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Landscape Dynamics and Land Surface Temperature in the Upper Citarum, Indonesia

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Abstract. The Citarum River Basin is a critical focus of the Indonesian government due to extensive landscape changes that cause environmental degradation. This study analyzes the landscape dynamics and land surface temperature (LST). A cloud computing platform and multivariate analysis were used to understand the phenomenon in the Cirasea Watershed, West Java, Indonesia, known as the Citarum River's zero point. Landscape data refers to land use and land cover (LULC) resulting from random forests in Google Earth Engine, whereas LST is obtained from the radiative transfer mechanisms formula. Both data were obtained from Landsat series satellite images, which were validated using field surveys. The data were analyzed quantitatively to understand the differences and correlations between variables. This study shows that landscape dynamics are associated with significant changes in LST from 1993 to 2023, reaching 2.34 °C. The LST in forests and water bodies was highest compared to other LULC types. Road (0.42), elevation (0.72), and population (0.58) were also significantly related to LST. The relationship between LULC and LST is an indicator for further and comprehensive investigation in order to better understand the potential accumulative impacts in the future.

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1 Introduction

Landscape change is a global phenomenon that implies population growth, the use of natural resources, and demands for industrialization to increase human welfare [1–3]. In this context, landscape can be interpreted as land use and land cover (LULC), which contain the interactions of various ecosystem components and processes [4]. Landscape dynamics characterized by an increase in anthropogenic land areas have the potential to significantly impact environmental quality, ranging from water and soil to air [5]. This process is characterised by different characteristics, such as an increase in developed areas, a decline in densely vegetated regions and landscape fragmentation. As a result, rural areas transform into urban-style environments [6]. The impact of landscape dynamics is observed early on through changes in surface temperature, where these weather and climate components are easily controlled by micro-environments such as vegetation, building layout, and human activities [7, 8].

An increase in surface temperature is commonly associated with the development and spread of cities, forming megacities where city boundaries are no longer administrative but have become eco-regions as a geosphere phenomenon [9]. To understand urban heat islands, it is very important to understand landscape dynamics that impact changes in surface temperature. In addition, it has a multiplier effect on reducing the quality of health, causing damage to property and infrastructure, decreasing agricultural productivity, and increasing air-conditioning electricity consumption costs [10]. LULC and surface temperature changes can be observed using a geospatial approach that combines aspects of space and time [11, 12]. Understanding the process of LULC change and its interaction with surface temperature is very influential in studying industrialization and urbanization in developing countries [13], with Indonesia being an example.

The economic viability of Indonesia is driven by dynamic landscapes near urban centers. Dede et al. [14] reported that the surface temperature of Cirebon City, located in the coastal region, increased by 1.18 °C over 20 years due to a reduction in densely vegetated land area and the expansion of built-up land. Research involving geospatial data and the Internet of Things (IoT) in the coastal industrial area of West Java showed that surface temperature and air humidity have a distribution pattern with LULC, Nurdian et al. [15] found that air humidity aligns with densely vegetated landscapes and contrasts with surface temperature. Research in Yogyakarta also indicates a similar phenomenon, where surface temperatures are highest in the city centre and continue to decrease in the peri-urban areas [16–18]. The majority of previous studies have been conducted in urban areas in coastal and lowland areas. However, urban regions in mountainous areas have not been studied much because researchers focus on broad scale surface temperature models, such as island units [19] or provinces [20].

Research on detailed landscape dynamics and surface temperatures in mountainous areas is very significant for environmental preservation because of the location of the upstream river basin [21], which provides environmental services for lower and downstream areas, such as Citarum [22]. This river basin flows its water from Greater Bandung to Jabodetabek, two important megacities in Indonesia, and has three reservoirs: Cirata, Saguling, and Jatiluhur. Landscape dynamics have become a common concern in protected areas and upstream watersheds (river basins) that play a vital role in the ecosystem [23]. Therefore, this study analyzes the landscape dynamics and land surface temperature (LST) in Citarum, Indonesia, with a particular focus on the upper area. Our research novelty uses cloud computing and multivariate analysis to comprehensively understand the upper Citarum's ecosystem.

