

Research

Spatiotemporal analysis of urban expansion in Srinagar city, Kashmir

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Abstract

Urbanization is a multifaceted process and a global phenomenon that encompasses various environmental and land cover changes. The expansion of Srinagar city, Kashmir, has changed its Land Use and Land Cover (LULC) due to an increase in population, horizontal expansion of the city, migration, and an increase in the built-up area. This has resulted in a change in Land Surface Temperature (LST). This study evaluates the dynamics of LULC in Srinagar city and its effect on LST using remote sensing, geographic information systems (GIS), statistical analysis techniques, and Landsat 4–5 TM and Landsat-8 OLI datasets. We analysed the LULC in Srinagar city from 2000 to 2020. The study calculated the Normalized Difference Vegetation Index (NDVI), LST, Fractional Vegetation Cover (FVC), and Emissivity from satellite remote sensing data of Srinagar city and analysed the relationship between them. The study shows that in terms of percentage change in LULC in Srinagar city from the year 2000 to 2020, built-up area showed the maximum change (75.58), followed by dense forest (– 62.74), vegetation (– 40.2), water bodies (– 25.41%), crop (23.16%), swamp (– 8.22), sparse forest (– 7.89), and open spaces (– 6.02). The findings of this study hold significance for researchers, urban planners, and policymakers to understand urbanization trends and their implications in the city.

Keywords Urbanization · LULC · Change detection · LST · Srinagar

1 Introduction

Urbanization is a socio-cultural phenomenon driven by complex social, economic, and political factors, as well as the geographical features of a region, and is an important demographic and spatial trend around the world [1, 2]. This has led to the loss of agricultural and forest lands, the emergence of barren areas, an increase in impermeable surfaces, a reduction in green cover, and the expansion of built-up areas, contributing to the Land Use and Land Cover (LULC) changes and rise in Land Surface Temperature (LST) [3–5]. Urban sprawl and the loss of natural habitats have a substantial effect on the regional thermal environment and affect the global surface thermal energy balance [6]. Globalisation, modernization, and the move from agrarian cultures to industrial societies have contributed to contemporary urbanization [7]. This is especially important in developing countries that have experienced a substantial increase in urban sprawl, population density, social inequalities, health exposures to pollution, and a decrease in natural vegetation cover [8, 9].

LST increases due to physical changes, which primarily include a decrease in green cover and an increase in built-up area [5]. Recognising the importance of monitoring LST, the International Geosphere and Biosphere Program has designated it as a high-priority parameter [10]. LULC has a significant impact on LST, which is exacerbated by the

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rapid growth of urban populations [11, 12]. Hence, understanding the relationship between LULC and LST is crucial for understanding and addressing the consequences of rapid urbanization [13].

Satellite-based remote sensing data is a valuable tool and is widely used to assess LULC changes [14]. This data efficiently extracts information about vegetation cover changes [15]. By utilising remote sensing data with various resolutions and descriptive models, researchers can analyse past, current, and potential future land cover patterns [2, 16]. This allows for the mapping of urban areas, modelling urban growth, and monitoring dynamic changes in land cover [17, 18]. Demographic and economic factors accelerate land use changes, impacting natural resources, making monitoring of LULC changes essential for resource management, assessing climate change impacts, and developing effective adaptation policies [19–21]. Remote sensing data play a crucial role in accurate LULC mapping, especially for ecosystem services, natural resource management, and environmental assessment [22].

Recent research has emphasised the substantial influence of urban expansion on LULC and LST in Srinagar city, with the rapid growth of the city leading to a decline in agricultural and vegetation area, and an increase in built-up areas, particularly in the central and southern parts of the city [23–25]. This expansion has resulted in a significant increase in land surface temperature [23] and flood risk [26]. The city's expansion has exhibited a scattered and irregular pattern, giving rise to concerns over sustainable development [24]. The use of geospatial methods and remote sensing has played a crucial role in evaluating these changes, offering valuable data for urban planning [27].

Srinagar city is the largest urban centre among all the Himalayan urban centres [28]. The spatial expansion of Srinagar, as is evident from the satellite imageries of the last century, is a testimony to the fact that wetlands and flood absorption basins have become soft targets for urbanization. Though Srinagar has a central location in the settlement pattern of the Valley, the city faces many obstacles to its expansion [29]. The urbanization process has significantly modified LULC of Srinagar city and its surrounding areas [30]. One of the prominent patterns of LULC change in the Kashmir valley is the increasing conversion of agricultural fields into urban areas [31].

A few studies have documented the LULC changes in Srinagar city by discussing land use dynamics in the rural–urban fringe, the linkage between LULC and LST, land cover change detection, LULC and its impact on water quality, and urban forest cover dynamics [31–34]. However, most of these studies are either old or mostly focus on the relationship between LULC and LST, while our study discusses the recent LULC dynamics and their relationship with NDVI, LST, FVC, and emissivity.

In this study, we assess and monitor several key aspects of urbanization in Srinagar city from 2000 to 2020 by using remote sensing. Firstly, we examine changes in different classes of LULC patterns. Secondly, we examine LST, Normalized Difference Vegetation Index (NDVI), Fractional Vegetation Cover (FVC), and Emissivity. Lastly, we analyse how urbanization has transformed the landscape over this period. By addressing these objectives, our aim is to gain a comprehensive understanding of the impact of urbanization on different land use classes in Srinagar and its influence on LST. These insights are important for developing strategies to promote sustainable urban development and mitigate the adverse effects of unplanned urban expansion in the region. However, the limitation of this study lies in not discussing the LULC changes in the city over the last three years due to the unavailability of reliable high-resolution datasets.

2 Database and methodology

2.1 Study area

The research was conducted in Srinagar city (Fig. 1), located in the centre region of Kashmir Valley, situated between the Pir-Panjal and Zaskar ranges of the Middle Himalayas. Srinagar is located at 33°05'14"N and 34°12'37"N latitude, and 74°04'06"E and 74°05'27"E longitude. It is situated on both sides of the Jhelum River, also known as Vyeth in Kashmir, and has a general relief of 1580 m above mean sea level [35]. Srinagar is the summer capital of Jammu and Kashmir. It is a primate city and an important socioeconomic and political centre in Kashmir. The city is the focal point of urban interaction, is expanding in both size and population, and is one of the most populous cities in the Himalayas [23]. Srinagar's population has grown at a rapid pace, from 0.1 million in 1901 to 1.2 million in 2011 [36] and is projected to be 1.7 million in 2024 [37]. The availability of educational and economic opportunities in the city makes it a major attraction [38].

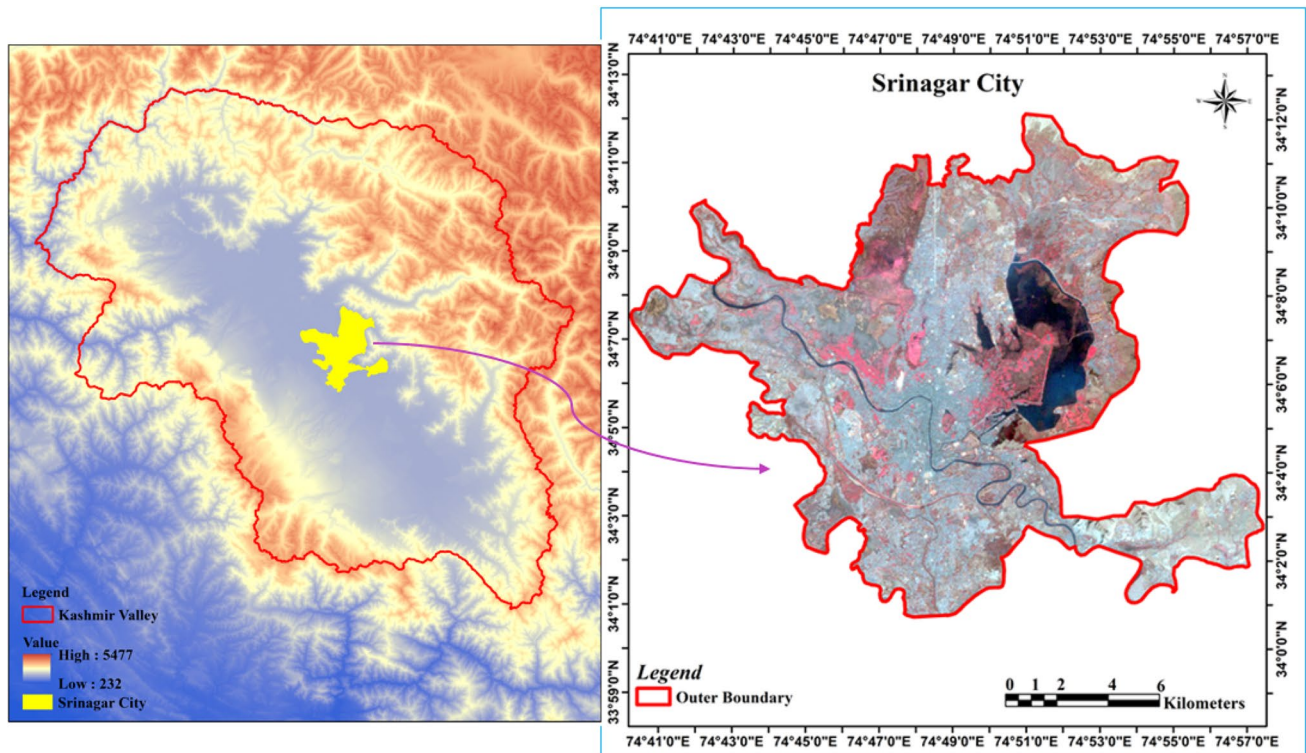


Fig. 1 Srinagar City (Study Area)

