Google Earth pro.

The classified image of 2022 produced from Landsat-8 data is presented in Fig. 3. The figure shows that there was a significant change in LULC pattern particularly with respect to agriculture and built-up with agriculture occupying an area of 9004 hectares (36.64% of total area) still being the major LULC class in 2022 followed by built-up area corresponding to an area of 8349.72 hectares (33.98% of total area). The other land use categories include barren land (3237 hectares, 13.17% of the total area), vegetation (2412.83 hectares, 9.82% of the total area), and waterbodies (1567.90 hectares, 6.38% of the total area). The 2022 LULC map had an overall accuracy level of 94% and a kappa coefficient of 0.91. The results are summarised in Table 2.

Pawe (2019) mentioned that in 2013 itself, the built-up area in Srinagar accounted for 8570 hectares (36.5% of the total area) which is more than the built-up area estimated here. However, Ahmad et al. (2024) reported the built-up area to be only 6063 (24% of the total area) hectares in 2020. There seems to be some differences in the built-up area reported in different studies. Over the course of three decades, agricultural land and waterbodies have shown decrease in their areal coverage with agriculture showing a maximum decrease of 7096.43 hectares (28.88% of total area) and waterbodies with a much smaller decrease of 20.13 hectares (0.08% of total area). On the other hand, all other classes have shown an increase in area with built up corresponding to maximum areal increase of 5030.55



**Fig. 2** LULC of Srinagar city in the year 1993



**Table 1** Areal extent of different land classes for the year 1993

| Class name  | Area in hectares | Percentage |
|-------------|------------------|------------|
| Agriculture | 16,100.43        | 65.52      |
| Barren land | 2013.27          | 8.19       |
| Built-up    | 3319.17          | 13.51      |
| Vegetation  | 1552.77          | 6.32       |
| Waterbodies | 1588.03          | 6.46       |

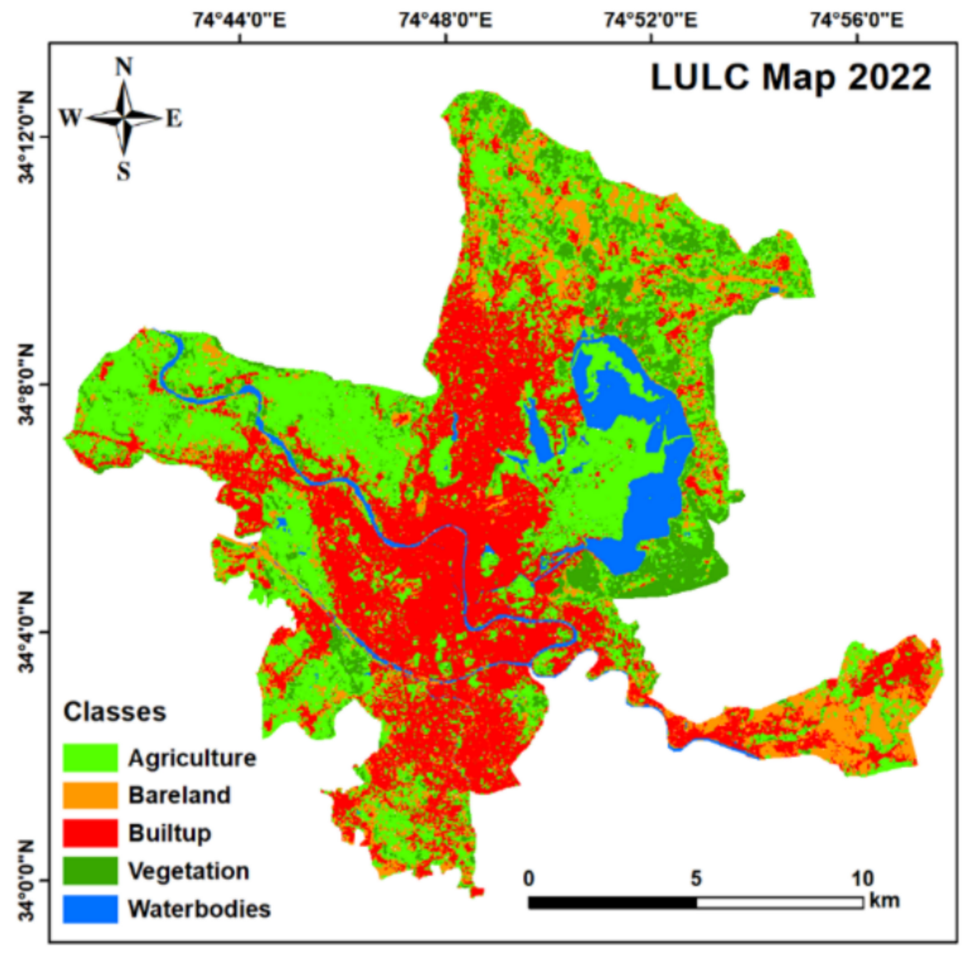
hectares (20.47% of total area) followed by barren land with 1223.73 hectares (4.98% of total area) and vegetation at 860.06 hectares (3.50% of total area). Looking at class-wise percentage increase we find that over the past 30 years, Srinagar city has undergone massive urbanization, where the built-up has increased by 151.56% compared to 1993.