2 Methodology

2.1 Study area and data acquisition

Our research was conducted in the Cirasea Watershed, part of an eco-region in Upper Citarum (Figure 1). This area is the zero point of the Citarum River basin, located at the southernmost point. Cirasea has an area of 366.17 square kilometres (km^2) with a population of 700,000 to 900,000 residents and is crossed by 106.02 km of perennial river [24]. The Cirasea Watershed is zero kilometres from the Citarum River, whose main flow stretches 297 km until it empties into the Java Sea [25, 26]. The importance of the Citarum River encourages us to analyze LULC and LST by relying on reliable primary and secondary sources. To explore various factors that correlate with LST, this research also utilizes other data such as road networks (BIG and OSM), elevation (DemNas BIG) and population (BPS and WorldPop). All data are integrated into a geospatial dataset using the geographic information system (GIS) [27].

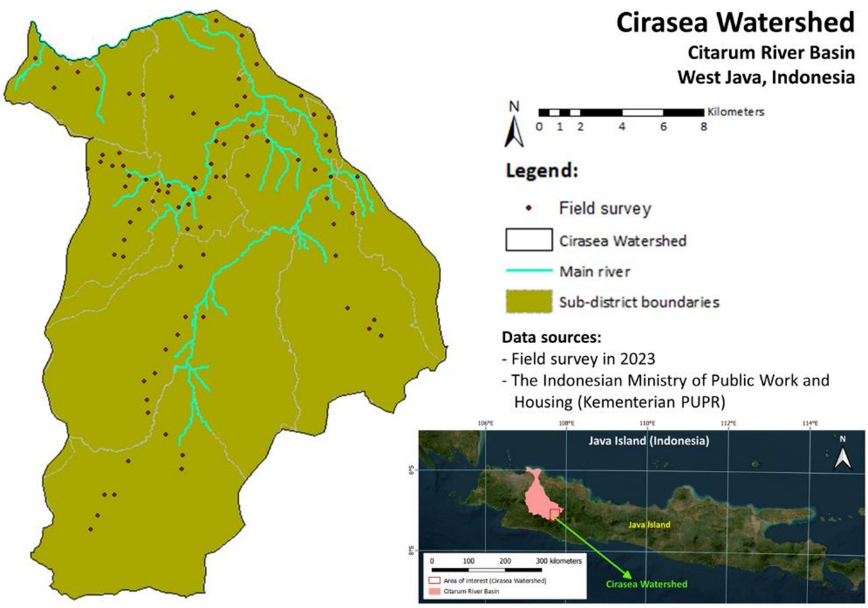

Fig. 1. Research study and ground check locations.

LULC data derived from remote-sensing satellite images, Landsat-5 TM (1993) and Landsat-8 OLI (2023) [28, 29], were processed using a random forest algorithm (80% training and 20% testing). Classification results were verified through a field survey involving 86 points. Random forest is a popular supervised learning algorithm that can be run on a desktop or cloud computing platform. Random forest classifiers are widely utilized in remote sensing for LULC classification due to their notable advantages, including high classification accuracy, non-parametric nature, and ability to determine variable importance. Random forests are known for their speed and resistance to overfitting; however, their sensitivity to the sampling design remains a consideration. This LULC classification has an overall accuracy value of 0.91 and an overall kappa value of 0.88; thus, it is valid as the reference for landscape information with eight types (agricultural land, built-up areas, forest, grassland, marsh, non-vegetated, plantations and horticulture, and water bodies) [30]. LST data were obtained using thermal bands from satellite images and radiative transfer mechanisms, as described in Equation 1 [31]. LST data does not require reconfirmation in the field because studies using Landsat series satellite imagery show high statistical and distribution pattern accuracy compared with other instruments [15]. Both LULC and LST data were processed via cloud computing using Google Earth Engine, and data throughout the year had passed the pre-processing stage to ensure the validity of the information [32, 33]. This cloud computing platform improves the efficiency of data acquisition by rapidly obtaining optimal satellite imagery with minimal cloud cover, which is precisely tailored to the specified area.

$$LST = Ai\ (Tb/\varepsilon) + Bi\ (1/\varepsilon) + Ci \quad (1)$$

where Tb is the TOA brightness temperature in the thermal band, ε is the surface emissivity, and ABC is the algorithm coefficient from the linear regression of total column water vapour values (TCWV) in Google Earth Engine.