2.2 Dataset and methodological flowchart

To achieve the study's objectives, multi-temporal cloud-free datasets Landsat 4–5 TM and Landsat-8 OLI obtained from the US Geological Survey (USGS) (<http://earthexplorer.usgs.gov>) for the years 2000–2020 were used to create LULC and LST distribution maps (Fig. 2). The spatial resolution of all datasets is 30 m. All datasets were projected to the Universal Transverse Mercator 43-N projection using the WGS-84 datum. To avoid seasonal fluctuations in the study area, all images were downloaded for the same season with the shortest possible time gap. For image processing, classification, and change detection, Erdas Imagine 14 software was used. Arc GIS software 10.5 was used for the LST distribution of the study area.

2.3 Preparation of LULC maps and accuracy assessment

LULC maps were classified into eight classes: water bodies, crops, vegetation, dense forest, sparse forest, open, built-up, and swamp. A supervised maximum likelihood technique was adopted for the classification of raster images in Erdas 14 software. Training data (Signatures) were developed from the ground survey point and Google Earth Pro. The classification accuracy was assessed based on the areal and spectral characteristics. The type was derived using the Kappa index and confusion matrix. Approximately 200 training samples were selected randomly from the LULC map for the accuracy assessment.

2.4 Calculation of NDVI

NDVI is the vegetation health of how the plant responds to the electromagnetic spectrum, and measures the difference between near-infrared light, which is strongly reflected by the vegetation, and red light, which is strongly absorbed by the vegetation. NDVI ranges from -1 to $+1$, where the value close to zero indicates the built-up area,

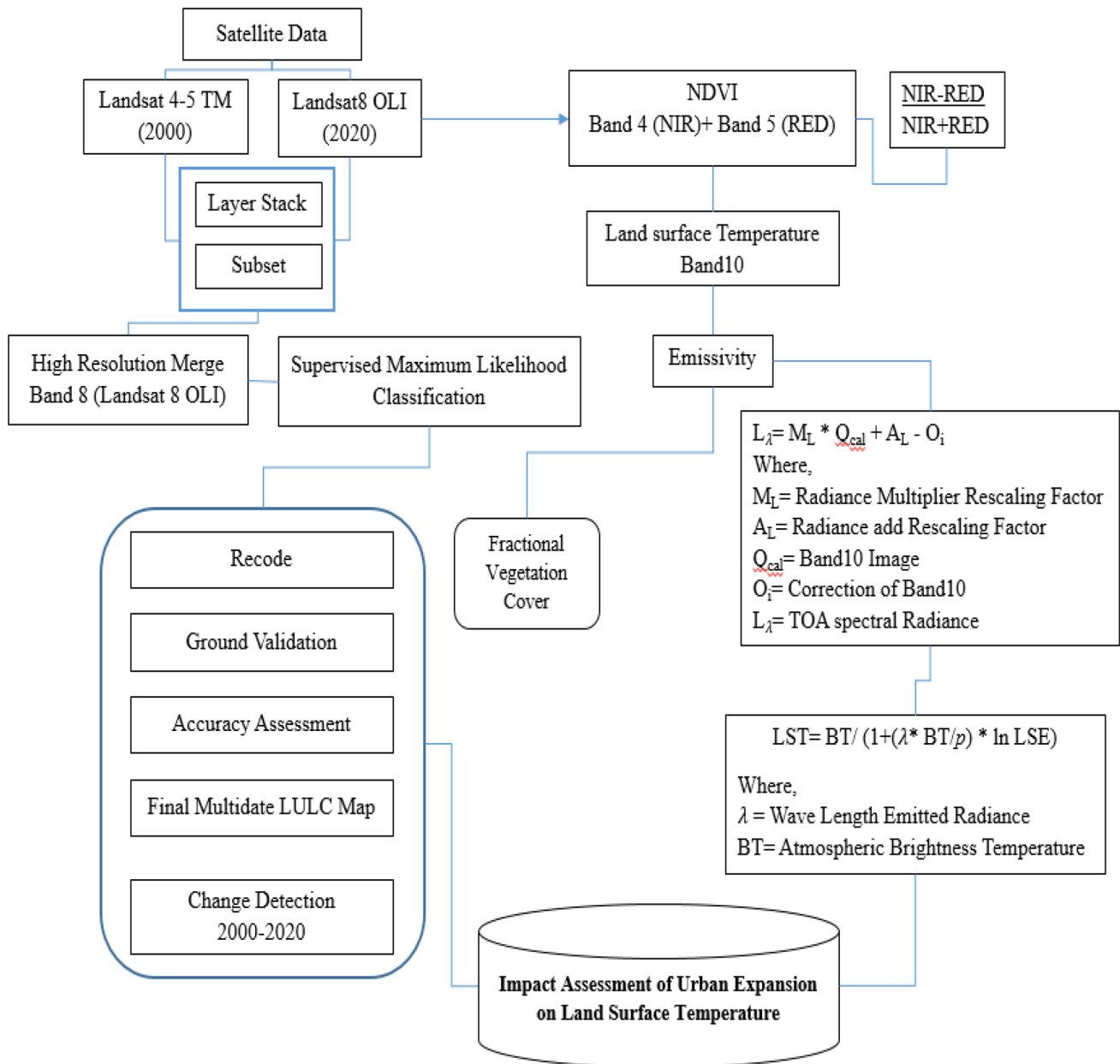


Fig. 2 Methodological flowchart

whereas the value near + 1 indicates the green and healthy vegetative cover. The NDVI utilises the near-infrared and red bands of the electromagnetic spectrum; the formula for the NDVI is given below.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

2.5 LST retrieval for the years 2000 and 2020

The first step involved in the calculation of LST is the conversion of digital numbers (DNs) into radiance using the Eq. (1) below:

$$L\lambda = L_{min} + (L_{max} - L_{min}) * DN/255 \quad (1)$$

where,

$L\lambda$ = spectral radiance.

The value of L_{min} and L_{max} are different for different Landsat sensor.

For Landsat 5 $L_{min} = 1.238$ and $L_{max} = 15.30$ and for Landsat 8 the $L_{min} = 0.10033$ and $L_{max} = 22.00180$ for both band 10 and band 11.

In the second step, the radiance is converted into brightness temperature (TB) in Kelvin using Eq. (2);

$$TB = K2(\ln(K1/L\lambda) + 1) \quad (2)$$

where $K1$ = calibration constant 1, and $K2$ = calibration constant 2.

For Landsat 5 $K1 = 607.96$ and $K2 = 1260.56$ and for Landsat 8 band 10 $K1 = 774.89$ and $K2 = 1321.08$ and for Landsat 8 band 11 $K1 = 480.88$ and $K2 = 1201.14$.

The third step is the conversion of brightness temp from Kelvin to Celsius using Eq. (3);

$$TB(^{\circ}C) = TB(\text{in Kelvin}) - 273.15 \quad (3)$$

The final step involves converting the brightness temperature at the sensor to LST by using the Eq. (4).

$$LST = TB / [1 + (\lambda * TB/\rho) * \ln(\epsilon)] \quad (4)$$

where: λ = wavelength of emitted radiance, the peak response and the average of the limiting wavelengths ($\lambda = 11.5 \mu\text{m}$);
 $\rho = h * c / \sigma$.

($1.438 \times 10^2 \text{ mK}$).

h = Planck's constant ($6.626 * 10^{-34} \text{ J s}$).

σ = Boltzmann constant ($1.380649 * 10^{-23} \text{ J/K}$).

c = velocity of light ($2.998 * 10^8 \text{ m/s}$).

ϵ = Surface emissivity.