### LST and SUHII during summer season in 1993 and 2022

The statistics summarising the LST distribution for each LULC class during June 1993 obtained from band 6 of Landsat-5 are given in Table 3 and the spatial distribution of LST is presented in Fig. 4a. Barren land has the highest mean land surface temperature among all the classes (35.97 °C) followed by built-up with a mean LST of 34.14 °C. Pu et al. (2006) and Zareie et al. (2016) had also shown that the LST of barren land may be higher than the LST values of built up areas. The soil content in these regions may result in the high LST values (Karakuş 2019). Agriculture, natural vegetation and water bodies with mean LST values of 29.72 °C, 28.15 °C and 24.98 °C respectively follows the above two class in decreasing order of LST. While the maximum LST followed the same land cover pattern as mean LST, the minimum LST observed over barren surface was found to be lower than natural vegetation. On examining the LULC map, it was understood that the barren surfaces on the close vicinity of water bodies or river channel exhibited cooler temperatures due to the presence of water.



**Fig. 3** LULC of Srinagar city in the year 2022



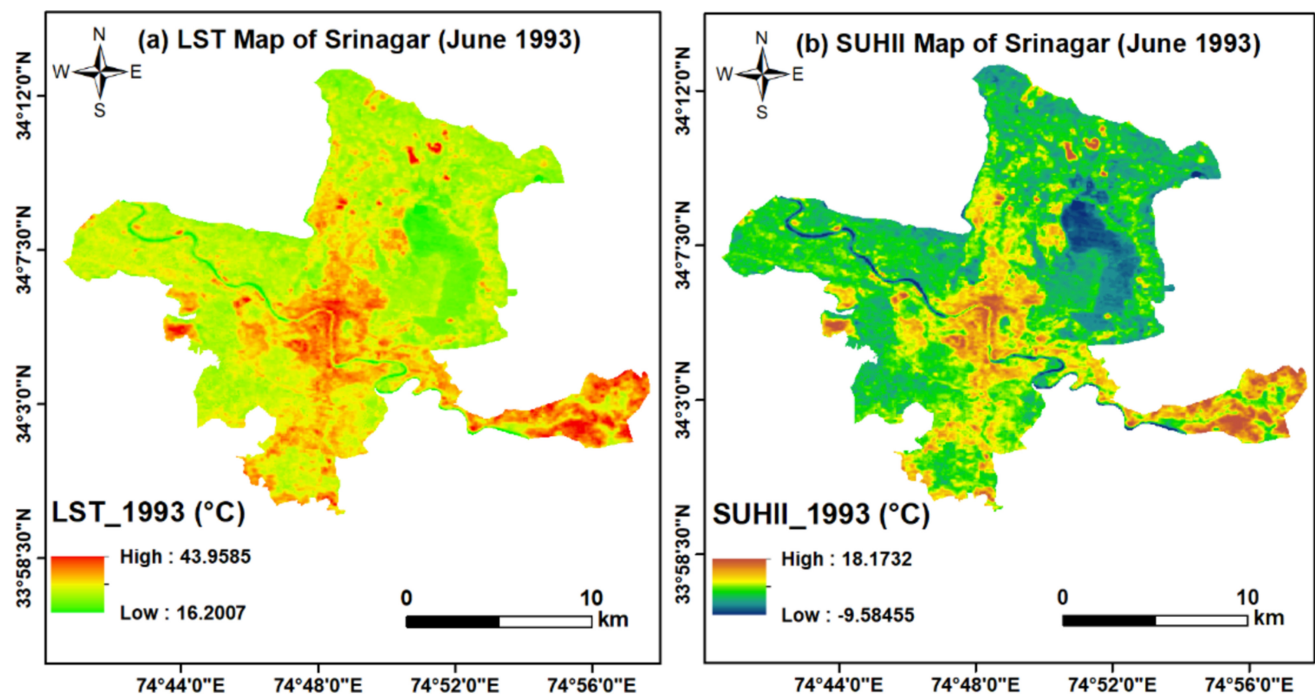
**Table 2** Areal extent of different land classes for the year 2022

| Class name  | Area in hectares | Percentage |
|-------------|------------------|------------|
| Agriculture | 9004             | 36.64      |
| Barren land | 3237             | 13.17      |
| Built-up    | 8349.72          | 33.98      |
| Vegetation  | 2412.83          | 9.82       |
| Waterbodies | 1567.90          | 6.38       |

**Table 3** LST distribution over different land cover classes for June 1993

| LULC class   | LST minimum (°C) | LST maximum (°C) | Mean LST (°C) |
|--------------|------------------|------------------|---------------|
| Water bodies | 16.20            | 37.39            | 24.98         |
| Barren land  | 22.12            | 43.96            | 35.97         |
| Agriculture  | 16.71            | 41.01            | 29.72         |
| Vegetation   | 23.12            | 40.55            | 28.15         |
| Built-up     | 23.88            | 42.56            | 34.14         |

The SUHII map of Srinagar city for the year 1993 is shown in Fig. 4b and the statistics are quantified in Table 4. It can be noted that the SUHII intensity follows the same pattern as LST where the mean SUHII was highest for barren land at 10.18 °C and built-up areas at 8.36 °C followed by agriculture, vegetation and waterbodies with mean SUHII of 3.94 °C, 2.36 °C and −0.80 °C respectively. The SUHII of barren land and built-up classes had significantly higher values when compared to the other three classes indicating how urbanization changes the temperature characteristics of natural landcover. The negative mean SUHII for waterbodies indicates that waterbodies had a lower LST as compared to reference vegetated area. The minimum SUHII was negative for all the classes and here too, the pixels with minimum values were either closer to waterbodies or were surrounded by dense vegetation similar to the trends observed in LST.