2.2 Data analysis

Multivariate analysis with correlated factors was used to analyze landscape dynamics and LST changes, as well as to ascertain other factors that could potentially alter temperature. Landscape dynamics in the Cirasea Watershed were observed from gain and loss analysis for each LULC type [34], in terms of area and presentation over 30 years (1993-2023). Meanwhile, the LST data are presented in degrees Celsius, complete with central tendency information [35]. The effect of LULC on LST was evaluated using inferential statistical analysis, namely analysis of variance (ANOVA), eta-squared (η^2) and t-test (Equations 2–4) [36, 37]. ANOVA analyzes group mean differences and is often used to compare three or more groups, whereas eta-squared measures the effect size in an analysis of variance and indicates the proportion of variance due to the independent variables. T-test was used to compare the means of the two groups and determine whether the observed differences were statistically significant. These methods can be used to determine differences between several types of treatment or groups by referring to the F-value and t-value [38]. A significant difference is declared if both values are greater than the table reference value (p-value 0.05, confidence interval 95%) [39]. In addition, the correlation between the three factors acting as LST controls is referred to as Pearson correlation. This method produces an r-value and p-value, which help determine the significance of the level of correlation between variables (Equation 5) [40–42]. Various numerical analyses have been conducted using free and open-source software named GNU PSPP 1.6.2 [43].

$$F = \frac{MSB}{MSW} \quad (2)$$

$$\eta^2 = \frac{SSB}{SST} \quad (3)$$

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad (4)$$

where F is the f-value of the test results, MSB is the mean square between (variance between groups), MSW is the mean square within (variance within groups), η^2 is eta-squared (effect size), SSB is the sum of squares between, SST is the total sum of a square, t is the t-value of the test results, $\bar{X}$ is the average value of each group, S is the standard deviation, and n is the samples size.

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 . \sum(Y_i - \bar{Y})^2}} \quad (5)$$

where r is the Pearson correlation coefficient (r-value), X and Y are the values at the observations, $\bar{X}$ and $\bar{Y}$ are the means of the test variables and $\sum$ is the sigma symbol indicating summation.

3 Results and discussion

LULC in the Cirasea Watershed has experienced significant landscape changes over the last 30 years, where built-up land continues to expand and causes other types of land to decrease, with agricultural land, non-vegetated land, plantations, and horticulture being the most significant contributors to loss (Table 1). Initially, the built-up land only had an allocation of less than 10%, and the area continued to increase by almost 375% with a distribution pattern in the downstream part of the watershed (Figures 2a and 2b). Indeed, this area is a growth center and is close to Bandung City [44]. Interestingly, although built-up land has eroded other land, the forest area in the Cirasea Watershed has experienced growth. This phenomenon cannot be separated from the efforts of the central and regional Indonesian government to restore the Citarum River Basin ecosystem and reduce critical land and water pollution [45, 46]. This program is part of environmental management, a national priority, and the Indonesian government named it "Citarum Harum" [47]. This breakthrough is undoubtedly outstanding, considering that in other regions in Indonesia and many other developing countries, landscape dynamics are the leading cause of environmental degradation because they give rise to critical land due to the loss of primary forests (deforestation) [48, 49].

Table 1. LULC and LST changes in 30 years.

