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Seasonal Analysis of Linkage between Land Surface Temperature and Actual Evapotranspiration: A Case Study of Prayagraj, Uttar Pradesh, India

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ABSTRACT

Land Surface Temperature (LST) is significantly influenced by Land Use and Land Cover (LULC), impacting the energy exchange between the Earth's surface and atmosphere. This study aims to explore the relationship between Actual Evapotranspiration (AET) and LST across various land cover types, focusing on how these variables interact during different seasons. The analysis covers the winter, monsoon, pre-monsoon, and post-monsoon seasons of 2021. We examine the correlation between LST and AET for each land cover class and both seasons of 2020. The study finds that areas with lakes and greenery exhibit lower LST and higher AET values, whereas urban areas show the opposite trend. This underscores the importance of understanding regional context to accurately assess the link between LST and AET. Our results highlight the role of vegetation and water bodies in moderating surface temperatures and suggest that land management strategies should consider these dynamics to mitigate urban heat effects.

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Introduction

Human activities have caused substantial changes to the trends of land use and land cover (LULC) in developing nations. Many types of environmental deterioration have resulted from these shifts in LULC, which caused far-reaching effects on the natural world. Urban heat islands are more likely to form as a result of modernization's contribution to higher Land Surface Temperatures (LST) [1-4]. Because of urbanisation, these places are hotter than average, which shows how important it is to have sustainable city planning and climate change mitigation measures to protect local ecosystems and people from the effects of climate change [5]. Buildings, roads, and pavements are examples of impermeable surfaces that trap heat for longer periods of time compared to natural land cover, which makes the urban heat island effect more severe [6]. This phenomenon highlights the importance of sustainable urban design and green infrastructure deployment, as it worsens the temperature disparity between urban and rural areas. It also poses issues to heat management. Because of the urban heat island effect, cities and other densely populated places get much hotter during heat waves than their more rural neighbours [7]. The importance of heat mitigation techniques in urban design and management is highlighted by the fact that heat retention is amplified by human activities, buildings, and infrastructure, which in turn exacerbates heat-related dangers.

A reduction in actual evapotranspiration plays a role in exacerbating the urban heat island effect [8,9]. In cities, impermeable surfaces like buildings and roads limit natural processes like evaporation and transpiration. This disrupts the balance of Land Surface Temperature (LST) and Actual Evapotranspiration (AET) observed in vegetated areas. The dominance of impermeable surfaces alters environmental behaviors, contributing to heightened temperatures and emphasizing the significance of urban planning strategies that prioritize green spaces and permeable surfaces. The built environment absorbs and re-emits heat, leading to higher surface temperatures in metropolitan locations, a phenomenon known as the urban heat island effect. Impermeabile surfaces, such as roadways and buildings, amplify this impact, leading to temperature differences between rural and urban regions. This has consequences for urban planning, public health, and the environment. Land surface temperatures are affected by evapotranspiration rates in urban areas, which depend on the number of plants and their transpiration capacity. The urban heat island effect is reduced when there is vegetation because plants absorb and release moisture, which in turn lowers temperatures. Reducing heat stress and increasing urban climate resilience, urban greening projects can boost evapotranspiration. Vegetation in expansive green spaces such as parks plays a crucial role in regulating temperatures within metropolitan areas. These green areas act as natural cooling systems, mitigating the urban heat island effect by providing shade, absorbing heat, and facilitating evapotranspiration. Consequently, they contribute significantly to creating more favorable thermal conditions in cities, highlighting the importance of preserving and expanding urban green spaces for climate resilience [10,11]. It is common for evapotranspiration and land surface temperature (LST) to have a negative correlation in cities. Heat stress on plants and greater evaporation from hard surfaces like roads and roofs cause LST readings to rise, which in turn indicates higher surface temperatures. As a result, evapotranspiration rates are higher under these conditions [12]. The intricate relationship between urbanisation, surface features, and evapotranspiration dynamics in determining urban microclimates and thermal conditions is highlighted by this negative connection. Current research examines the relationship between Land Surface Temperature (LST), Actual Evapotranspiration (AET), and Land Use/Land Cover (LULC) categories. This investigation aims to understand how each LULC type influences the exchange of energy and water vapor, elucidating their role in shaping urban microclimates and thermal characteristics. This study aims to quantify the disparity in Actual Evapotranspiration (AET) and Land Surface Temperature (LST) across various land cover types within urban environments. By establishing correlations between these variables, researchers seek to understand how different urban land covers impact the exchange of energy and water vapor, influencing urban thermal characteristics.

Literature Review

The relationship between Land Surface Temperature (LST) and Actual Evapotranspiration (AET) has been extensively studied across various geographical contexts, highlighting its significance in understanding regional climate dynamics and land management. Previous research has explored how different land cover types influence LST and AET, with studies showing that vegetation and water bodies generally moderate surface temperatures and enhance evapotranspiration. Seasonal variations in these relationships have also been investigated, revealing that urban areas often experience higher LST and lower AET compared to rural and vegetated landscapes.

However, existing studies predominantly focus on either global or regional scales, with limited research addressing the seasonal dynamics of LST and AET at a more localized level. Furthermore, there is a noticeable gap in studies examining these relationships within the context of culturally and historically significant cities, such as Prayagraj.

