# Remote Sensing Analysis of Urban Heat Island Effect in Colombo City from 2001-2019

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**Abstract**

Urban Heat Island (UHI) is a metropolitan area where the temperature is several degrees higher than surrounding rural areas. In the context of UHI phenomenon, Land Surface Temperature (LST) was estimated using Landsat satellite images covering Colombo city, which is one of the main commercial metropolitan cities in South Asia. Results revealed that UHIs have expanded into northern, eastern and south eastern regions of Colombo city within the period 2001-2019. The Land Use change indicated the rapid urbanization. The correlation of Normalized Difference Built up Index (NDBI) and Normalized Difference Vegetation Index (NDVI) with LST were analyzed and obtained negative correlation between NDVI & LST and positive correlation between NDBI & LST at four time period (2001,2009,2016 & 2019) indicating the vegetation can weaker the UHIs while built up land can strengthen the UHIs. The results of Albedo analysis show that the low albedo materials have more potential influence towards formation of UHI. Finally, according to the ecological evaluation of the city using Urban Thermal Field Variance Index (UTFVI), 27% of the area is experienced worst case of heat stresses remaindering that mitigation measures should be applied in future urban planning to uplift the quality of lives and environment.

**Keywords:** Albedo, LST, NDVI, NDBI, UTFVI

## 1. Introduction

According to the industrial revolution, globalization and the migration of rural population to urban areas, leads to the urbanization, which is the major reason to the conversion of land use/ cover to fulfill the needs associated with growth of population and economy. As of the year 2001, 54% of the global population up from 34% in 1960, accounted for urban population which implies that majority of the people lives in urban areas instead of rural areas. The global urban population is expected to grow approximately 1.84%, 1.63% & 1.44% per year in the years between 2015-2020, 2020-2025 & 2025-2030 respectively [1]. This urbanization is mainly characterized by urban infrastructure facilities such as low-density residential housing, single-use zoning, roads, bridges and increased reliance on the private automation and transportation leads to rapid changes in land use patterns. These urban areas generally have higher solar radiation absorption, greater thermal conductivity and capacity because most of the infrastructure facilities such as roads, pavements, parking lots, roof tops and buildings with darker surfaces are made up from low albedo materials which have low reflective coefficient hence low solar reflectivity. Therefore, urban areas tend to experience a relatively higher temperature compared to surrounding rural areas. This temperature difference forms the land effect called "Urban Heat Island" [2]. Removal of large natural land-cover from an area that replaced by built up area is a major contributor to UHI formation, which trap the incoming solar radiation during the daytime and re-radiate during the night and this is noticeable when the wind is weak. Forest and vegetation cover reduce the surrounding air temperature by releasing water vapor trough evapotranspiration, photosynthesis processes and lower the land surface temperature (LST) by providing shade. Waste heat release from urban houses, factories, motor vehicles and air conditioners are some of other major contributors [3] to form UHIs.

In Colombo city area the land use patterns have undergone a significant change due to accelerated expansion since late 1990. Since then the urban population has begun to increase and started to extreme stress to the environment, and lack of appropriate land use planning. According to the Census of Population and Housing 2012, the highest number of household units have been recorded from the Western Province and only Colombo city has residential population of 558755 leading, Colombo as the densest city in Sri Lanka (15101 people/km$^2$). Therefore, it is essential for address the environmental impact of rapid urban expansion which has caused to disappearing of vegetation land in the city every year.

In detection of thermal energy released from earth surface over a large spatial area with precise accuracy, cost effective and time saving manner, integration of Remote sensing (RS) & Geographic information system (GIS) plays a major role as a powerful and effective tool which is capable of estimating surface temperature to study UHI phenomenon and applicable in many other fields. Here the parameters from Remote sensing data were integrated to describe UHI phenomenon in Colombo city. Although several studies have conducted Colombo's UHI effect, the spatial ecological evaluation of UHI effect using Urban Thermal Field Variance Index (UTFVI) is still lacking for Colombo city.

Therefore, the main objectives are, identify the spatial distribution and temporal behavior of UHIs and evaluate the ecological condition in Colombo city, to study the relationship between LST,NDVI and NDBI, to identify the Land use/cover distribution of Colombo city and its influence towards UHI phenomenon, to determine surface albedo variation in the city and to carry out an Urban Thermal Field Variance Index (UTFVI) and identify alarming areas that are exposed to greater risks of thermal discomfort.