**Fig. 4** a LST and b SUHII map for Srinagar city for June 1993

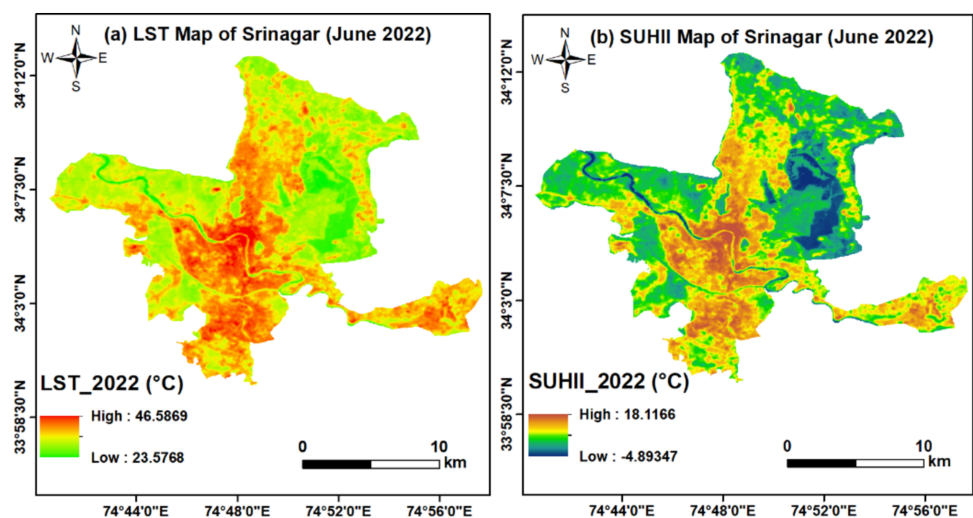
**Table 4** Statistics of SUHII over different classes in June1993

| LULC class  | Minimum SUHII (°C) | Maximum SUHII (°C) | Mean SUHII (°C) |
|-------------|--------------------|--------------------|-----------------|
| Waterbodies | −9.58              | 11.61              | −0.80           |
| Barren land | −3.66              | 18.17              | 10.18           |
| Agriculture | −9.07              | 15.22              | 3.94            |
| Vegetation  | −2.66              | 14.76              | 2.36            |
| Built-up    | −1.91              | 16.78              | 8.36            |

### LULC, LST and SUHII pattern of Srinagar city in 2022

The LST map for June 2022 is presented in Fig. 5a along with details in Table 5. It can be observed that mean LST of all the LULC classes was higher when compared with June 1993. Built up area has the highest mean LST of 38.90 °C among all the classes followed by barren land with a mean LST of 36.27 °C. This is followed by agriculture, vegetation

**Fig. 5** a LST and b SUHII map for Srinagar city during June 2022





**Table 5** LST distribution over different LULC classes in June 2022

| LULC class  | LST minimum (°C) | LST maximum (°C) | Mean LST (°C) |
|-------------|------------------|------------------|---------------|
| Waterbodies | 23.58            | 42.02            | 28.32         |
| Barren land | 26.84            | 45.02            | 36.27         |
| Agriculture | 25.11            | 44.40            | 33.40         |
| Vegetation  | 26.63            | 41.18            | 31.14         |
| Built-up    | 28.24            | 46.59            | 38.90         |

**Table 6** Statistics of SUHII over different classes for June 2022

| LULC class  | Minimum SUHII (°C) | Maximum SUHII (°C) | Mean SUHII (°C) |
|-------------|--------------------|--------------------|-----------------|
| Waterbodies | −4.89              | 13.55              | −0.15           |
| Barren land | −1.63              | 16.55              | 7.80            |
| Agriculture | −3.36              | 15.93              | 4.93            |
| Vegetation  | −1.84              | 12.71              | 2.67            |
| Built-up    | −0.23              | 18.12              | 10.43           |

and waterbodies with a mean LST of 33.40 °C, 31.14 °C and 28.32 °C respectively.

Similar to LST, SUHII too increased among all classes in 2022 (Fig. 5b) with mean SUHII of built-up found to be highest at 10.43 °C followed by barren land at 7.80 °C as shown in Table 6. While agriculture and vegetation had relatively lower mean SUHII of 4.93 °C and 2.67 °C respectively, waterbodies had a negative value of −0.15 °C indicating the cooling effect.

Over the last 30 years, SUHII in summer had increased over all classes except barren land where SUHII showed a decrease of −2.38 °C. The SUHII increase was highest in built-up areas (2.08 °C) followed by agriculture (1.00 °C), waterbodies (0.66 °C) and vegetation (0.31 °C). From Tables 3 and 5 it can be inferred that the mean LST increased over all the classes in 2022. However, the increase in LST over barren land was much smaller than increase in LST over other classes. This was the reason for barren lands exhibiting negative SUHII change. However, it should be noted that barren lands had much higher mean LST than all other classes in 1993 itself.

Next, we analysed the change in SUHII over pixels that underwent LULC change. For this, all the pixels that changed from class 'x' to class 'y' were identified (where x and y are the LULC classes) and the mean change in SUHII over such changed pixels were estimated. SUHII change was found to be maximum positive in vegetation-built-up conversion and maximum negative in barren land-vegetation conversion with SUHII values of 5.19 °C and −7.04 °C respectively. SUHII change was also found to be negative for transformations of barren land-agriculture, barren