Research Gap and Aim

This study aims to address the identified gap by focusing on Prayagraj, India, a city with a unique blend of historical significance and modern urbanization challenges. By analyzing the seasonal interactions between LST and AET across different land cover types in Prayagraj, this research seeks to provide insights into the specific dynamics of these variables within a culturally and environmentally significant context.

Summary of Innovations

This study introduces several innovative aspects:

- **Localized Focus:** It applies a detailed analysis of LST and AET within the context of Prayagraj, providing a localized understanding of these dynamics.
- **Seasonal Analysis:** It examines the seasonal variations in LST and AET, offering a comprehensive view of how these relationships fluctuate throughout the year.
- **Cultural and Environmental Context:** It integrates the cultural and environmental significance of Prayagraj into the analysis, highlighting how historical and urban development factors influence LST and AET.

By addressing these gaps, this study contributes valuable insights into sustainable urban planning and environmental management tailored to the unique context of Prayagraj.

Study Area

Prayagraj, celebrated for its rich historical heritage and spiritual significance, is one of India's most ancient and revered cities. Nestled at the confluence of the sacred Ganga, Yamuna, and the mythical Sarasvati rivers, Prayagraj holds a unique place in Indian culture and religion. The city is situated between approximately 25.43°N to 25.44°N latitude and 81.84°E to 81.87°E longitude. Characterized by its tropical climate, Prayagraj experiences hot summers, mild monsoons, and cool winters. The average annual temperature ranges from 25°C to 30°C, while the city receives an average of 976 millimetres of rainfall each year.

With an area of about 3,404 square kilometres, Prayagraj's geographical location and climatic conditions significantly contribute to its prominence as a key religious and cultural hub in India. As a focal point for urban studies, Prayagraj exemplifies the complex challenges associated with rapid urbanization in India. The city's evolving population dynamics and economic transformations prompt critical research into infrastructure development, urban planning, and environmental sustainability. Analysing Prayagraj's spatial organization, land use patterns, and socio-economic disparities provides valuable insights for crafting policies that support equitable and sustainable urban growth, addressing both present and future needs of the community.

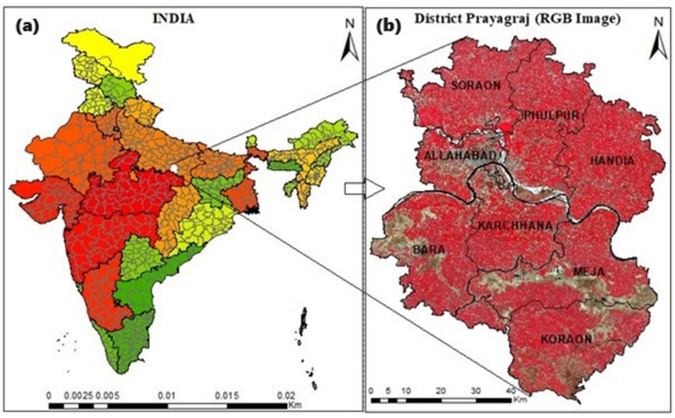


Figure 1: Study area of the Prayagraj, India (a), Sentinel-2 Imagery of Uttar Pradesh Prayagraj (b).

Data Used

LULC Classification: Our research utilised the most of Landsat 8 Level 2 (Table 1) data for the purpose of classifying land use and land cover, making use of surface reflectance information whenever possible. This data, which was easily accessible and adjusted for the conditions of the atmosphere, served as an invaluable resource for conducting an accurate analysis of the environmental dynamics and spatial patterns that were present in the area that we were studying. We used only data from Landsat 8 Level 2 Collection 2, which is of higher quality than Collection 1, in our analysis. Our land use and land cover classifications were enhanced for accurate analysis and interpretation by utilising Tier 1 data, which prioritised excellent optimal radiometric and geographical accuracy.

• **Land Surface Temperature:** We utilised MODIS's daily Land Surface Temperature (LST) data (Table 1) to build monthly composites and seasonal datasets for the winter, monsoon, pre-monsoon, and post monsoon of year 2021. These datasets were constructed at a resolution of 1 kilometre. By taking this technique, we were able to capture temporal fluctuations as well as spatial patterns in temperature, which made it easier for us to conduct an in-depth examination of seasonal dynamics and climatic trends [13].

• **Actual Evapotranspiration:** Actual Evapotranspiration (AET) data is obtained from the Modis satellite (Table 1), that specialises in hydroclimatic data. This information, which is necessary for determining the availability of water and the state of the ecosystem, offers advantageous insights into the hydrological processes that occur in the region, which helps with the monitoring and management of water resources as well as agricultural productivity. The operational Simplified Surface Energy Balance (SSEBop) model was employed to compute evapotranspiration. Monthly composite data (in millimeters per month) were utilized from the dataset, enabling the determination of average values for the seasons as winter, monsoon, pre-monsoon, and post monsoon of 2021 year. This approach facilitated the assessment of water consumption by vegetation and provided insights into seasonal variations in evapotranspiration dynamics for effective water resource management strategies.