## 2. Methodology

### 2.1 Study Area

Colombo is island's commercial capital city which is situated in the western province of Sri Lanka and located between Northern latitudes 6° 55'-6°59' and Eastern longitudes 79° 51'-79° 53' extending over 37 km$^2$ (Figure 1). Colombo city is one of the urbanized cities in South Asian region, and according to the Census of population and housing 2001 data, total population of Colombo District was 2,254,174 and population have been increased from 552033 during 1981 - 2001 with 1.4% of average annual growth rate.

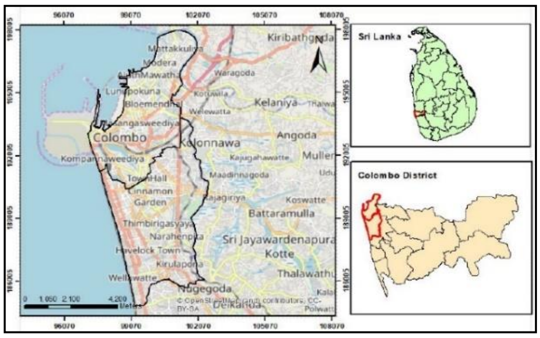


*Figure 1: The study area, Colombo City*

### 2.2 Data Sources

*Table 1: Characteristics of Landsat TM, ETM+, OLI/TIRS data*

| Acquisition Date | Satellite Type | Cloud Cover (%) | Path | Row | Sun Elevation (Degree) | Time (GMT) |
|---|---|---|---|---|---|---|
| 03/14/2001 | Landsat 7 ETM+ | 4.00 | 141 | 55 | 57.90309966 | 4:44:13 |
| 02/8/2009 | Landsat 5 TM | 12.00 | 141 | 55 | 50.49876176 | 4:39:37 |
| 01/27/2016 | Landsat 8 OLI / TRIS | 4.71 | 141 | 55 | 51.46836212 | 4:53:59 |
| 03/31/2019 | Landsat 8 OLI / TRIS | 1.98 | 142 | 55 | 62.89190086 | 4:59:39 |

Mainly 4 near cloud free Landsat Satellite images related to 3 different satellite sensors (Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI ) & Thermal Infrared Sensor (TIRS)) while thermal bands have 120 m, 60 m and 100m spatial resolution were obtained from the U.S. Geological Survey (USGS) web site. The images were acquired on 14 March 2001, 08 February 2009, 27 January 2016 and 31 March 2019, as shown in Table 1. In this study, we used preprocessed datasets (Level 1T) downloaded from http:// earth explorer. usgs.gov. The data has already georeferenced to the UTM coordinate system (Zone 44N).

#### 2.2.1 Other Auxiliary data

Daily average gauge temperature data for 2001, 2009, 2016 and 2019 were obtained from the Department of Meteorology, Sri Lanka Colombo Topographic map and Colombo Regional map from the Survey General Department, Sri Lanka were used in the study.

### 2.3 Land Use/Cover Classification

The first step in the analysis was to detect the Land Use/ Cover changes over the period from 2001 to 2019. After resampled all the images into 30 m resolution, Supervised classification was then used to classify the RGB color composite of the individual Landsat images of 2001, 2009, 2016 & 2019 acquired for this study. Maximum Likelihood Algorithm was the main parametric rule utilized in the image classification where the covariance and variance of the spectral response patterns of a pixel was used to classify the image. Finally, the images were classified into 4 Land Use classes namely, a) Water bodies; b) Vegetation; c) Barren Land d) Built up Area.

### 2.4 Land Surface Temperature (LST) Retrieval

In order to identify the LST distribution pattern of Colombo city, thermal band (band 10) of Landsat 8 satellite image was analyzed using digital image processing techniques. Landsat 8 Science Data Users Handbook describes the retrieval method of LST from the thermal band of an image. The process requires the conversion of the Digital Number (DN) values of the thermal bands into spectral radiance values as in Equation (1)

$$L_\lambda = (\text{Gain} \times \text{QDN}) + \text{Bias} \quad (1)$$

where QDN is quantized calibrated pixel value in DN and $L_\lambda$ is the spectral radiance of the sensor in $Wm^{-2}\ Sr^{-1}\ lm^{-1}$, Which can be also represented as in Equation (2).