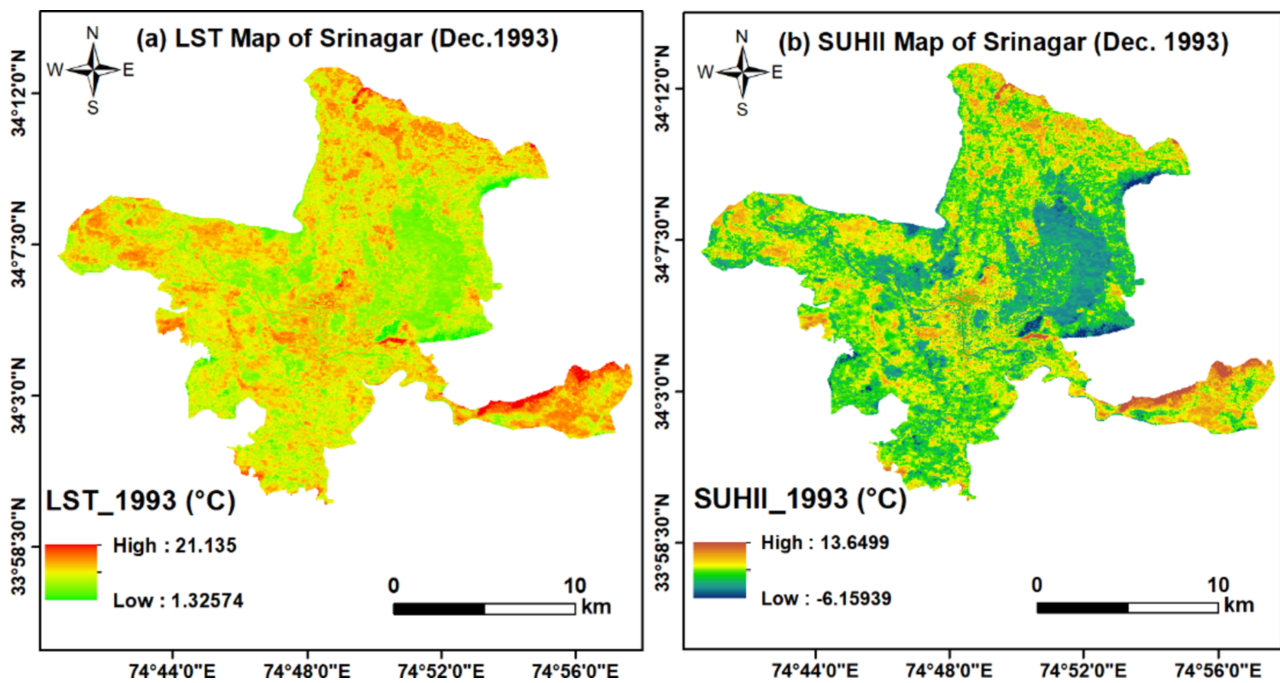
**Table 7** LST distribution over different land cover classes for December 1993

| LULC class   | LST minimum (°C) | LST maximum (°C) | Mean LST (°C) |
|--------------|------------------|------------------|---------------|
| Water bodies | 4.61             | 14.03            | 7.50          |
| Barren land  | 2.92             | 21.14            | 11.95         |
| Agriculture  | 1.85             | 19.22            | 9.85          |
| Vegetation   | 1.33             | 17.52            | 8.70          |
| Built-up     | 3.48             | 20.23            | 10.49         |

land-waterbodies, vegetation-waterbodies and built-up-vegetation with respective values of −2.36 °C, −1.60 °C, −1.28 °C and −1.22 °C. The negative change in SUHII means that these particular conversions resulted in decrease in the SUHII which signifies that the pixels had become cooler (relative to the vegetated reference pixels used) in 2022 than what it was in 1993. It is to be noted that the change in SUHII for those classes that remained unchanged was found to be positive except barren land because of overall increase in LST for all the classes in 2022 compared to 1993. The change in SUHII intensity was found to be maximum when a LULC transformed to built-up and barren land and minimum in the case when it transformed to vegetation and waterbody. The cooling effect of vegetation on lowering the UHI effect can be easily understood by the results of barren land-vegetation conversion where a small change of 49.57 hectares produced a maximum negative change of −7.04 °C in SUHII. In addition to vegetation, waterbodies are also responsible for lowering the UHI effect.

### LST and SUHII during winter season in 1993 and 2022

The onset of winter was clearly noticeable in the LST values with significant decrease over all land cover classes (Table 7 and Fig. 6a) compared to June. To indicate the conditions, the maximum and minimum air temperature from December 1 to 4 were extracted from the ERA-5 reanalysis and they were respectively around 11 °C and 1 °C on an average. The Landsat image was acquired on December 5 and hence we analysed few days before that to understand the prevailing conditions. The LST distribution across different landcover classes followed similar pattern as that of June 1993. Barren lands and built-up areas had higher mean and maximum LST values compared to all other classes. However, the difference in mean LST between vegetated surfaces (both natural vegetation and agriculture areas) and built-up areas decreased quite significantly. While in June 1993, the difference in mean LST between these classes was more than 4 °C, in December it decreased to less than 2 °C. Especially, agricultural areas had only a marginal mean LST difference



**Fig. 6** **a** LST and **b** SUHII map for Srinagar city for December 1993

**Table 8** SUHII statistics over different land cover classes for December 1993

| LULC class   | SUHII minimum (°C) | SUHII maximum (°C) | Mean SUHII (°C) |
|--------------|--------------------|--------------------|-----------------|
| Water bodies | −2.87              | 6.54               | 0.02            |
| Barren land  | −4.56              | 13.65              | 4.47            |
| Agriculture  | −5.63              | 11.73              | 2.36            |
| Vegetation   | −6.16              | 10.04              | 1.21            |
| Built-up     | −4.01              | 12.74              | 3.01            |

**Table 9** LST distribution over different land cover classes for December 2022

| LULC class   | LST minimum (°C) | LST maximum (°C) | Mean LST (°C) |
|--------------|------------------|------------------|---------------|
| Water bodies | 2.38             | 10.53            | 5.88          |
| Barren land  | 3.18             | 16.29            | 8.73          |
| Agriculture  | 2.83             | 14.70            | 8.69          |
| Vegetation   | 2.30             | 13.71            | 7.88          |
| Built-up     | 3.48             | 12.82            | 7.66          |

of 0.65 °C compared to built-up areas in December. This indicates that over colder regions, the presence of vegetation help maintain warmer temperatures during winter (Chun and Guldmann 2018). Geletic et al. (2019) too have reported decrease in SUHII over built-up areas in winter when using