Table 1: Datasets Used in the Study Area

Data	Satellite/Sensor	Resolution
LULC	Landsat 8 OLI	30m
LST	Modis	500m
AET	Modis	500m

Methodology

Within the scope of our research, we concentrated on a number of different forms of land use and land cover (LULC) in order to investigate the influence that these types have on the Land Surface Temperature (LST) and Actual Evapotranspiration (AET). In order to gain a better understanding of the unique associations that built-up, cropland, water bodies, tree cover, shrubland and grass land have with LST and AET dynamics, we conducted analyses. For our examination of space and time in 2021, we used a geographical resolution of one km. Our concentration was specifically on the winter, monsoon, pre-monsoon, and post monsoon. We were able to gather information on the changes in land features and climate parameters, such as Land Surface Temperature (LST) and Actual Evapotranspiration (AET), that occur during different seasons and across various types of Land Use and Land Cover (LULC) [14,15]. An initial step in the process involves the utilisation of Google Earth Engine (GEE), a cloud-based computing platform, for the purpose of data collecting and LULC categorization. Daily land surface temperature (LST) data is obtained from MODIS LST from GEE, where mean values are extracted. Monthly Actual Evapotranspiration (AET) data is directly retrieved and averaged across selected the winter, monsoon, pre-monsoon, and post monsoon. This comprehensive approach integrates remote sensing technology, cloud-based computing, and Geographic Information Systems (GIS) software to facilitate precise spatio-temporal analysis of LST and AET dynamics across different seasons and land cover types. Both the Land Surface Temperature (LST) and the Actual Evapotranspiration (AET) data were provided on a per-square-kilometer basis for the purpose of this study. In order to ensure that the analysis is consistent, a grid measuring one kilometre by one kilometre is applied to each land cover class. A calculation is made to determine the total area that each class occupies within the grid. Consequently, grids that have a certain land cover class that accounts for less than sixty percent of the entire grid area are not included in the subsequent analysis. This guarantees that a consistent technique is used throughout the various types of land cover, and it eliminates grids in which the dominant land cover is not sufficiently representative, which ultimately results in an increase in the accuracy of results obtained from later analyses.

Assessment of Correlation

One part of the investigation is calculating the overall association between ET and LST (Land Surface Temperature). Furthermore, for every land cover class, we separately analyse the connections between LST and ET. In order to see how different types of land cover change between the summer and winter, scatter plots are created. We study at how the link between LST and ET changed and how different it was for both seasons by comparing and analysing the results. This comparative approach provides light on the dynamics of surface temperature and evapotranspiration processes by comparing the effects of seasonal fluctuations on the connection between LST and ET across various land cover categories.

Results and Discussions

The 2020 Landsat 8 image was subjected to Land Use and Land Cover categorization, resulting in an overall accuracy of 85.38% and a kappa score of 84.12%. These metrics confirm the dependability of the classification process, demonstrating significant concurrence between the categorised maps and reference data. The significant overall accuracy indicates a strong and reliable categorization method, which increases confidence in the obtained outcomes. The kappa score provides additional evidence of the consistency between the categorised maps and ground truth data, indicating a high degree of agreement. This validation highlights the usefulness and precision of the categorization method, providing valuable information about the changes in the landscape and patterns of land use throughout the defined period. The classification of land use and land cover (LULC) is illustrated in Figure 2, whereas Table 2 offers comprehensive information regarding the coverage and distribution of each land cover category within the designated region of Prayagraj. Significantly, the analysis demonstrates that built-up comprises 4.78% of the overall area, cropland comprises 70.75%, water bodies comprise 2.24%, tree cover comprises 12.40%, shrubland comprises 0.33% and grass land constitutes 9.40%. The provided percentages furnish a comprehensive depiction of the spatial arrangement of different land cover categories within the designated research region. This aids in comprehending the composition of the landscape and provides valuable insights for decision-making processes pertaining to environmental management and urban planning.

Table 2: Percentage area of Prayagraj in Term of land Cover Class

Class	Area (km^2)	% Area
Built-up	338.82	4.78
Cropland	5009.81	70.75
Water bodies	165.68	2.34
Tree cove	878.36	12.40
Shrubland	23.03	0.33
Grass land	665.78	9.40

The Land Surface Temperature (LST) changes throughout the year, and figure 3 shows that it does so throughout winter, monsoon, pre-monsoon, and post-monsoon. Seasonal changes in weather can be better understood with the help of these temperature ranges.

The summer LST, which occurs before the monsoon, shows higher temperatures, which could lead to heat stress, while the winter LST, which occurs during the winter, shows cooler temperatures, which could impact natural processes like evapotranspiration rates. The environmental thermal dynamics and their effects on different ecosystems can be better understood with the use of this data.

The information shown in Table 3 provides a summary of the mean values for Land Surface Temperature (LST) and Actual Evapotranspiration (AET) for varieties of land cover that have a density of at least sixty percent. Consequently, this makes it possible to conduct detailed comparisons across a variety of land cover categories, which in turn helps with the analysis of the thermal and hydrological properties of each of these categories. Throughout the pre-monsoon season, the Land Surface Temperature (LST) (shown in Figure 3) values of water bodies are the lowest, while the LST values of bare land and built-up regions are the greatest. This is because there is no building taking place in these places. For the duration of the winter season, this pattern continues. In a similar vein, the Actual Evapotranspiration (AET) (shown in figure 4) is maximum for water bodies prior to the onset of the monsoon, whereas the values obtained from exposed and developed land are the smallest. When compared to bare ground and built regions, which have the lowest AET values, water bodies register the highest AET values throughout the winter months. The influence of land cover on the dynamics of temperature and moisture is demonstrated by this, as indicated. These differences in LST and AET across different types of land cover highlight the significance of taking into account patterns of land use in order to gain an understanding of the dynamics of the local climate and the hydrological processes that occur. This understanding is essential for the development of successful strategies for environmental management and urban planning.