Surface emissivity was calculated from PV (Proportion of vegetation) derived from NDVI of the respective years of 2000 and 2020. The PV is derived by the following formulae proposed by Sobrino et al. [34]:

$$PV = (NDVI - NDVI_{min} / NDVI_{max} - NDVI_{min})^2 \quad (5)$$

Finally, the surface emissivity was calculated by using Eq. (6) [39]

$$\text{Surface emissivity, } \epsilon = 0.004 PV + 0.986 \quad (6)$$

LST from Landsat 8 was derived from bands 10 and 11 and then averaged using cell statistics to calculate the average per cell.

2.6 LST retrieval from Landsat-8 OLI

Radiance additive scaling factor in case of Landsat-8 OLI was used to calculate TOA (top of the atmosphere) spectral radiance for the bands of the satellite data using Meta data file using the following equation (Zanter, 2016):

$$L\lambda = ML * Q_{cal} + AL - O_i \quad (7)$$

where,

ML = Radiance Multiplier Rescaling Factor

AL = Radiance add Rescaling Factor

Q_{cal} = Band10 Image

O_i = Correction of Band10

Thermal band was then converted to effective at sensor brightness temperature from TOA with uniform emissivity and includes effects of atmosphere using the following equation:

$$"BT = K2/\ln(K1/L\lambda+1)-273.15"$$

where, K_1 = Calibration constant 1 (774.8853); K_2 = Calibration constant 2 (1321.0789).

The dark maroon colour on the map depicts the highest temperatures, and the light-yellow colour depicts the lowest temperatures in the study area. Such a pattern of LST highlights the rapid LULC changes, particularly in urbanised areas reinforced by congestion and concretization. The range of the LST varies from a maximum of 26.13 °C to a minimum of 10.6 °C. The urban core area of Srinagar city is much more sensitive to high concentrations of LST, thereby increasing the impact of the urban heat island phenomenon. The areas of the city where the settlement is dense exhibit higher vegetation, and those parts of the city area dominated by water bodies and vegetation show a low range of temperature.

3 Results and discussion

3.1 LULC change of Srinagar city (2000—2020)

LULC of Srinagar city has changed drastically between 2000 and 2020 because of rapid urbanization, population growth, migration from rural areas, development activities, tourism activities, and changes in agricultural patterns. Urbanization has changed the dynamics of LULC in Srinagar city, as depicted in Tables 1, 2, 3, and 4 and Figs. 3, 4, and 5. The LULC changes are detected in water bodies, crops, vegetation, dense forest, sparse forest, open area, built up area, and swamp classes.

Overall Classification Accuracy = 85.00% (2000) & 88.50% (2020).

Kappa (K^{\wedge}) Statistics.

Overall Kappa Statistics = 0.8286 (2000) & 0.8686 (2020).

This study shows that the extent of water bodies in Srinagar city was 19.36 km² in 2000, which has been reduced to 14.44 km² in 2020 (Table 4 and Figure 5). The percentage of area of water bodies was 7.48% in 2000, which has reduced to 5.58% in 2020, thus showing a decline of 25.41%, i.e., a change of -25.41%. The area of Dal Lake has reduced in the southern part of the lake at Boulevard Road, while the area of Nigeen Lake has reduced in the northern and north-eastern parts of the lake due to waste dumping, encroachment on the banks of these lakes, and tourism activities. The wastage from households, infrastructure, and industries in Srinagar city goes into these lakes, which has resulted in large-scale siltation and pollution of these lakes and rendered their water unfit for drinking [40]. The tourism activities along with developmental policies at Dal Lake and Nigeen Lake have resulted in the construction of several hotels and other infrastructure, which has resulted in the land cover change of these lakes [41].

Extent of crop area in Srinagar city was 20.68 km² in 2000, which has increased to 25.47 km² in 2020. The percentage of area of crops was 7.8% in 2000, which has increased to 9.85% in 2020, thus showing an increase of 23.16%, i.e., a change of 23.16%. The crop area has increased in the northern, north-eastern, and eastern parts of the city at Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Akhon Mohalla, Mazgam, Syedpora, and the Botanical Garden. The crop area has increased at Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K) due to experiments for diversification of agriculture and finding new varieties of crops and fruits like apples, rice, and vegetables. The crop area has increased mainly on the outskirts of Srinagar due to the presence of rural areas that grow crops like rice and vegetables.

Table 1 LULC statistics of Srinagar City, 2000

LULC classes	Area (Sq.km)
Water body	19.36
Crop	20.68
Vegetation	43.87
Dense forest	1.02
Sparse forest	0.76
Open	131.95
Built up	34.53
Swamp	6.93

Table 2 LULC statistics of Srinagar City, 2020

LULC classes	Area (Sq.km)
Water body	14.44
Crop	25.47
Vegetation	26.23
Dense forest	0.38
Sparse forest	0.7
Open	124.39
Built up	60.63
Swamp	6.36

The extent of vegetation in Srinagar city was 43.87 km² in 2000, which has been reduced to 26.23 km² in 2020. The percentage of area covered by vegetation was 16.96% in 2000, which has reduced to 10.14% in 2020, thus showing a decline of 40.2%, i.e., a change of -40.2%. The vegetation area has decreased mainly in the northern and eastern parts of Srinagar city, at places like Khaja Bagh Colony, Pahal, Mazgam, and Mughal Gardens, due to population increases and developmental activities. The vegetation cover has experienced one of the highest LULC changes from 2000 to 2020 in Srinagar city, and it has experienced a reduction in area throughout the city.

Dense forest area in Srinagar city was 1.02 km² in 2000, which has been reduced to 0.38 km² in 2020. The percentage of area covered by dense forest was 0.39% in 2000, which has reduced to 0.14% in 2020, thus showing a decline of 0.14%, i.e., a change of -0.14%. The dense forest area of Srinagar city has decreased due to deforestation and the conversion of forest areas into agricultural areas.

Table 3 Classification of Accuracy Assessment: Landsat 4–5 TM (2000) & Landsat 8-OLI (2020)

Class name	Accuracy Totals											
	Reference Total		Classified Total		Number Correct		Producers' Accuracy (%)		Users' Accuracy (%)		Kappa	
	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
Water Body	25	24	25	25	20	21	80.00	87.50	80.00	84.00	0.7714	0.8182
Crop	23	24	25	25	19	20	82.61	83.33	76.00	80.00	0.7288	0.7727
Vegetation	26	27	25	25	22	23	84.62	85.19	88.00	92.00	0.8621	0.9075
Dense Forest	26	26	25	25	22	23	84.62	88.46	88.00	92.00	0.8621	0.908
Sparse Forest	27	24	25	25	23	22	85.19	91.67	92.00	88.00	0.9075	0.8636
Open	24	26	25	25	21	23	84.00	88.46	84.00	92.00	0.8171	0.908
Built-up	24	25	25	25	22	23	91.67	92.00	88.00	92.00	0.8636	0.9086
Swamp	24	24	25	25	21	22	87.50	91.67	84.00	88.00	0.8182	0.8636
Totals	200	200	200	200	177	177						

Table 4 LULC change statistics from 2000–2020

LULC classes	Area in sq. km (2000)	Area in %age (2000)	Area in sq. km (2020)	Area in %age (2020)	Change in %age
Water body	19.36	7.48	14.44	5.58	- 25.41
Crop	20.68	7.8	25.47	9.85	23.16
Vegetation	43.87	16.96	26.23	10.14	- 40.2
Dense forest	1.02	0.39	0.38	0.14	- 62.74
Sparse forest	0.76	0.29	0.7	0.29	- 7.89
Open	131.95	51.04	124.39	48.1	- 6.02
Built up	34.53	13.35	60.63	23.44	75.58
Swamp	6.93	2.69	6.36	2.46	- 8.22