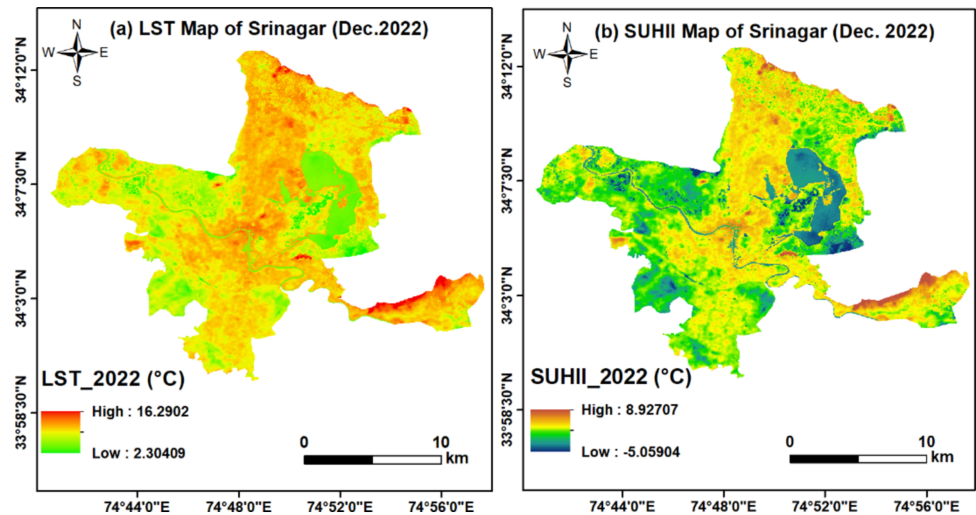
LST over vegetated pixels as reference. Compared to other classes, water bodies exhibited the least temperature range (maximum–minimum) of 9.42 °C due to the high thermal inertia.

The SUHII distribution (Table 8 and Fig. 6b) during December 1993 again, followed a pattern similar to summer time with barren surfaces and built-up areas having the largest maximum and mean SUHII values. The decrease in temperature difference between vegetated and built-up areas has led to decrease in the SUHII effect.

December 2022 presented a relatively colder environmental conditions with the maximum and minimum air temperature hovering around 11 °C and −1 °C during December 1 to 4. Across all land cover classes, the LST observed in December 2022 was less than that was observed in December 1993. The persistent colder temperatures had resulted in built-up areas to have colder LST than vegetation as given in Table 9. Though the minimum LST reported over agricultural and natural vegetated areas are lower than built-up areas, the mean and maximum LST for the vegetation classes are higher. However, it is to be noted that built-up areas still had relatively warmer temperatures overall as can be seen in Fig. 7a. On comparing this LST image with the landcover map in Fig. 3, the warmer LST over built-up areas can be clearly observed. The warmer LST of vegetated areas influenced the SUHII calculations in which the built-up areas exhibited related lower SUHI effect than vegetated areas (Table 10). This is because of the definition of the SUHII followed in this study.



**Fig. 7** Same as Fig. 6 but for December 2022. **a** LST and **b** SUHII



Summer and winter SUHII analysis gave contrasting results especially in 2022 due to the varying environmental conditions. To further understand the relationship between LST, vegetation and built-up areas, we performed a linear regression between LST-NDVI and LST-NDBI, (Zha et al. 2003). The relationship between LST and NDVI over Srinagar is given in Fig. 8 and the LST-NDBI relationship is given in Fig. 9. In Figs. 8 and 9, sub-plots (a) and (c) are for the June month and (b) and (d) are for the December months.