Table 3: Seasonal Average LST and ET by Land Cover Class of Prayagraj

Class	LST				AET			
	Winter	Pre-monsoon	Monsoon	Post monsoon	Winter	Pre-monsoon	Monsoon	Post monsoon
Built-up	22.73	36.23	34.27	27.07	53.57	63.43	65.75	50.81
Cropland	23.51	38.35	35.07	27.10	64.58	61.27	64.49	64.29
Water bodies	23.15	36.28	35.07	27.10	64.58	61.27	64.49	64.29
Tree cove	22.61	36.41	35.07	27.10	64.58	61.27	64.49	64.29
Shrubland	24.65	37.93	35.07	27.10	64.58	61.27	64.49	64.29
Grass land	24.14	37.60	35.07	27.10	64.58	61.27	64.49	64.29

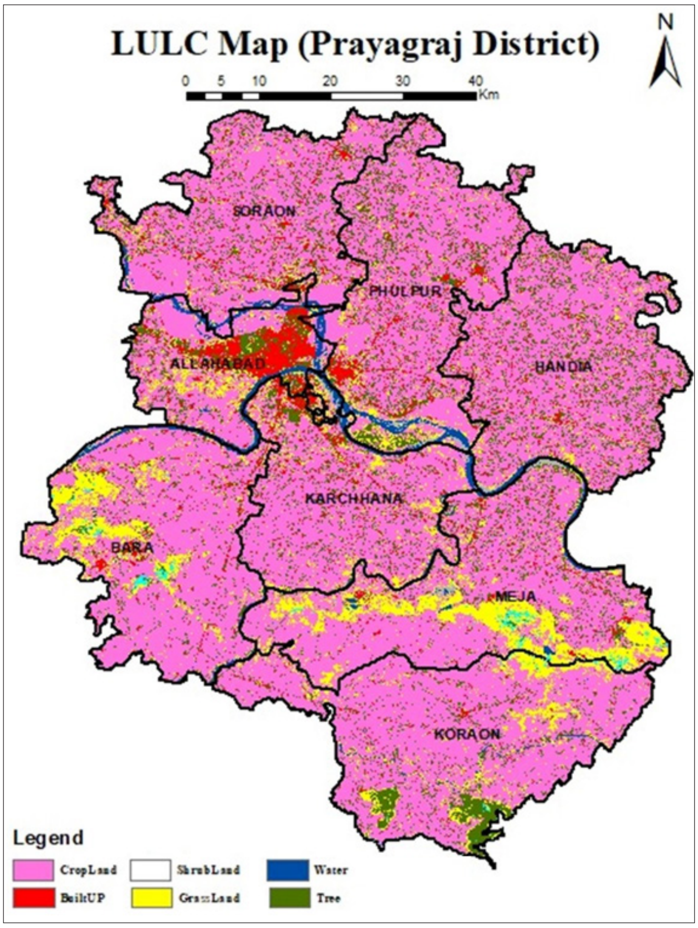


Figure 2: LULC Classification Map of Prayagraj, U.P.

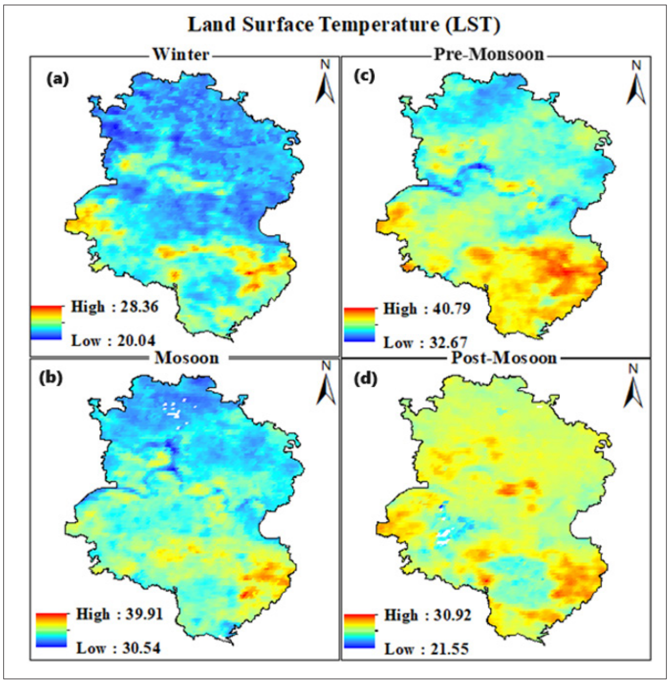


Figure 3: LST of the Prayagraj in the Winter (a), Monsoon (b), Pre-Monsoon (c), and Post-Monsoon (d). Seasons