LULC type	LULC (km²)			LST (°C)		
	1993	2023	Δ	1993	2023	Δ
Agricultural land	77.56	70.15	-7.41	29.83	31.82	2.00
Built-up areas	12.80	47.80	35.00	33.51	34.45	0.94
Forest	71.86	88.72	16.86	20.73	24.47	3.73
Grassland	16.64	14.15	-2.49	29.19	30.10	0.92
Marsh	18.23	12.31	-5.92	26.85	28.66	1.81
Non-vegetated	17.60	7.87	-9.73	31.77	29.57	-2.20
Plantations and horticulture	151.13	124.56	-26.57	27.16	29.34	2.18
Water bodies	0.88	1.14	0.26	23.68	28.52	4.83

Although the forest is still maintained, changes in the landscape in the Cirasea Watershed with a rural to urban transformation pattern certainly resulted in an increase of LST. In addition to increasing global temperatures due to increasing concentrations of greenhouse gases in the Earth's atmosphere [50], temperature is a weather and climate parameter that is strongly influenced by the landscape as its controller [51]. The LST at the Cirasea Watershed increased by 2.34 °C from 1993 to 2023, with a central tendency changing from 27.72 °C (4.43) to 29.61 °C (4.45). With respect to distribution, the area with temperatures above 30 °C increases, as shown in Figures 2c and 2d, respectively. LST in almost all LULC types increased in the range of 0.92-2.83 °C, where forests and water bodies became warmer areas.

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LULC and LST had a significant interaction pattern with a determination value of more than 0.50, as seen in η^2 and ANOVA values (Table 2). Although there appears to be a decrease in the influence of landscape on LST, this interaction cannot be sanctioned, especially in areas where high temperatures have previously occurred.

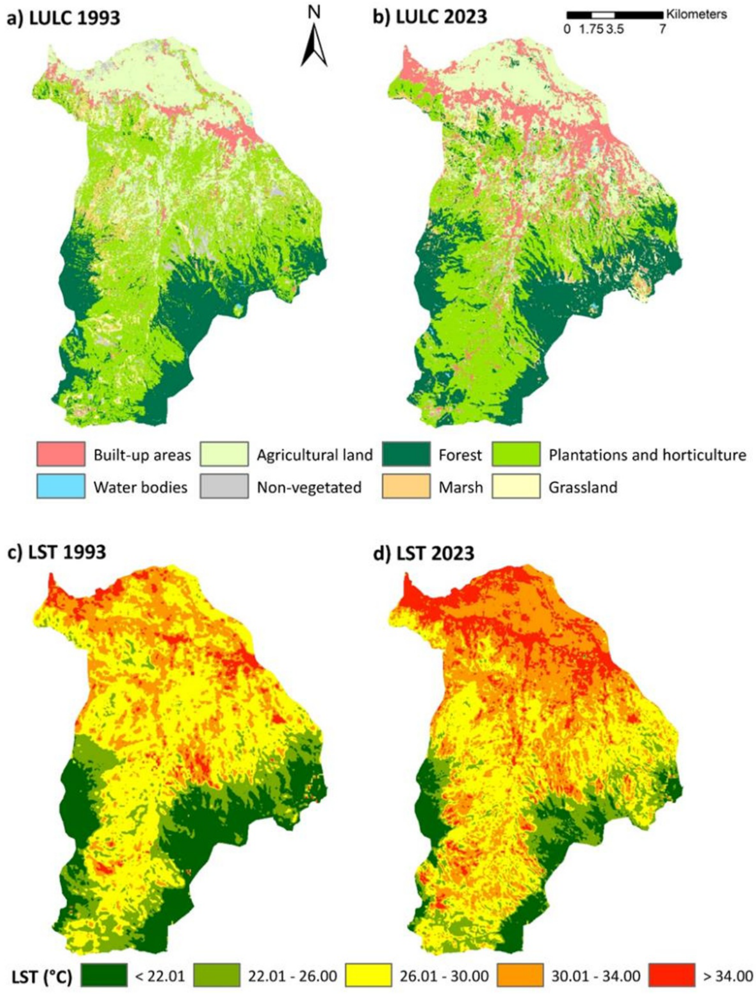

Fig. 2. LULC and LST dynamics in the Cirasea Watershed (1993-2023).

Table 2. LULC interaction with LST in 1993 and 2023.

X variable	Y variable	F	H	η^2	Ɛ	p-value
LULC 2023	LST 2023	69726.27	0.72	0.52	0.48	0.00
LULC 1993	LST 1993	104221.76	0.79	0.62	0.38	0.00

* p-value based on 2-tailed and 95% confidence level.

Table 3. Statistical differences for LULC and LST.