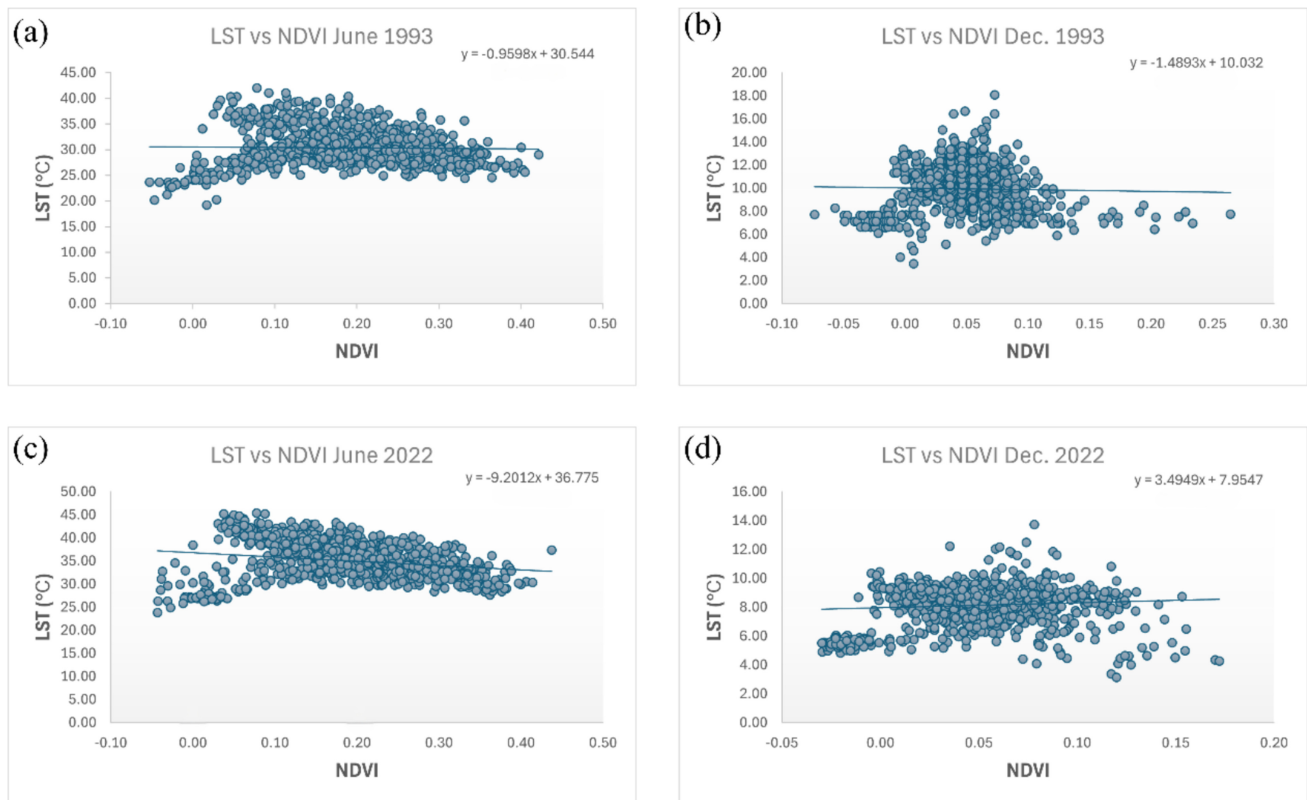
The slope of the LST-NDVI plot is an indicator of the factor controlling evaporation and vegetation productivity. If the slope is negative, the water is major limiting factor over the region and when the controlling factor is radiation or temperature, then the slope turns positive (Karnieli et al. 2010). From Fig. 8, it can be observed that the slope values are negative in June 1993 (−0.96), December 1993 (−1.49) and June 2022 (−9.20). However, the slope was positive in December 2022 (3.49) indicating that the colder environmental conditions has made temperature a controlling factor for evaporation and vegetation productivity. Under these conditions, higher vegetation cover will be found over warmer areas and built-up and barren surfaces marked by lower NDVI values will have lower LST. This is the major reason for lower SUHII values observed

over built-up areas in December 2022. The LST-NDBI relationship (Fig. 9) on the other hand had positive slope in both June and December of 1993 and 2022 indicating the warming nature of built-up areas. The positive correlation between LST and NDBI was also mentioned by Chen et al. (2006) over China. This also reconfirms the reason for the lower SUHII values observed over built-up areas in December 2022.

The summer and winter time analysis of LST and SUHII gave a contrasting picture with LST increasing between 1993 and 2022 in June, whereas, in December a fall in LST values were observed. The LST images used are instantaneous in nature and will indicate the conditions existed at the time and day of satellite overpass. LST can vary due to multiple factors and we wanted to understand if this trend is general or due to the prevailing environmental conditions on the day of satellite overpass. The mean LST over Srinagar city was calculated from Landsat images in June and December every year between 1993 and 2022. While in June, images acquired during the entire month was used in the averaging, in December we have used the images acquired only between December 1 to 15 every year. Typically, Srinagar experiences its harsh winter period (known as chillai-kalan) between December 21 to Jan 29 with temperatures dropping several degrees below the freezing point and we have avoided images acquired during the harsh winter period. The trend of mean LST over Srinagar is plotted in Fig. 10 and it can be quickly observed that the mean LST is having an increasing trend during June and during December the trend is slightly negative. Though a significant scatter in LST is observed indicating that the trends may not be significant always, in general it can be understood that the summer time LST values are increasing over the city. This along with the increase in built-up area can significantly affect the prevailing thermal conditions in the city during summer.

**Table 10** SUHII statistics over different land cover classes for December 2022

| LULC class   | SUHII minimum (°C) | SUHII maximum (°C) | Mean SUHII (°C) |
|--------------|--------------------|--------------------|-----------------|
| Water bodies | −4.98              | 3.17               | −1.49           |
| Barren land  | −4.18              | 8.93               | 1.37            |
| Agriculture  | −4.54              | 7.33               | 1.33            |
| Vegetation   | −5.06              | 6.34               | 0.51            |
| Built-up     | −3.88              | 5.45               | 0.29            |



**Fig. 8** LST-NDVI relationship over Srinagar for **a** June 1993, **b** December 1993, **c** June 2022 and **d** December 2022