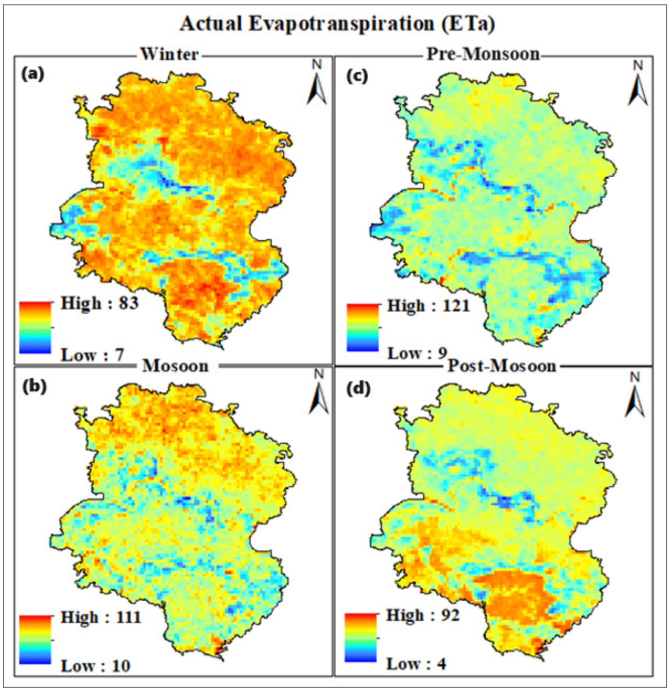


Figure 4: AET of the Prayagraj in the Winter (a), Monsoon (b), Pre-Monsoon (c), and Post-Monsoon (d). Seasons

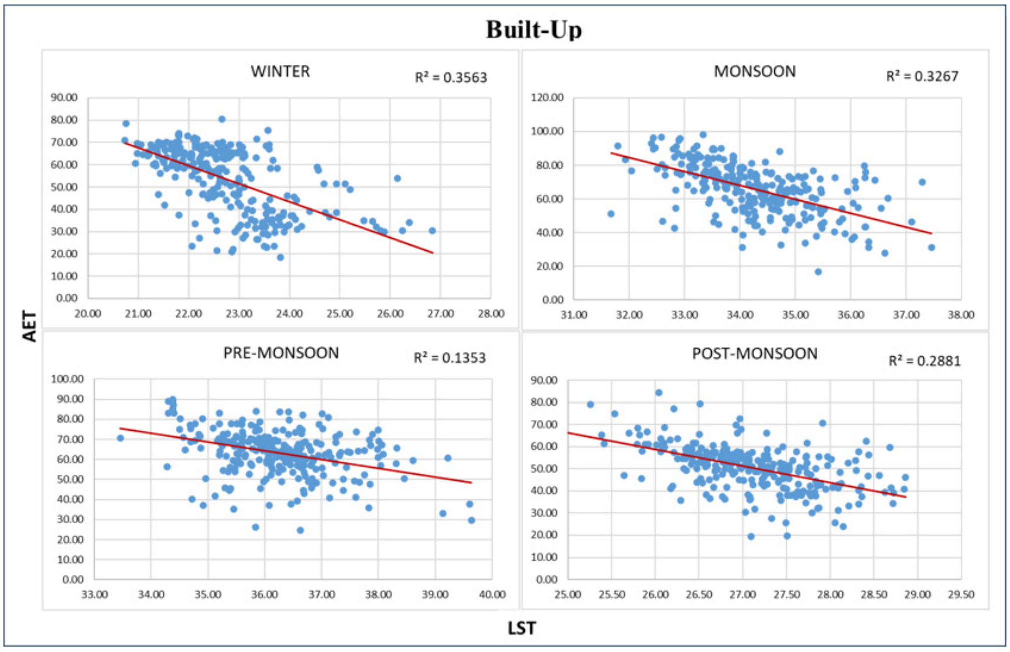
The scatter diagrams that indicate the link between LST and AET for the winter, monsoon, pre-monsoon, and post-monsoon seasons are depicted in Figure 5a. The six different types of land cover such as that built-up, cropland, water bodies, tree cover, shrubland and grass land that were taken into consideration for the study are represented by these scatter plots.

In the built-up land class, there is a negative association between the LST values and the AET values obtained. According to the urban heat island effect, which occurs when surfaces absorb and retain heat, the Land Surface Temperature (LST) has a tendency to be greater in places that are densely populated. On the other hand, Actual Evapotranspiration (AET) levels are often lower in these places when compared to areas that contain vegetation and bodies of water. This is due to the fact that built-up regions do not have a considerable amount of vegetation cover and have restricted access to water, which results in lower evapotranspiration rates despite higher temperatures.