$$L_\lambda = \left(\frac{LMAX\lambda - LMIN\lambda}{QCALMAX - QCALMIN}\right).(QCAL\text{-}QCALMIN) + LMIN \quad (2)$$

where $LMIN_\lambda$ is minimum spectral radiance, $LMAX_\lambda$ is maximum spectral radiance, QCALMIN is the minimum quantized calibrated pixel value and QCALMAX is the maximum quantized calibrated pixel value. All these values can be obtained by the meta data file of the image. Then spectral radiance value is used to derive at-satellite brightness temperatures as in Equation (3) which represents black body temperatures.

$$T_B = \frac{K2}{\ln(\frac{K1}{L\lambda}+1)} \quad (3)$$

where K1 and K2 are pre-launch calibration constants. It is necessary to make the corrections using ground surface emissivity values to estimate the real LST. To retrieve land surface emissivity (ε) values we first derived the Equation (4)

$$\varepsilon = 0.004\ PV + 0.986 \quad (4)$$

PV is the proportion of vegetation extracted from the NDVI Equation (5).

$$PV = [(\frac{(NDVI - NDVImin)}{(NDVImax - NDVImin)})]^2 \quad (5)$$

Where NDVI is the normalized difference vegetation index derived in Equation (7) The NDVImin and NDVImax are the minimum and maximum values of the NDVI, respectively. The emissivity corrected LST values were then retrieved using Equation (6).

$$\mathbf{T_S} = \frac{\mathbf{TB}}{\mathbf{1+\left(\lambda\times\frac{TB}{\rho}\right)\ln(\varepsilon)}} \quad (6)$$

Where Ts is the emissivity corrected LST in Kelvin (K), TB is the black body temperature in Kelvin (K), λ is the wave length of emitted radiance (λ = 11.5 11.5μm), q = h c $K^{-1}$ (1.438 × 10-2 mK), h = Planck's constant (6.626 × 10-34 $Js^{-1}$), c is the Velocity of light (2.998 × 108 $ms^{-1}$) and K is Boltzmann constant (1.38 × 10-23 $JK^{-1}$), ε is surface emissivity.

### 2.5 The Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is one of the most widely applied satellite-based vegetation indices. Various features on the ground have different absorption and reflection capacities in the visible and Near Infrared (NIR) radiation and that phenomena are used to distinguish between features like vegetation cover, water bodies and bare land etc. Red band (0.64 - 0.67 μ$m$) representing visible spectrum and NIR band (0.85- 0.88 μ$m$) were utilized to calculate NDVI as in Equation (7).

$$NDVI = \frac{NIR - R}{NIR + R} \quad (7)$$

### 2.6 The Normalized Difference Built-up Index (NDBI)

The Normalized Difference Built-up Index (NDBI) is a useful measure of the intensity of imperviousness using satellite data. It highlights the urban areas distribution where there is typically a higher reflectance in the short-wave infrared band compared to the near-infrared band. The NDBI is calculated as in Equation (8).

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (8)$$

Where $SWIR$ is the short-wave infrared band (1.57 - 1.65 μ$m$), and $NIR$ is the near-infrared band (0.85 - 0.88 μ$m$), respectively.

### 2.7 Albedo calculation using Landsat satellite imagery of Colombo city

Albedo is an important property of the Earth surface heat budget. A simple definition of albedo is the average proportion of solar energy that is reflected by Earth's surface. To understand the impacts of local land use changes, taking precise albedo measurements using Landsat images is very much important. The input to the albedo calculation is a Landsat 8 OLI image bands of 2019, which have been converted from DN values to Top of

Atmosphere (TOA) reflectance using reflectance rescaling coefficients provided in the Landsat 8 OLI metadata file. Following Equation (9) is used to convert DN values to TOA reflectance for OLI bands.

$$\rho_{\lambda}` = M_{\rho} * QCAL + A_{\rho} \qquad (9)$$

where $\rho_{\lambda}`$= TOA planetary reflectance, without correction for solar angle; $M_{\rho}$ = Band-specific multiplicative rescaling factor from the metadata; $A_{\rho}$= Band-specific additive rescaling factor from the metadata; QCAL = Quantized and calibrated standard product pixel values. Correcting the Reflectance value with sun angle Reflectance with a correction for the sun angle is then according to Equation (10).