## Discussions

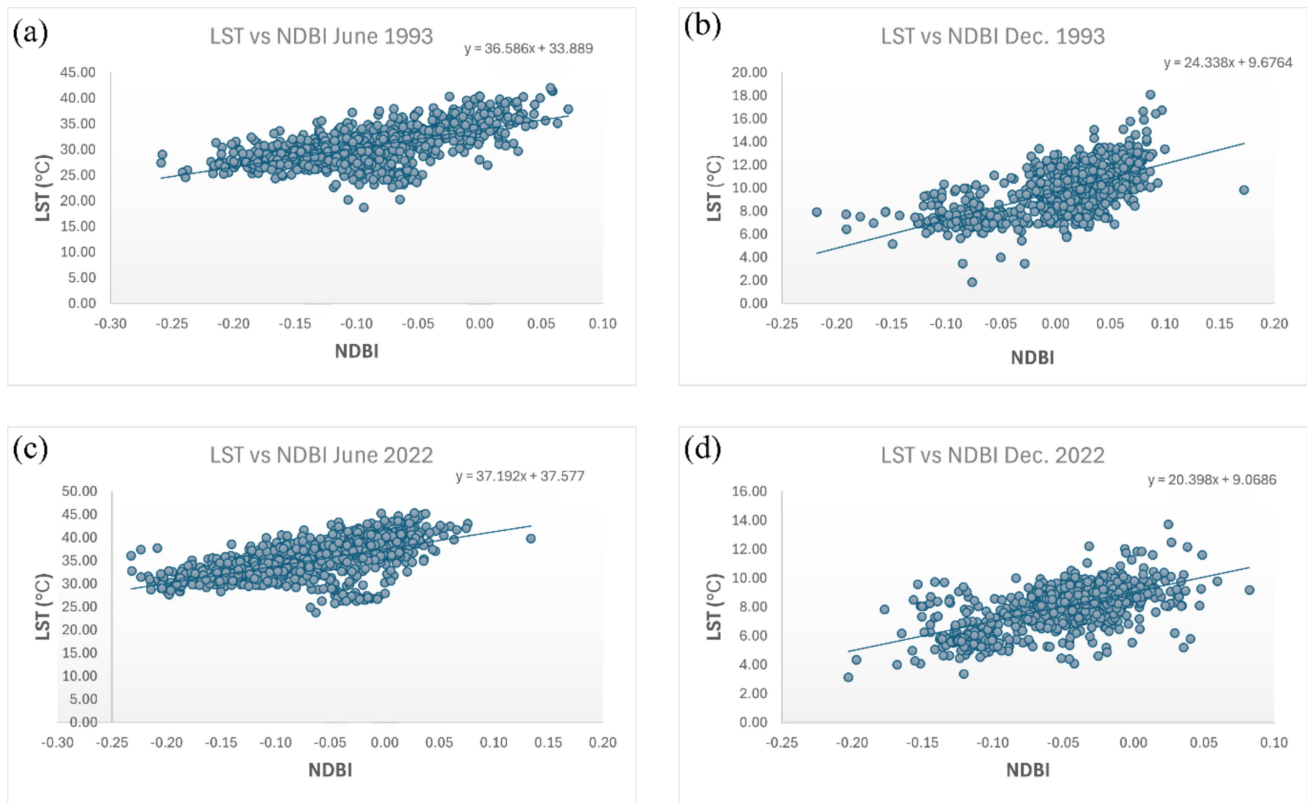
The study finds that there has been a significant change in the LULC pattern of Srinagar city, where two classes viz. agriculture and waterbodies have seen a decrease in area while built-up, barren land and vegetation have increased over the past 30 years. The city has witnessed massive urbanisation where built-up area (20.47%) and barren land area (4.98%) had increased mostly at expense of agricultural lands. The increase in built-up and barren land in a city is a characteristic feature of emerging or developing cities to accommodate large population which migrate from rural areas to city centres which often results in urban sprawl (Rahman et al. 2011). Several LULC and UHI studies have also reported increase in built-up areas during multi-temporal analysis (Guha and Govil 2020; Kikon et al. 2016; Pramanik and Punia 2020; Shahfahad et al. 2022). The increase in built-up land mainly at the cost of agriculture have been reported in various cities in India where the major driver of this LULC change has been majorly linked to economic development and expansion of real estate activities (Fayaz et al. 2020; Kikon et al. 2016; Rahman et al. 2011; Shahfahad et al. 2022). Sand filling around the Dal Lake and Jhelum River to facilitate the growth of built-up areas and increase in floating vegetable garden may be the cause of the

decreased area of waterbodies which was also noted by Fazal and Amin (2011). Differences were noted in the built-up area reported in this study and previous studies. Though the individual studies have done independent accuracy assessment, various factors such as the definition of each land cover class followed, training datasets, algorithm used, manual operator error and differences in the reference data itself (Stehman and Foody 2019) would have resulted in these differences. Further, the use of individual pixels in accuracy assessment of land cover maps can introduce uncertainty in the results (Gu and Congalton 2020).

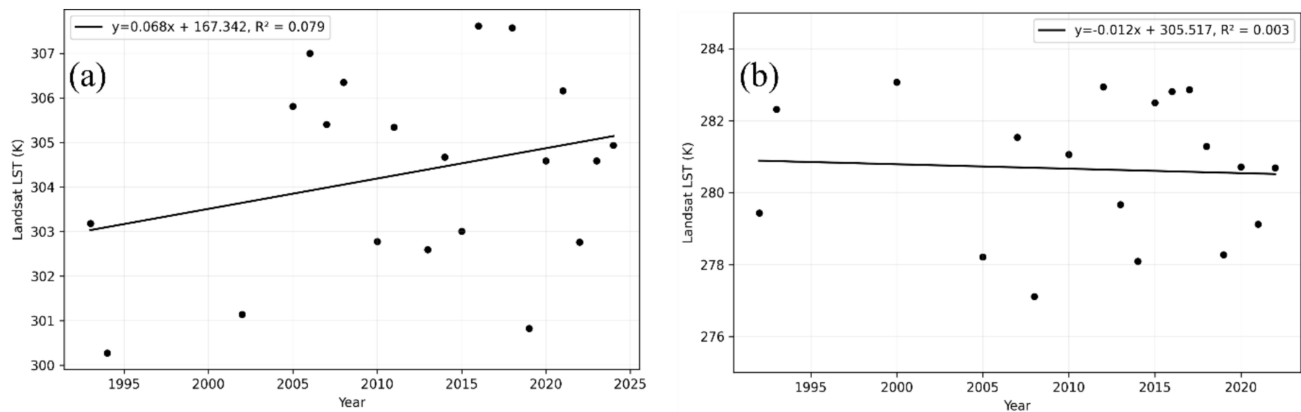
Although temperatures have been increasing all over the world the increase is clearly felt more in the urban centres. Many cities in developing countries are witnessing increase in local warming induced by urbanization (Wang and Yan 2016). In India, studies reveal that various cities are witnessing an increase in LST (Sahana et al. 2019; Sharma et al. 2014; Sussman et al. 2019). Similar trend was also witnessed in our study where all LULC classes saw an increase in LST in the summer season with maximum increase in built-up class. The negative SUHII over waterbodies in both years i.e.,  $-0.8^{\circ}\text{C}$  in 1993 and  $-0.15^{\circ}\text{C}$  in 2022 indicate the cooling effect of waterbodies as they act as sinks of UHI (Huang et al. 2017). This becomes critical in summer where vegetation and water can counter the increasing LST and SUHII