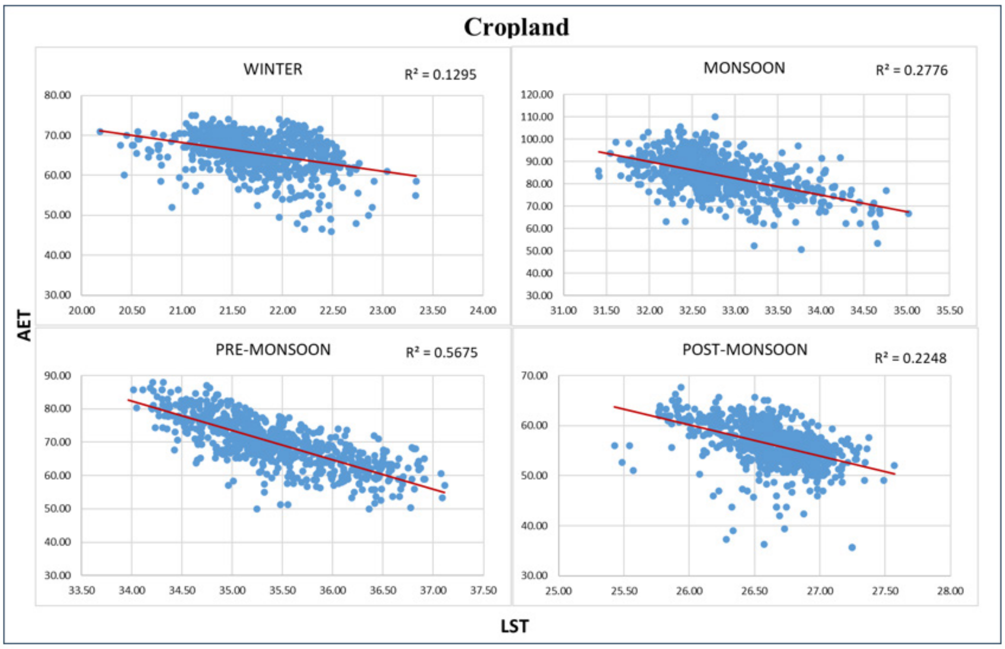
The cropland class, there is a negative association between the LST values and the AET values obtained in the winter, monsoon, pre-monsoon, and post monsoon shown in the figure 5b. In contrast, increased temperature values are usually indicative of higher AET. There is a strong correlation between elevated LST and higher AET, which indicates that crops are actively using water. In order to detect water stress, monitoring this link is helpful; a high LST in conjunction with a low AET indicates the possibility of water deficiencies in the crop, which in turn prompts urgent irrigation interventions. On the other hand, a lower LST in conjunction with a higher AET indicates that the crop conditions are healthy and that there is sufficient water availability. The integration of LST and AET data enables precise irrigation scheduling, the identification of drought, and overall optimisation of water resources, all of which are essential for maintaining crop yield and resilience in agricultural systems.

Studies on water bodies reveal a consistent negative association between Land Surface Temperature (LST) and Actual Evapotranspiration (AET) across winter, monsoon, pre-monsoon, and post-monsoon seasons, indicating that higher LST corresponds to lower AET levels (shown in figure). The monsoon season, LST and AET show some positive correlation with respect to winter, pre-monsoon, and post-monsoon seasons shown in figure 5c. The water level in the bodies continues to decline throughout the winter, pre-monsoon, and post-monsoon seasons, which results in the appearance of additional patches of land that are devoid of vegetation or are completely naked. In the event that the water in the soil evaporates, these regions are going to get dry and will no longer play a role in absorption. As a consequence of such, high temperatures are produced, albeit the respective AET values might not always be large. The negative association that was seen during the winter, pre-monsoon, and post-monsoon seasons can be understood to be the cause of this phenomenon. On the opposite hand, during the monsoon season, which comes after the pre-monsoon period, there is a presence of vegetation surrounding the bodies of water, which helps with the process of evapotranspiration. In light of this, the minor upward trend that was noticed throughout the monsoon season can be explained.

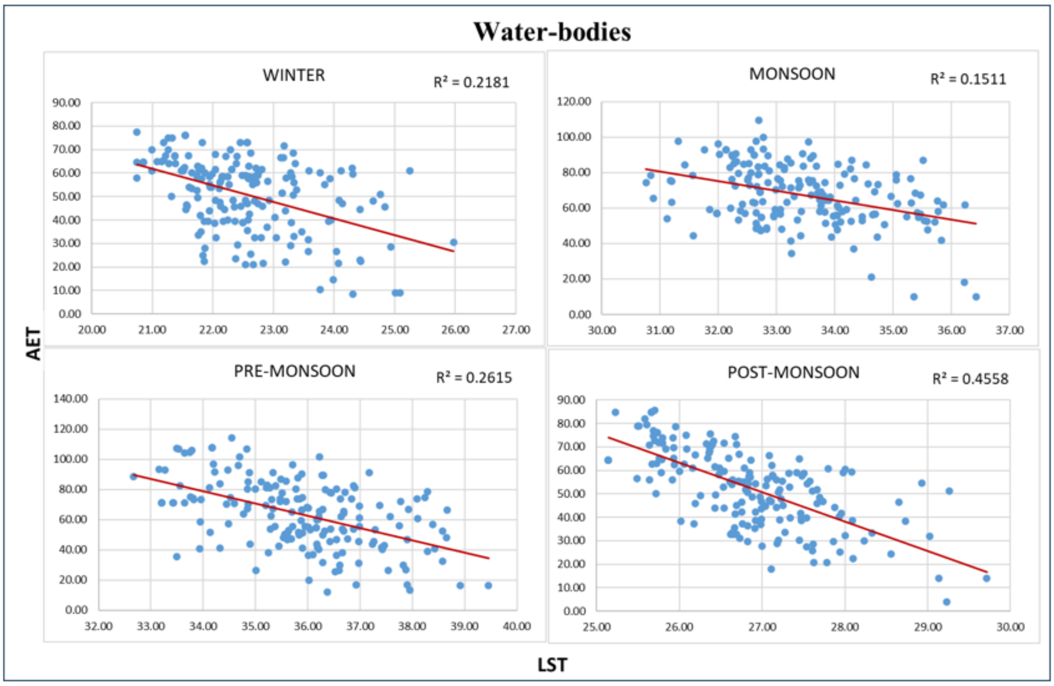
The relationship between LST and AET in tree, shrubland, and grassland areas is negative during the winter, monsoon, pre-monsoon, and post-monsoon seasons. Whereas, in general, greater temperature values would signify higher AET. In the case of trees during the pre-monsoon season, AET increases somewhat as increases LST. Warmer areas, such as sparsely vegetated shrublands and grasslands, often have lower AET and greater LST (shown in Figure 5 d, e, f). Ecosystem health and resilience, particularly in light of climate change, can be better understood by examining the relationship between surface temperature, the amount of vegetation cover, and the dynamics of the water cycle. These insights are useful for planning water resources and land management in a sustainable way.