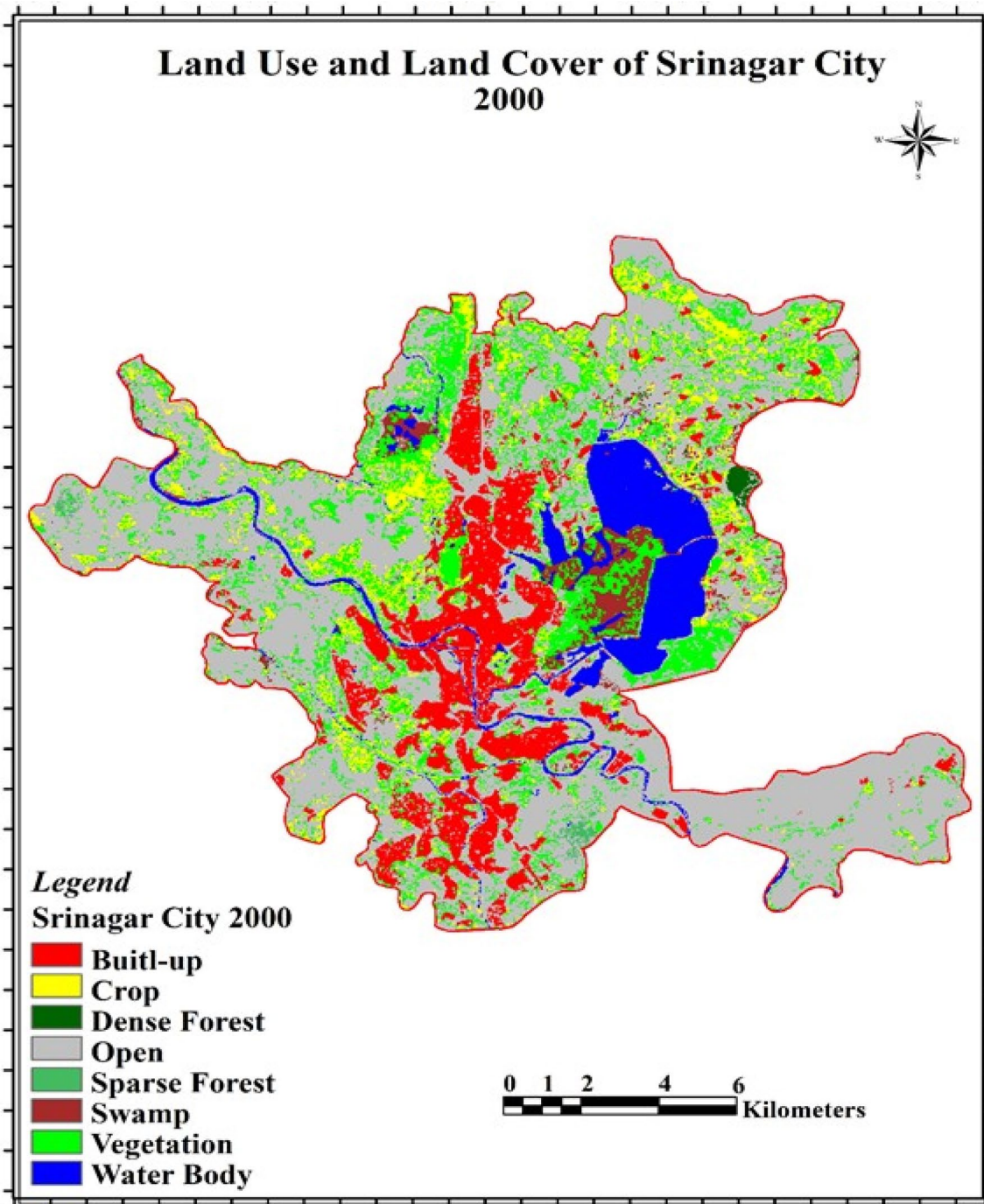


Fig. 3 LULC of Srinagar City, 2000

Sparse forest area in Srinagar city was 0.76 km² in 2000, which has reduced to 0.7 km² in 2020. The percentage of area covered by sparse forest was 0.29% in 2000, which has reduced to 10.14% in 2020. It shows a decline of 7.89%, i.e., a change of -7.89%. The sparse forest area has decreased due to intensive agricultural activities and the establishment of industries and factories.

The extent of open areas in Srinagar city was 131.95 km² in 2000, which has been reduced to 124.39 km² in 2020. The percentage of open areas was 51.04% in 2000, which has reduced to 48.1% in 2020, thus showing a decline of 6.02%, i.e., a change of - 6.02%. This study shows that open area has experienced a reduction in area due to the

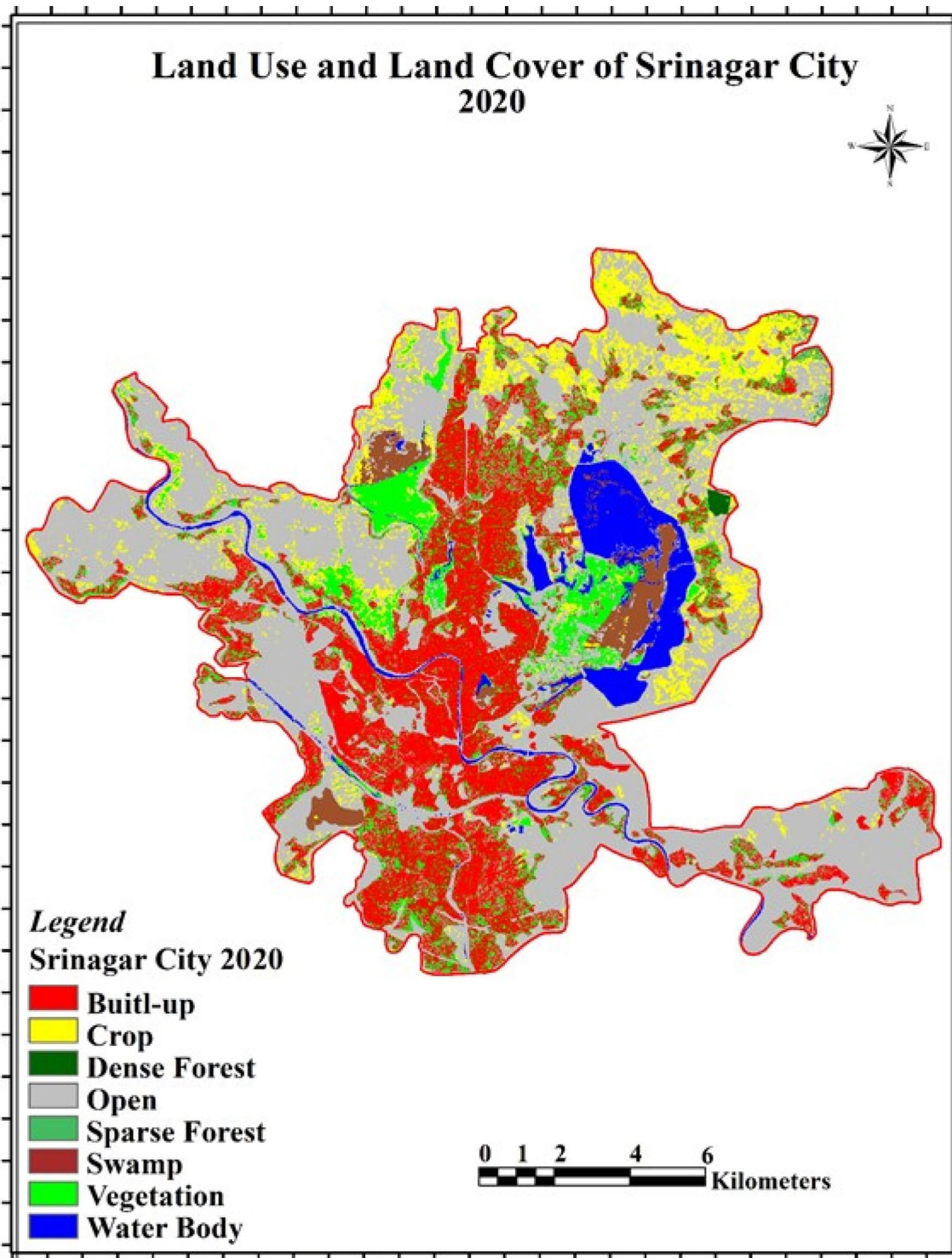


Fig. 4 LULC of Srinagar City, 2020

construction of hotels, buildings, and amusement parks at places like Lal Chowk, Batamaloo, and Boulevard Road, which has resulted in the shrinkage of the open spaces in the city.