X̄ difference	Interval differences	F	t	p-value
-0.076	-0.06 – -0.09	4494.14	-10.19	< 0.01

* p-value based on 2-tailed and 95% confidence level.

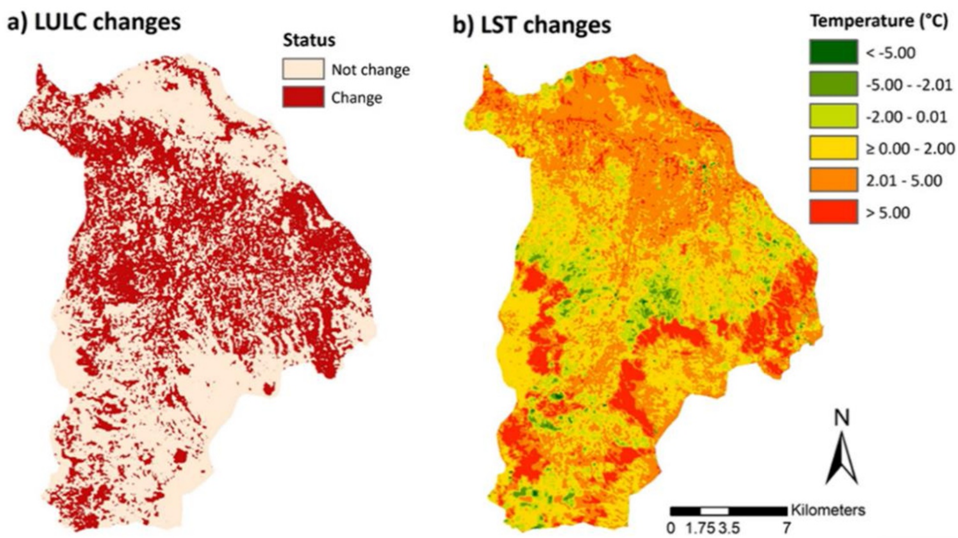

Fig. 3. LULC and changes in 30 years.

Pearson's correlation test revealed a strong correlation (r-value 0.84, p-value 0.00), indicating that the distribution of LST during the warm period (1993) notably increased in the present period (2023). This phenomenon shows an increase in heat due to the increasing number of human activities, such as the use of motorized vehicles, housing design, the emergence of congestion points, thermal energy-based industries, as well as the lack of open green space and greenbelts [52]. In the case of the Cirasea watershed, landscape changes have begun to spread to the central and riverbank areas. As a result, the LST increased (Figure 3). As shown in the ANOVA and t-test results in Table 3, the increase in LST caused by landscape changes was confirmed to be significant. The rise in temperature on riverbanks and water bodies indicates that the riparian area has not yet been able to achieve optimal ecological function due to anthropogenic patterns [53, 54].

Table 4. Correlation of three factors with LST.

Variable		R	p-value
Road	LST	0.42	0.00
Elevation		-0.72	
Population		0.58	

* p-value based on 2-tailed and 95% confidence level.