$$\rho_{\lambda} = \frac{\rho_{\lambda}`}{\cos\theta_{SE}} = \frac{\rho_{\lambda}`}{\sin\theta_{SZ}} \qquad (10)$$

where $\rho_{\lambda}$ = TOA planetary reflectance; $\theta_{SE}$ = Local sun elevation angle; $\theta_{SZ}$ = Local solar zenith angle; $\theta_{SZ} = 90^0 - \theta_{SE}$.
Many researchers have developed different algorithms for calculating albedo from various satellite sensors. In 2010, Smith has developed an algorithm to calculate shortwave albedo ($\alpha_{short}$) from Landsat products as presented in Equation (11).

$$\alpha_{short} = \frac{0.356\,\rho1 + 0.130\rho3 + 0.373\rho4 + 0.085\rho5 + 0.072\rho7 - 0.0018}{0.356 + 0.130 + 0.373 + 0.085 + 0.072} \qquad (11)$$

where, ρ represents Landsat bands 1, 3, 4, 5 and 7 Note that Landsat band 2 (green) is not used. To facilitate our analysis, we classified the Albedo values into five categories based on the histogram values.

### 2.8 Ecological Evaluation of Colombo

Urban thermal field variance index (UTFVI) was used to quantitatively describe the urban heat island effect. by identifying environmentally critical areas based on the ratio between Land Surface Temperature and the mean temperature of the area. LST layer is used to derive the UTFVI using Equation (12) as below.

$$UTFVI = \frac{T_S - T_{MEAN}}{T_{MEAN}} \qquad (12)$$

***Table 2: Classification of Albedo in Colombo***

| Albedo Values | Classification |
|---|---|
| 0.05 - 0.10 | Very Low |
| 0.10 - 0.15 | Low |
| 0.15 - 0.18 | Fair |
| 0.21 - 0.27 | Moderate |
| > 0.27 | High |

## 3. Results and Discussion

### 3.1 Accuracy Verification

In this study daily average air temperature measurements by department of meteorology were used to verify the final retrieved LST results (Table 3) due to lack of simultaneous land surface temperature data when the satellite passes.

***Table 3: Accuracy comparison of LST***

| Date | Retrieved Mean Temp (°C) | Mean Air Temp (°C) | Error |
|---|---|---|---|
| 03/14/2001 | 32.67 | 32.00 | -0.67 |
| 02/08/2009 | 30.85 | 32.10 | -1.25 |
| 01/27/2016 | 32.45 | 34.70 | +2.25 |
| 03/31/2019 | 35.26 | 33.20 | +2.06 |

Thus, the Radiative transfer equation method from Landsat TM data has significant accuracy (± 2.25$^0$C), which can provide good quality retrieved LST data for the analysis of UHIs.

### 3.2 LULC Distribution (2001 -2019)

The Land Use/ Cover maps of Colombo City area for the years 2001, 2009, 2016 and 2019 are shown in Figure 2 and 3.