Built-up area in Srinagar city was 34.53 km² in 2000, which has increased to 60.63 km² in 2020. The percentage of built-up area to the total area was 13.35% in 2000, which has increased to 23.44% in 2020, thus showing an increase of 75.58%, i.e., a change of 75.58%. The built-up area in Srinagar city has experienced the highest LULC change in the last

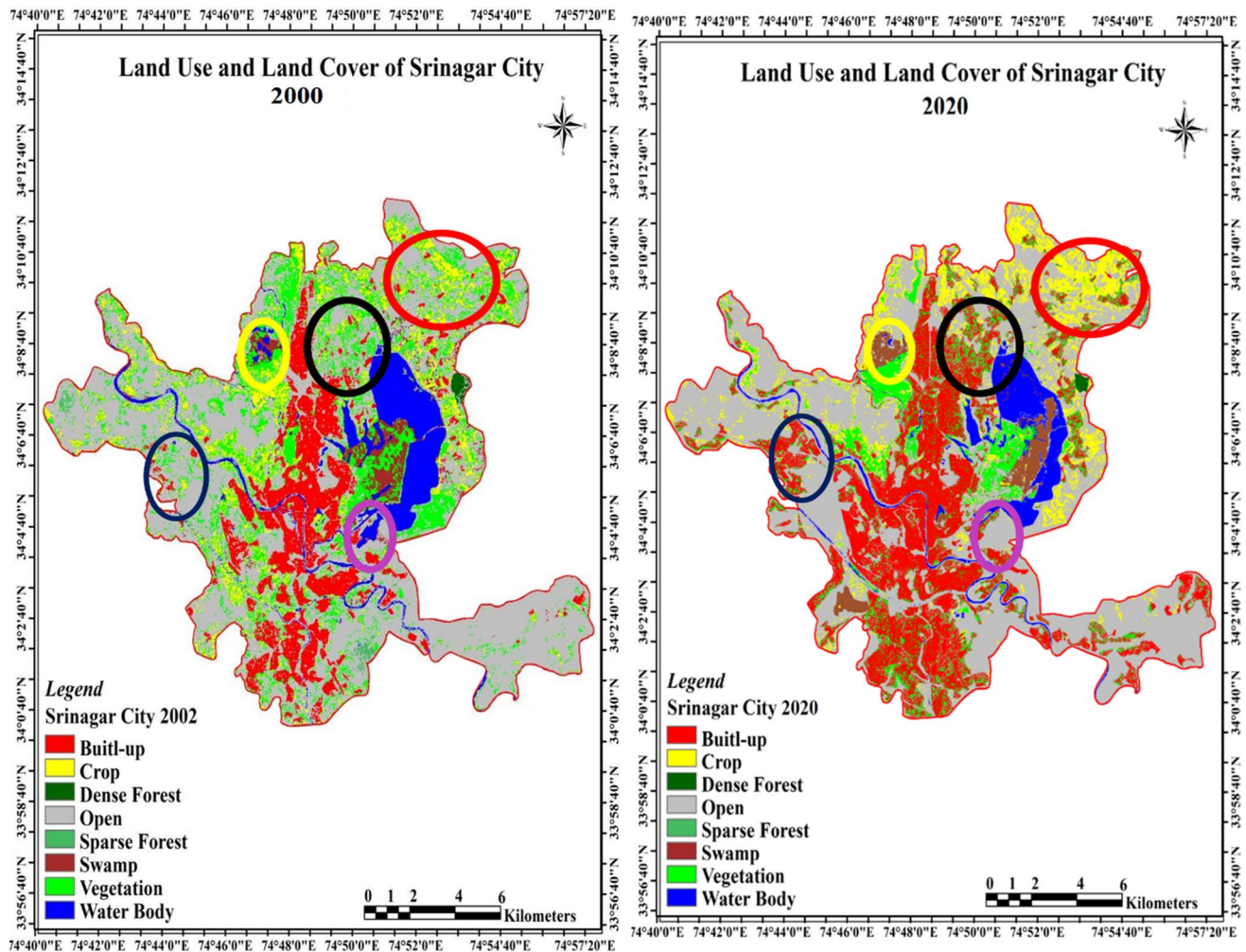


Fig. 5 LULC change in Srinagar City from 2000–2020

20 years due to the high rate of urbanization, population increase, migration, and tourism. The LULC changes have been experienced at the urban hotspots of Srinagar city like Lal Chowk, Natipora, Hyderpora, Rajbagh, Nowgam, Dangarpora, the Dargah area, Chhatabal, Batamalo, and Bemina. These places have experienced the highest level of urbanization in Srinagar city. People from rural areas of Kashmir migrate to Srinagar city for the purpose of jobs and other economic opportunities, which has increased the population of the city, which in turn has resulted in the construction of more houses and thus an increase in the built-up area. The neo-liberal developmental activities like the construction of hotels, artificial amusement parks, encroachment on the banks of the Jhelum River and wetlands, unplanned urbanization, faulty developmental activities, and establishment of industries in Srinagar have resulted in an increase in the built-up area of the city. In the last few years, the Srinagar metropolitan area has expanded to the outskirts of district Pulwama in Pampore, which includes areas like Zafran Colony, which has seen outmigration from Srinagar city as some people of the city are migrating to the Pulwama district due to the proximity of Pulwama with Srinagar city, a lack of space, and high land rates for the construction of houses in Srinagar city [32]. To attract more tourists, various hotels and restaurants have been built along the Jhelum River and Dal Lake banks [40] because of developmental policies [42], resulting in a considerable increase in built-up area [43].

The extent of swamps in Srinagar city was 6.93 km² in 2000, which has been reduced to 6.36 km² in 2020. The percentage of swamps was 2.69% in 2000, which has reduced to 2.46% in 2020, thus showing a decline of 8.22%, i.e., a change of – 8.22%. The swamp area has decreased due to encroachment and developmental activities.

Srinagar city has shown significant changes in LULC from 2000 to 2020. The highest change has been observed in built-up areas, followed by dense forest cover, vegetation, water bodies, crop areas, swamps, sparse forest areas, and open areas. LULC changes in Srinagar city have occurred due to an increase in the urban population, migration, unplanned

urbanization, tourism, and horizontal expansion of the city. The dynamics of the city have changed, particularly in the last two decades, resulting in an increase in the city's urban area and changes in LULC. The open area has been reduced due to infrastructural development, and the city is facing problems of congestion, increasing land rates, improper drainage systems, and water, noise, and air pollution [30].

4 Analysis of relationship between NDVI, LST, FVC, and emissivity of Srinagar city

The NDVI is the most widely and most popular tool for assessing the vegetation distribution and density in any part of the world [44]. The NDVI must be estimated because the amount of vegetation present is an important factor in estimating LST [45]. The NDVI map depicts vegetation cover as well as bare ground, with the highest NDVI value representing dense

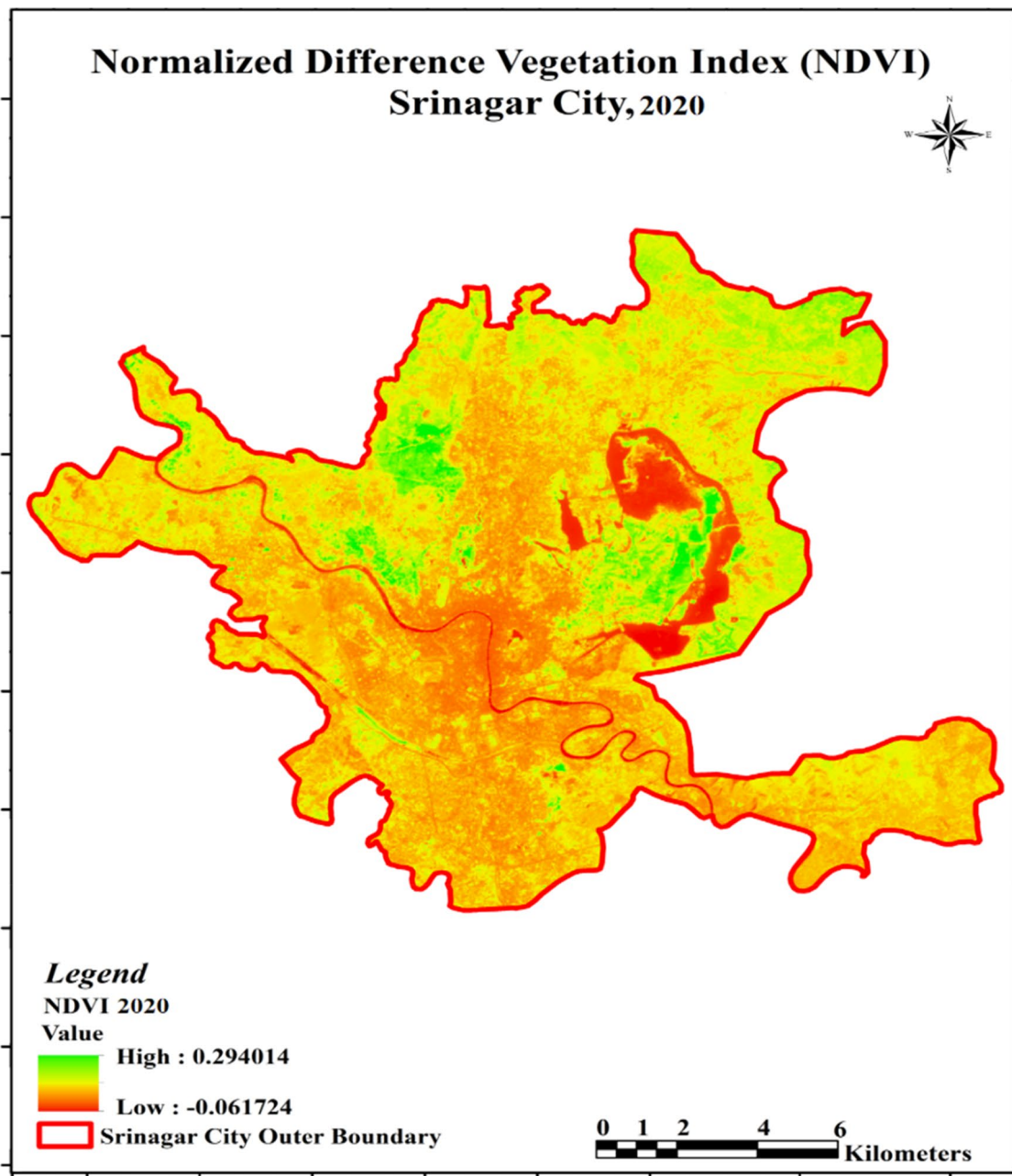


Fig. 6 NDVI of Srinagar City (2020)