Built-Up
WINTER
R² = 0.3563
MONSOON
R² = 0.3267
PRE-MONSOON
R² = 0.1353
POST-MONSOON
R² = 0.2881
AET
LST

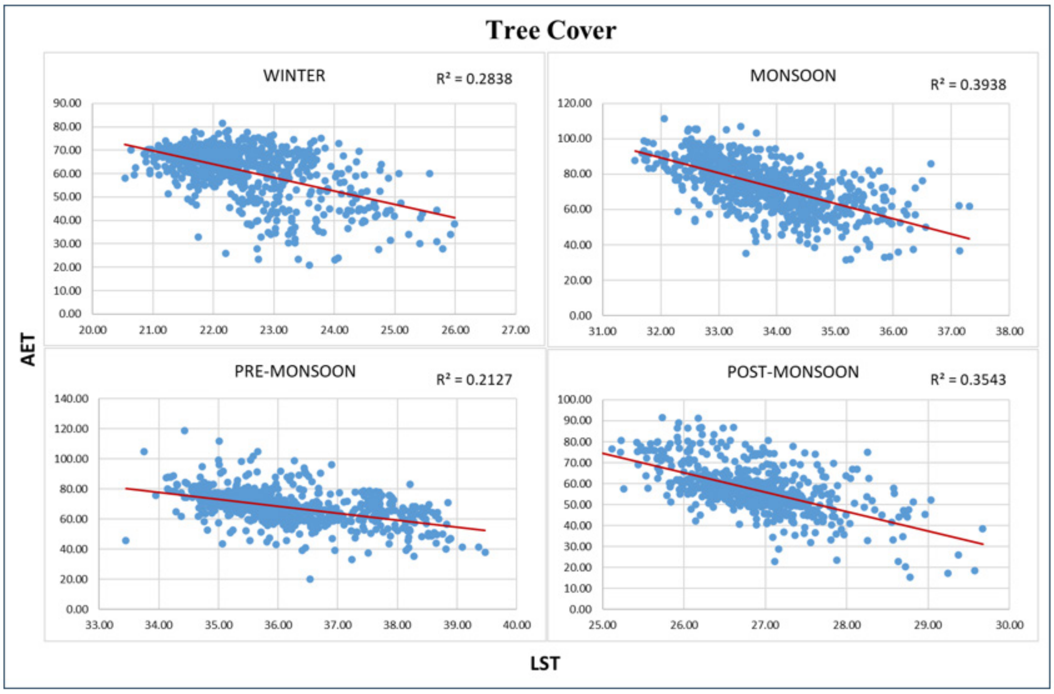
(a)


Cropland
WINTER
R² = 0.1295
MONSOON
R² = 0.2776
PRE-MONSOON
R² = 0.5675
POST-MONSOON
R² = 0.2248
AET
LST

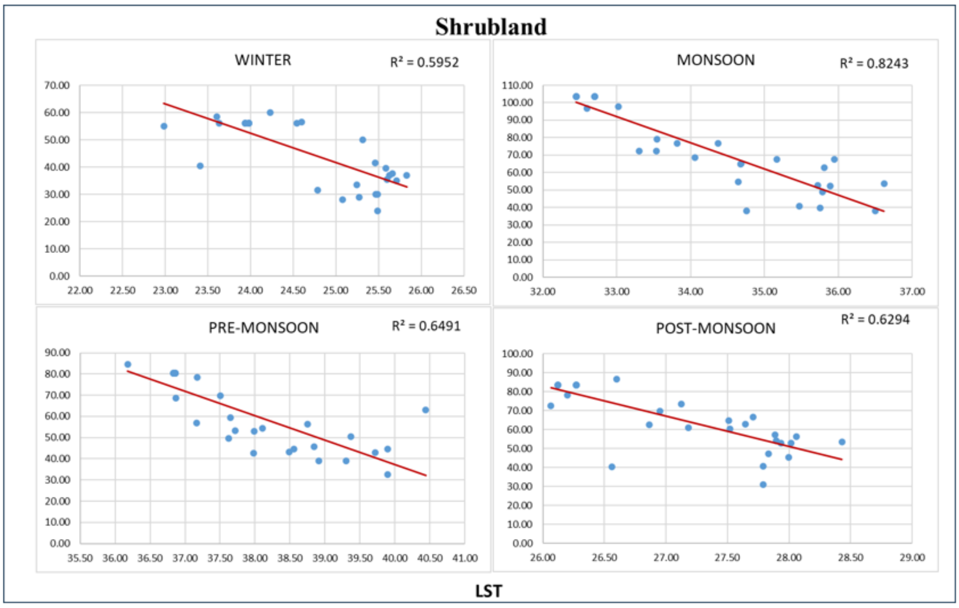
(b)