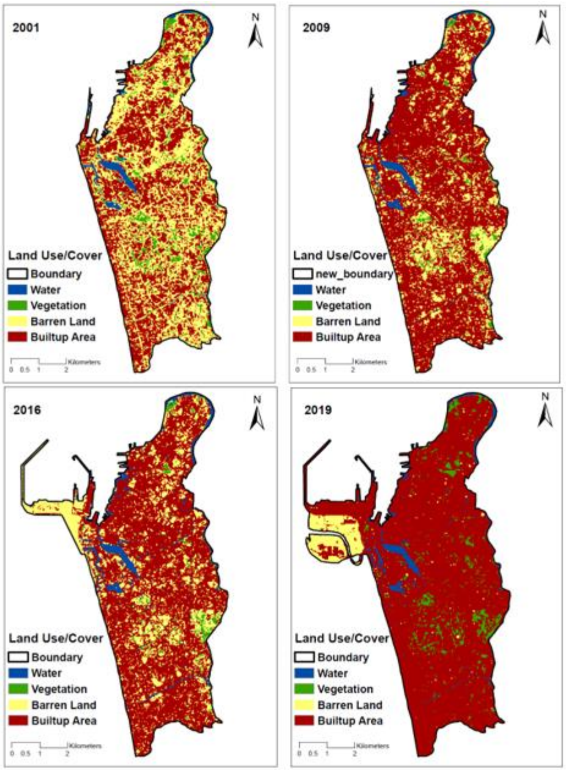


*Figure 2: LULC Classification*

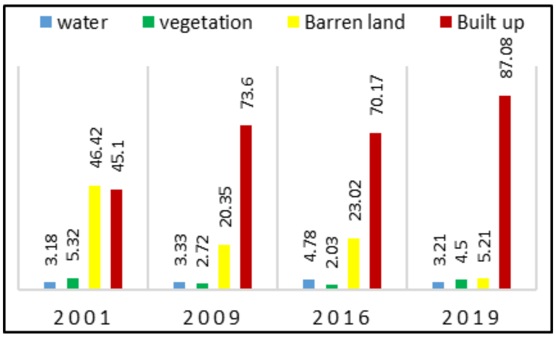


*Figure 3: Statistics of LULC distribution*

According to above results from 2001 to 2019 barren land area is decreased from 46.42% to 5.21% and area occupied by the built-up area is rapidly increased from 45.10% to 87.08% from total area. Slight loss of vegetation cover can be observed in 2009 and 2016 compared to 2001.

### 3.3 LST Distribution (2001-2019)

The LST maps of Colombo city in 2001, 2009, 2016 & 2019 are shown in Figure 4 and the descriptive statistics of the retrieved LST values are summarized in Table 4. Here red & green colors indicate highest and lowest temperature classes, respectively.

*Table 4. Statistics of LST distribution*

| year | Min (°C) | Max (°C) | Mean (°C) | Standard Deviation |
|---|---|---|---|---|
| **2001** | 25.86 | 37.9 | 32.8 | 1.64 |
| **2009** | 24.6 | 34.67 | 30.85 | 1.34 |
| **2016** | 26.2 | 36.32 | 32.45 | 1.22 |
| **2019** | 28.71 | 40.33 | 35.26 | 1.64 |

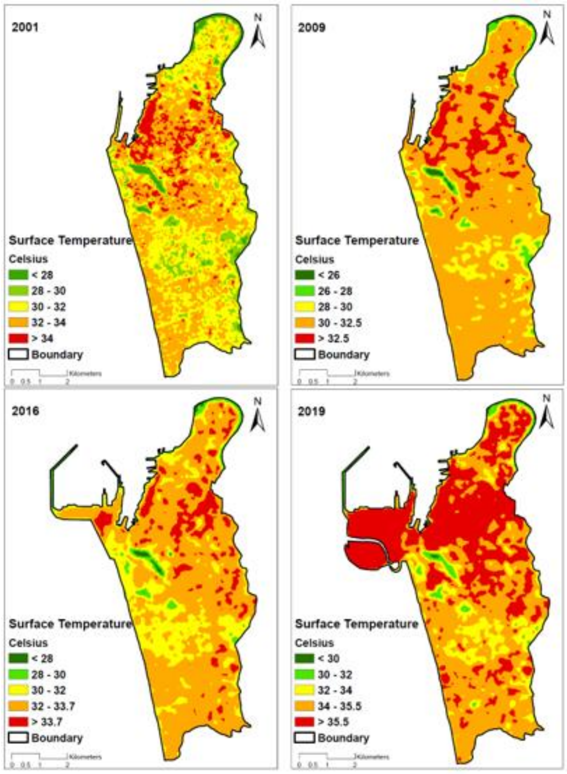


*Figure 4: LST Distribution*

In 2001 and 2009 areas with highest LST were concentrated in the vicinity of Colombo harbor (near jetty and the container storage area) and pettah area. But in 2016 and 2019 the areas with the highest LST have greatly expanded towards northern, eastern, central, and south east regions of the city following the spatial pattern of urban development, high building density and paved surfaces as well as high vehicle traffic. By integrating the regions with highest temperature classes (red color regions) in each year, an overall UHI map was generated (Figure 5).