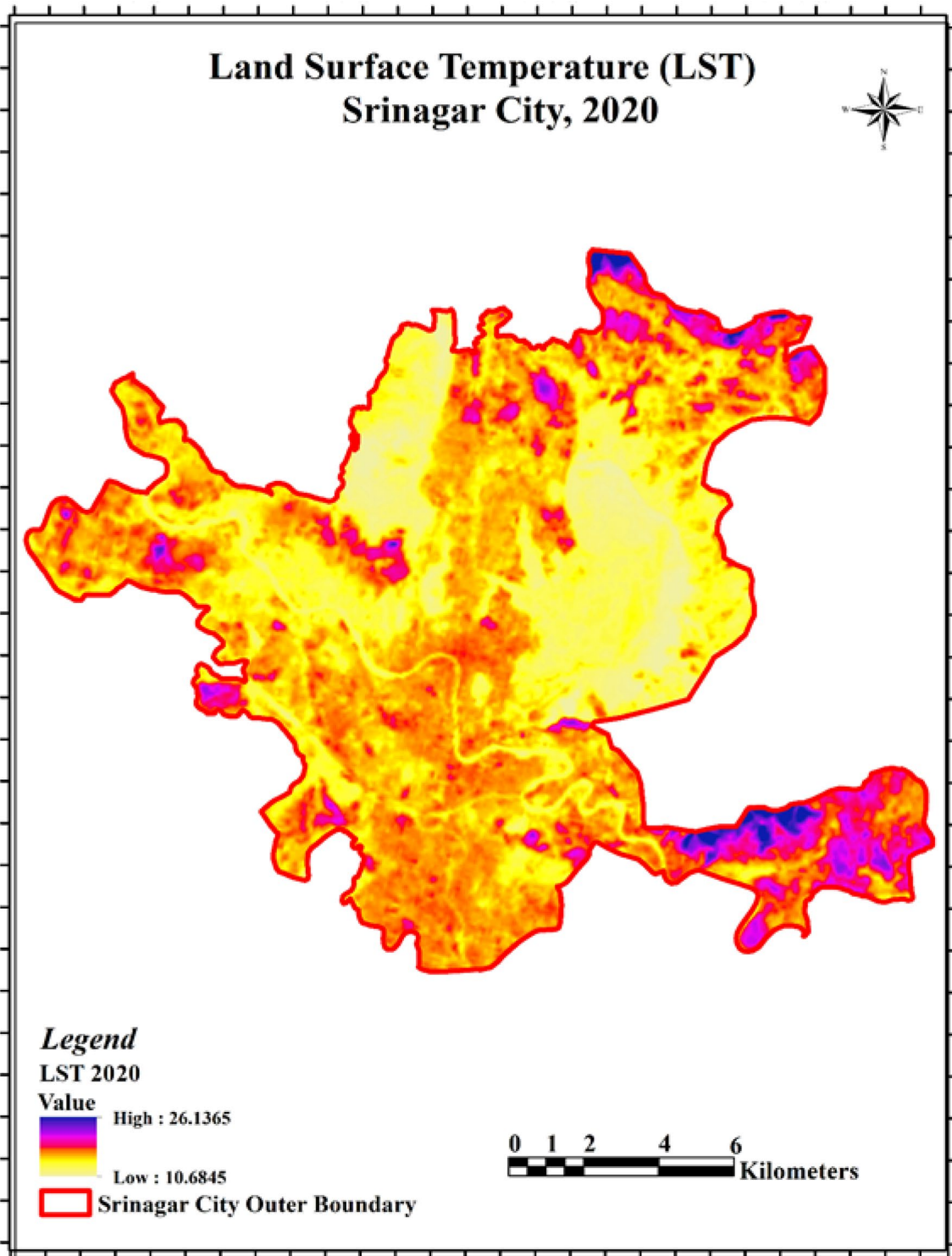


Fig. 7 LST of Srinagar City (2020)

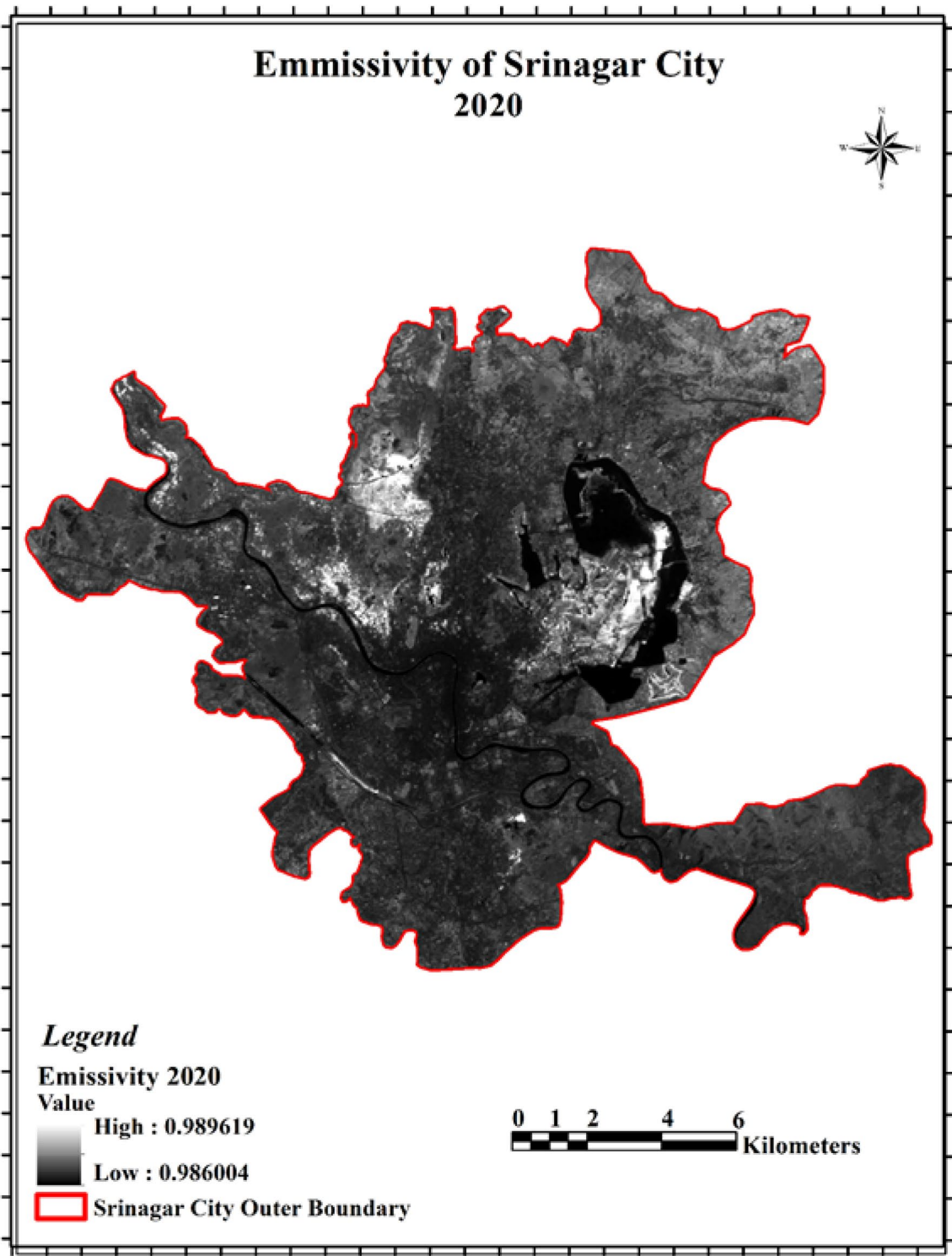


Fig. 8 Emissivity of Srinagar city (2020)