**Fig. 9** LST-NDBI relationship over Srinagar for **a** June 1993, **b** December 1993, **c** June 2022 and **d** December 2022



**Fig. 10** Trend of mean LST over Srinagar city in **a** June and **b** December

effects. However, it is also true where the cooling impact of the green spaces and waterbodies may get reduced due to the increased presence of built-up land and barren land surrounding them (Pramanik and Punia 2020).

During winter, the SUHII had decreased over built-up areas and in 2022 with temperature limited conditions, SUHII over built-up was less than SUHII over vegetated areas. The decrease in daytime SUHII during winter over cities in colder climates has also been found by Yang et al.

(2020) and the study has also highlighted the uncertainty in SUHII due to the reference pixels selected for the calculation purposes. In this study, LST over vegetated areas have been used as reference for SUHII estimation in previous studies (Roy et al. 2024; Budhiraja et al. 2020; Bechtel et al. 2019, Geletic et al. 2019). Further, Bechtel et al. (2019) mentioned that using properly identified vegetated pixels based on local climate zone concept as reference temperature in SUHII estimation can help reduce uncertainties in reference LST using

traditional methods such as LST of rural areas or mean LST estimated over buffer area outside the city. However, under temperature or energy limited conditions indicated by the positive LST-NDVI slope (Karnieli et al. 2010), the use of vegetated pixels as reference will make the built-up areas to appear cooler. This must be considered when multi-temporal and multi-seasonal SUHII analysis are carried out over cities with colder climates.

Various studies carried on the effect of changing LULC on LST suggest that changes in LST may result from the change in LULC categories from those that already exist (Fatemi and Narangifard 2019; Kikon et al. 2016; Pal and Ziaul 2017; Tran et al. 2017). In summers, rapid urbanisation can result in a reduction in vegetation cover, which can lower evapotranspiration and strengthen the SUHII (Wang et al. 2016). Secondly, with urbanisation there are more impermeable surfaces (roads and buildings), which can trap heat from the sun during the day. This coupled with the increased aerodynamic resistance (Li et al. 2019a) leads to increased LST over urban areas. Thirdly, the sensible heat flux from increasing anthropogenic heat release can also indirectly increase the LST (Zhou et al. 2014). On the other hand, significant impact of green space and waterbodies on reducing increasing temperature is well established, which also reflected in this study. Further, in winter season too, the presence of urban areas can help maintain warmer temperatures (Chun and Guldmann 2018). Keeping all these things in view, the present study suggests that the planning authorities in Srinagar City should come up with more sustainable way of urban development as the city is being developed under the Smart City Mission which was launched by Ministry of Housing and Urban Affairs (MoHUA).

## Conclusions

The study focuses on the impact of changing LULC on LST and SUHI intensity for Srinagar city, Jammu and Kashmir, India between 1993 and 2022 using Landsat 5 and Landsat 8 images in both summer and winter. The study had found that Srinagar city has witnessed massive urbanisation during the last three decades mainly at the expense of agricultural land indicating urbanisation. SUHII intensity also increased in summer except over barren land ( $-2.38^{\circ}\text{C}$ ) with maximum increase witnessed over built-up areas ( $2.08^{\circ}\text{C}$ ) and minimum over vegetation ( $0.31^{\circ}\text{C}$ ) and waterbodies ( $0.66^{\circ}\text{C}$ ). The results clearly show that between 1993 and 2022 there was a clear increase of urbanisation activities in the city with an increase in LST and SUHII. The SUHII effect over built areas reduced in winter and during persistent cold conditions, built areas become cooler than the vegetated surfaces. The study's findings demonstrate that the decision-makers and stakeholders in the region need to be aware of the rapid

growth and changes in the land use pattern and its impact on LST and SUHII in Srinagar. This study recommend that policymakers should ensure that the greenness of the city is maintained through the regulation of sustainable urban development with an aim to minimise the effect of Urban Heat Island as well as to maintain warm temperatures during winter season. Various studies (Li et al. 2019b; Rizvi et al. 2020; Siddiqui et al. 2021; Zhou et al. 2015) have shown that in some cities night time UHI is more prominent than daytime UHI. This makes it necessary to have a more comprehensive study on UHI which needs to incorporate day time as well as night time LST data. This might become possible with the planned TIR missions such as TRISHNA and LSTM. Moreover, the UHI footprint analysis needs also to be included in those studies to determine the footprint extent over and beyond the city. Furthermore, hotspot identification studies within the footprint can also be done to single out areas where the impact of UHI intensity is more and necessary measures can be incorporated to reduce the impact and improve the thermal comfort.

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**Data availability** This is not applicable as all the analysis have been carried out using publicly available satellite data.

## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interest to disclose.

**Ethical approval** Our paper does not have negative societal impacts.

**Informed consent** All authors agreed with the content and submission.

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