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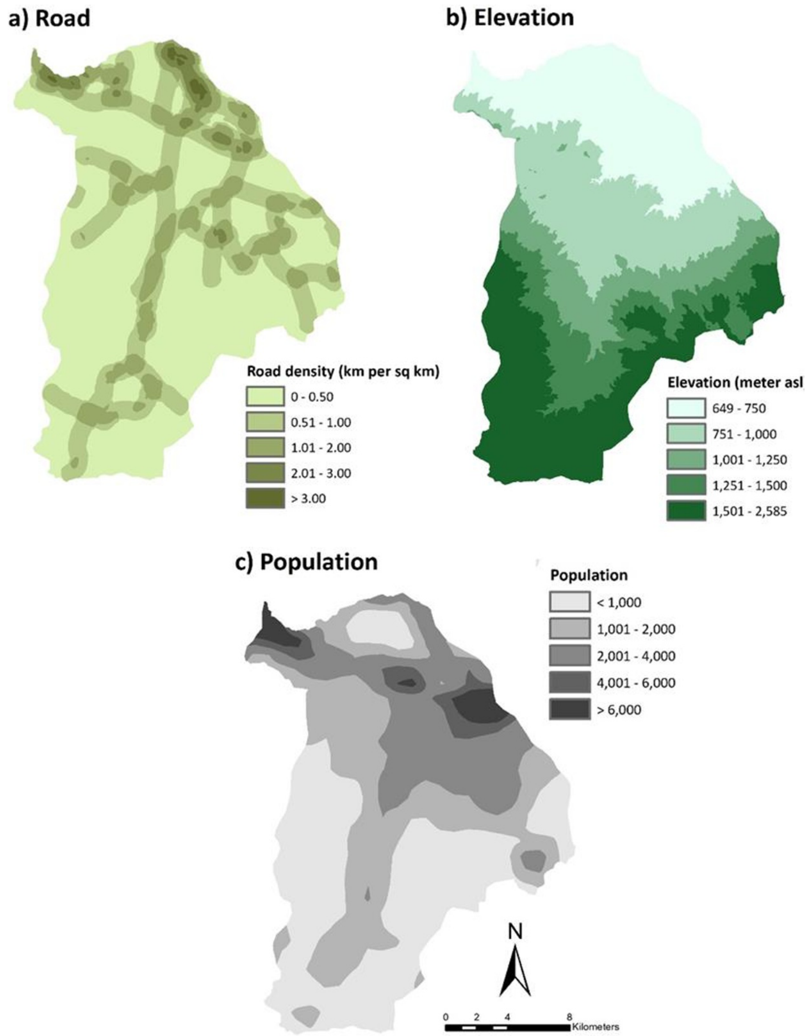

Fig. 4. Factors that have potential relation with LST in the Cirasea Watershed.

LST in the Cirasea Watershed was significantly correlated with infrastructure accessibility (road), elevation, and population (Figure 4 and Table 4). Roads and population form a positive correlation, which means that the presence of roads and humans agrees with increasing LST, but this is inversely proportional to elevation according to Pearson's correlation test results. This close relationship between temperature and elevation with opposite but significant patterns proves the existence of the gradient thermometric phenomenon [55–57]. Meanwhile, the positive correlation of LST with other factors indicates that its increase can be influenced by other factors, especially as the η^2 value leaves epsilon (Ɛ) in the range of 0.38-0.48. Further investigation is certainly needed because this analysis helps control LST and prevent the emergence of various harmful socioeconomic and ecological impacts, such as the emergence of urban heat islands, heat stress, and changes in chemical compounds due to thermal reactions [58–61]. The significant changes in LULC and LST in the upstream area of the Citarum River Basin should warn us to take environmental management more seriously for future generations.

This study at Cirasea Watershed illustrates that landscape and LST changes have occurred in the upstream part of Citarum River Basin. They are very dynamic because they are located in the megapolitan region [62]. Of course, it differed from the upstream part of Cisanggarung River Basin or Wanggu watershed. In the Cisanggarung River Basin, West Java, LST changes are greater in urban areas located downstream and middle regions, especially in Losari Town and Luragung Town [63]. A similar phenomenon occurred in the Wanggu Watershed in Southeast Sulawesi, where LST was concentrated in Kendari City, which is the downstream area [64]. With major changes in the Cirasea Watershed, in-depth studies are needed to analyze the potential dynamics in the future, including various scenarios following regional development plans, optimizing conservation, or leaving the river basin without intervention.

4 Conclusion

As reflected in the LULC, landscape dynamics are associated with LST changes in the Cirasea Watershed between 1993 and 2023. Significant differences in LST values for each LULC indicate that landscape characteristic contributes to this phenomenon. Over the last 30 years, the expansion of built-up land and a reduction in agricultural land, non-vegetated land, plantations and horticulture have increased LST by 2.34 °C. LST increased the most in forests and water bodies, and the temperature distribution pattern showed a very strong relationship between the present and the past (r-value 0.84). Road and population are positively correlated with LST, whereas elevation has the opposite effect because the thermometric gradient influences it. To prevent future environmental impacts and accumulative damage, further investigation is needed to more comprehensively understand the interaction between changes in LULC and LST by involving various quantitative models.

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