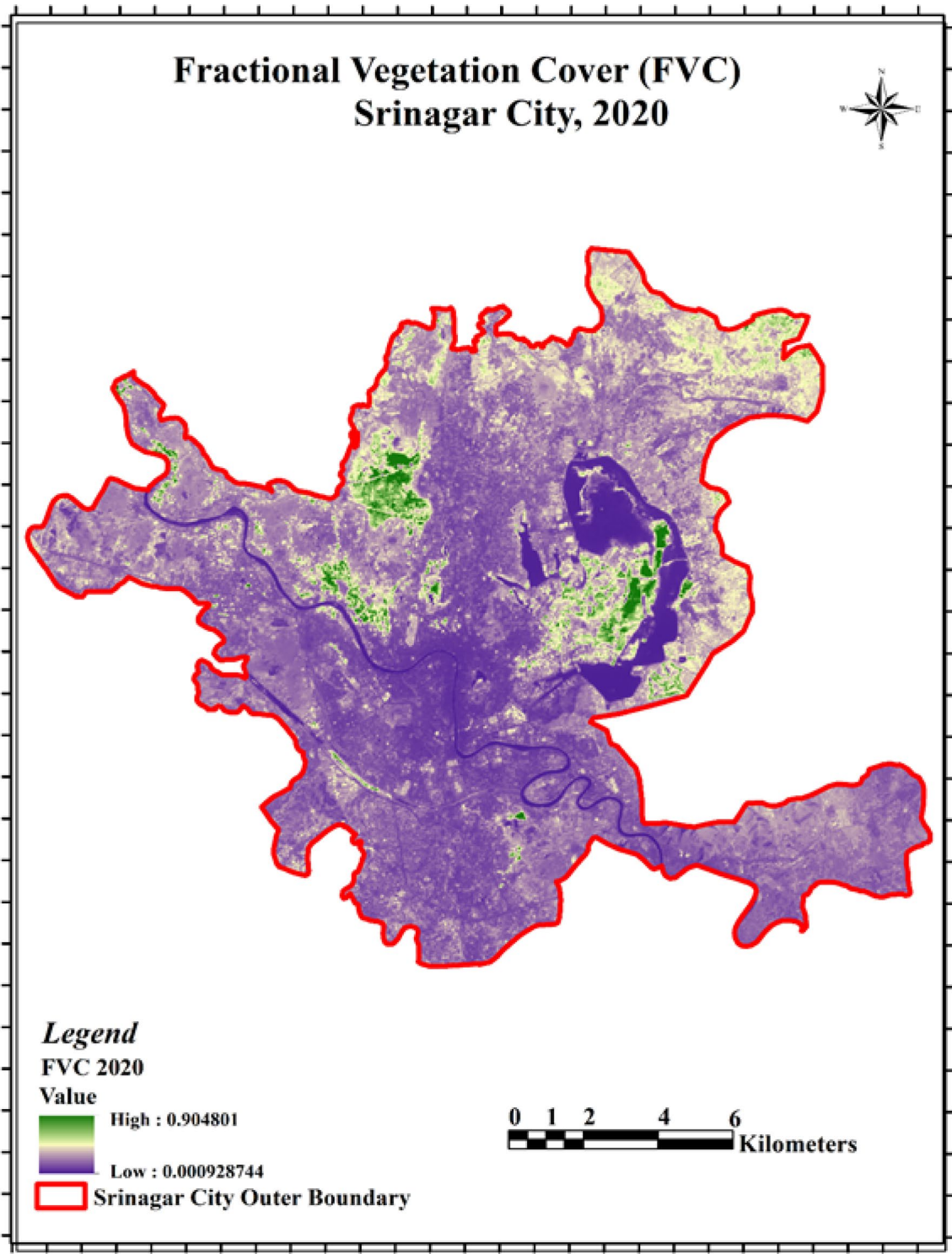


Fig. 9 FVC of Srinagar city (2020)

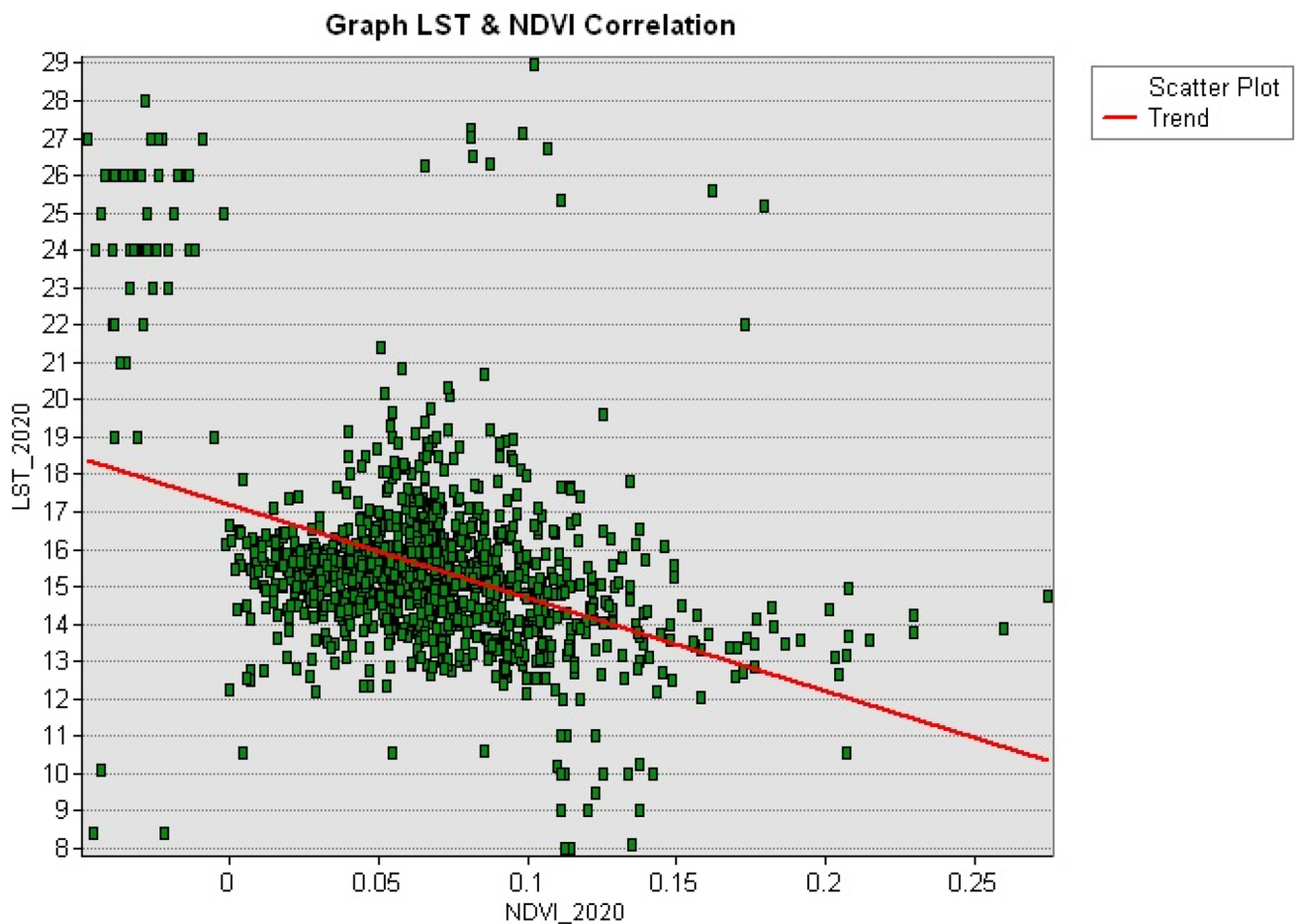


Fig. 10 Correlation scatter plot for LST and NDVI

vegetation and the lowest NDVI value representing exposed rock material. NDVI of Srinagar City in 2020 is depicted in Fig. 6 while as LST is depicted in Fig. 7, Emissivity in Fig. 8 and FVC in Fig. 9.

5 Relationship between NDVI, LULC, and LST in Srinagar city

This study shows that the vegetation cover has a low radiant temperature as the vegetation reduces the amount of heat stored in the soil and surface through transpiration. The land with sparse vegetation and crops and exposed bare soil reflected a significant temperature increase. Surface soil, water, and vegetation all contributed to the wide range of surface radiant temperatures observed in both vegetation cover and cultivated land. Thus, it can be stated that urban sprawl, degradation of crop land and vegetation, encroachment, and an increase in built-up area have all contributed to the observed urban heat island intensity over Srinagar.