Water-bodies
WINTER
R² = 0.2181
MONSOON
R² = 0.1511
PRE-MONSOON
R² = 0.2615
POST-MONSOON
R² = 0.4558
AET
LST

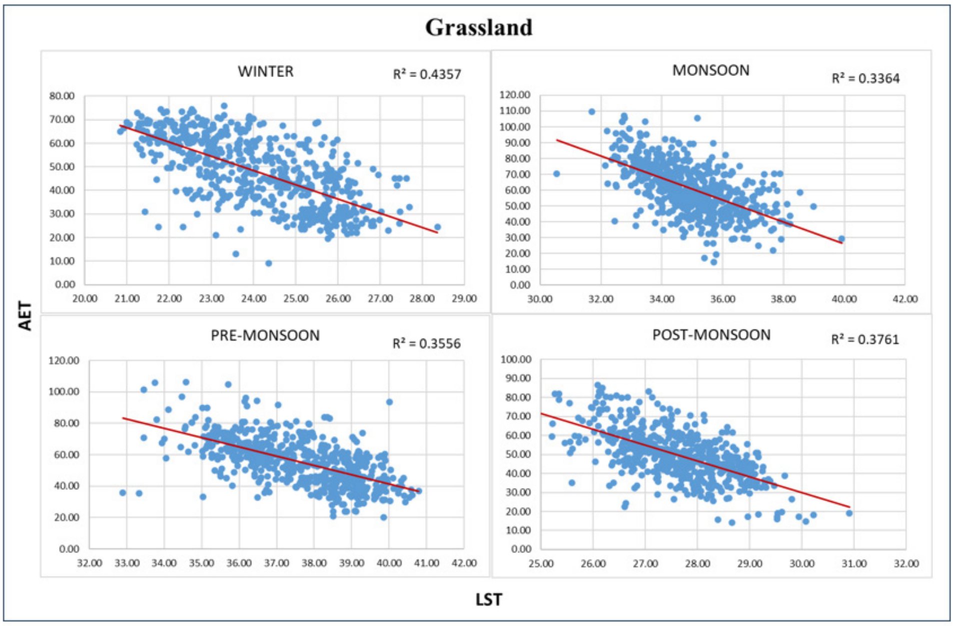
(c)


Tree Cover
WINTER
R² = 0.2838
MONSOON
R² = 0.3938
PRE-MONSOON
R² = 0.2127
POST-MONSOON
R² = 0.3543
AET
LST

(d)



(e)



(f)

Figure 5 (a, b, c, d, e, f): Scatter Plots of LULC Classes (Built-up, Cropland, Water Bodies, Tree Cover, Shrubland and Grass Land) vs LST and AET of Winter, Monsoon, Pre-monsoon, and Post Monsoon Seasons

Conclusion

The categorization of the 2021 Landsat 8 image for Land Use and Land Cover (LULC are such as built-up of 4.78%, cropland of 70.75%, water bodies of 2.24%, tree cover of 12.40%, shrubland of 0.33%, and grassland of 9.40% of the region in Prayagraj, providing valuable insights for environmental management and urban planning. Seasonal variations in Land Surface Temperature (LST) depicted across winter, monsoon, pre-monsoon, and post-monsoon—aid in understanding weather patterns. LST and AET values for various land covers, facilitating detailed comparisons and highlighting differences across seasons. For different types of land cover, the relationship between LST and AET throughout winter, monsoon, pre-monsoon, and post-monsoon seasons. Because of the urban heat island effect, wherein dense populations retain heat yet lack vegetation and water access, lower AET is associated with higher LST in built-up areas. An important indicator for cropland water stress monitoring and irrigation optimisation is the negative correlation between LST and AET. A negative link between LST and AET is constantly shown in bodies of water, while a positive correlation is observed during monsoon seasons due to the increased vegetation that aids evapotranspiration. Vegetation has a crucial role in controlling evapotranspiration, as seen by the negative association between LST and AET across seasons in tree, shrubland, and grassland environments. These results help with resilience strategies and sustainable planning by shedding light on how to best manage land and water resources in the face of changing environmental circumstances.

Broader Implications for Policymakers and Urban Planners

- **Sustainable Urban Development:** The results of this study offer valuable insights for sustainable urban development. Policymakers should prioritize the integration of green spaces and water bodies in urban planning to mitigate the urban heat island effect. By increasing vegetation cover and enhancing water features, cities can reduce surface temperatures and improve overall environmental quality. Urban planners should consider these factors when designing new developments or retrofitting existing ones to ensure that urban environments are more resilient to temperature extremes.
- **Climate Resilience Strategies:** The findings also contribute to climate resilience strategies. Understanding the dynamics between LST and AET can help in developing strategies to adapt to climate change impacts. For instance, incorporating green infrastructure and water management practices can help cities adapt to rising temperatures and increased evaporation rates. This approach not only enhances urban resilience to climate variability but also contributes to improved quality of life for residents.
- **Policy Formulation:** The study's insights can inform policy formulation aimed at promoting environmental sustainability and climate adaptation. Policies encouraging the preservation and expansion of green areas and the integration of sustainable water management practices are essential. Additionally, the findings can guide the development of urban heat management plans and support efforts to enhance the overall resilience of urban areas against climate-related challenges.

Declarations

Competing Interests: Always applicable and includes interests of a financial or personal nature.

This is to declare by all the authors that no financial and personal relationships with other people or organizations have been taken and there is no conflict of interest with other people or organizations.

Availability of Data and Materials: A statement on how any datasets used can be accessed.

Data and material are given in the manuscript.

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