5.1 Determination of relationship between LST and NDVI

The analysis of LST and NDVI in Srinagar city reveals an inverse correlation between NDVI values and LST values (Fig. 10). As NDVI values increase, indicating healthier vegetation and higher levels of greenery, the corresponding LST values tend to decrease. This relationship is indicative of the cooling effect of vegetation cover, where areas with more vegetation exhibit lower temperatures compared to areas with sparse or no vegetation.

According to Landsat calculations, the highest recorded LST values in Srinagar city reach a maximum of 26 degrees Celsius, with minimum values around 10 degrees Celsius. These temperature ranges reflect the thermal characteristics of different land cover types within the city, with urban areas typically exhibiting higher LST values due to the

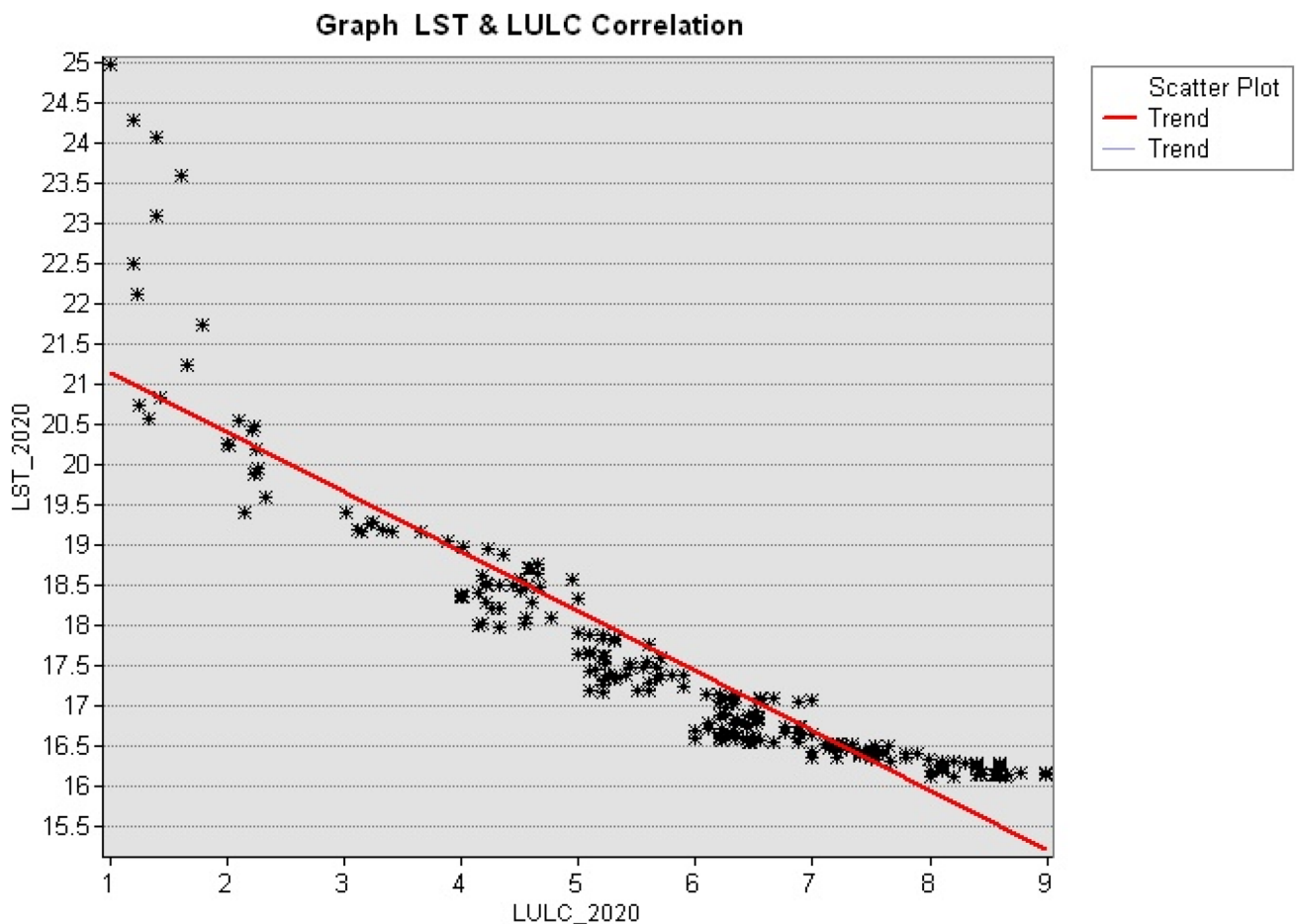


Fig. 11 Correlation scatter plot for LST and LULC

heat-absorbing nature of built-up surfaces like concrete and asphalt. Conversely, NDVI values in the study area range from a maximum of 0.29 to a minimum of -0.06. Higher NDVI values are associated with dense vegetation, such as parks, gardens, and forested areas, which contribute to lower LST values due to the cooling effect of vegetation transpiration and shading. In contrast, areas with lower or negative NDVI values often correspond to built-up or barren land, which absorbs more heat and experiences higher LST values.

The expanding nature of Srinagar city underscores the importance of monitoring and understanding these thermal and vegetation dynamics. Urban expansion can lead to changes in land use patterns, deforestation, and increased impervious surfaces, all of which can impact LST and NDVI values. Managing urban growth sustainably by preserving green spaces, promoting vegetation cover, and implementing heat mitigation strategies can help mitigate the urban heat island effect and enhance the overall thermal comfort and environmental quality of the city.

5.2 Determination of relationship between LST and LULC

The analysis of LULC changes and their impact on LST in Srinagar city reveals notable correlations between different land cover types and thermal characteristics (Fig. 11). The various LULC classes considered include built-up areas, open spaces, crops, vegetation, sparse forests, dense forests, swamps, and water bodies, each contributing uniquely to the urban heat environment.

Built-up areas, characterised by impervious surfaces like concrete and asphalt, exhibit the highest LST values among the LULC classes. These areas absorb and retain heat, resulting in elevated temperatures compared to other land cover types. Open spaces, such as parks and playgrounds, also contribute to increased LST due to limited vegetation cover and high solar radiation absorption. Crop areas, depending on vegetation density and agricultural practices, can have varying LST values. Areas with dense crops or irrigated fields may exhibit lower temperatures due to

transpiration and cooling effects, while dry or sparse croplands may contribute to higher LST values. Vegetated areas, including forests, gardens, and green spaces, play a crucial role in reducing LST through shading, evapotranspiration, and heat absorption. Dense forests, characterised by thick vegetation cover, contribute significantly to cooling the surrounding environment and maintaining lower LST values.

Sparse forests, with less dense vegetation cover, still provide some cooling benefits but may experience higher LST compared to dense forest areas. Swamps and water bodies, although contributing to local cooling through evaporative processes, can also experience higher LST under certain conditions, especially during periods of low water levels or high solar exposure. Understanding the dynamics of changing land use and its impact on LST is essential for sustainable urban planning and climate resilience. As Srinagar city expands and undergoes land use transformations, preserving green spaces, promoting vegetation cover, and incorporating heat mitigation strategies can help mitigate the urban heat island effect and enhance the thermal comfort and livability of the city. Additionally, monitoring LULC changes over time can provide valuable insights into environmental trends and inform effective land management practices for urban sustainability.

6 Conclusion

This study shows that Srinagar City faces urban expansion, which affects the land cover and the physical environment. The vegetation cover in the city is facing a great threat, which could lead to a lack of urban green spaces in the future. The implications of urban expansion in the city are manifold. Loss of agricultural land and natural habitats has significant consequences for both food security and the conservation of biodiversity. Urban expansion into ecologically vulnerable places could affect flood regulation and water purification. The rapid expansion of the built-up area could put pressure on essential services like transportation, waste management, and water supply. These concerns need to be addressed to ensure the sustainable development of Srinagar city. Several policy recommendations can be made to successfully manage urbanization and mitigate its negative effects. To ensure sustainable urban expansion, comprehensive land use planning and zoning restrictions are required. This should involve identifying and protecting ecologically sensitive regions, such as wetlands and water bodies, using buffer zones and conservation measures. Efforts should be made to promote compact and mixed land use development patterns in order to limit the conversion of agricultural land and prevent urban sprawl. To support evidence-based decision-making, urban growth trends must be continuously observed and assessed. In this sense, remote sensing and GIS technology can be helpful in obtaining precise and current data on changes in land use. Frequent monitoring can assist in pinpointing problem areas, evaluating the success of policies put into place, and directing future actions.

Author contributions W.S.A. and I.H.M. wrote the main manuscript. W.S.A and A.S. prepared the figures. S.J. edited and supervised the manuscript. All authors reviewed the manuscript.

Data availability Data is provided within the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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