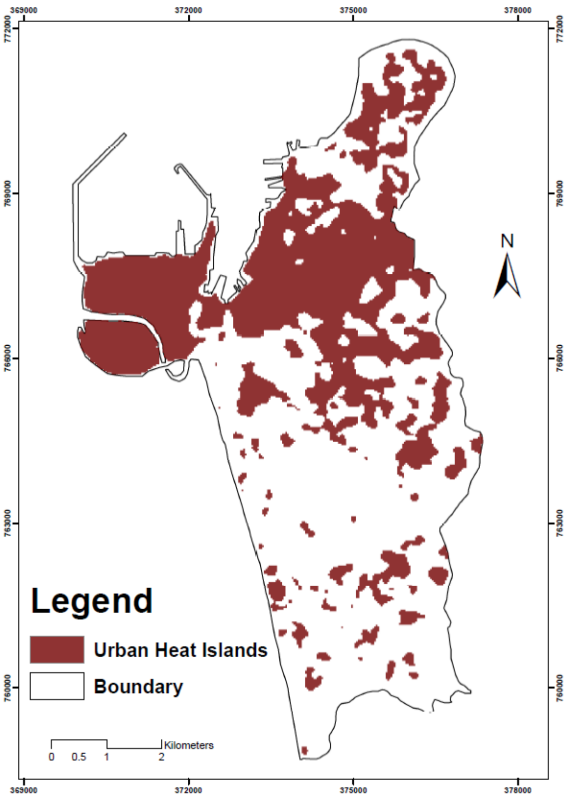


*Figure 5: Overall UHI distribution*

### 3.4 Correlation Analysis between LST, NDVI and NDBI

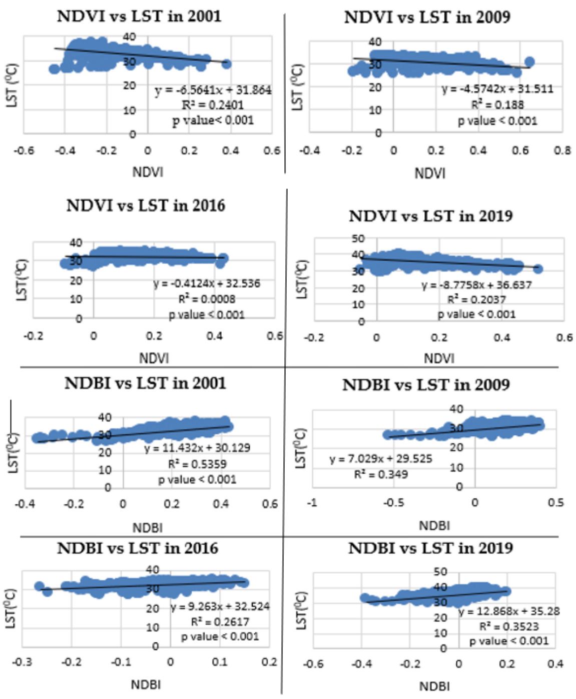


*Figure 6: Scatter plots between LST, NDVI & NDBI*

Figure 6 shows that the scatter plots and the results of regression analysis between LST & NDVI and NDBI. All the considered four years showed a negative relationship between NDVI and LST explaining that LST is inversely correlated with NDVI. Although the $R^2$ values were not that much of high, they were statistically significant (with 95% confident limit) in all 4 years since the p – value < 0.001. Generally, negative coefficient between NDVI and LST indicate that the impact of green land on UHI is negative and UHI effect can be weaken through increasing the green lands. it can be observed that the spatial distribution of NDBI values significantly follows the spatial patterns of LST values. The positive relationships between NDBI & LST were also statistically significant at each year since the p-value < 0.001. Here $R^2$ values were comparatively higher than NDVI values and the relationship between NDBI & LST was stronger than the relationship between NDVI & LST. The positive relationship between NDBI & LST suggest that built up area can strengthen UHI effect in this case study.

*Table 5: Correlation Analysis results*

| Correlation | LST | | | |
|---|---|---|---|---|
| **NDVI** | -0.489 | -0.433 | -0.028 | -0.451 |
| **NDBI** | 0.732 | 0.5907 | 0.5115 | 0.5935 |
| **YEAR** | 2001 | 2009 | 2016 | 2019 |

### 3.5 Albedo Distribution in Colombo City

The Albedo distribution map of Colombo city related to 2019 is shown in Figure 7 as below. According to Figure 5 and Figure 7, most of the UHIs were formed where the low and fair albedo surface types such as like asphalt, tar, gravel, corrugated roof and concrete etc., were present. Most of the buildings are rooted with asbestos roofing sheets or concrete which belongs to low albedo category. Although barren land area near Colombo harbor has high albedo due to sand pits, most of the parking lots and Colombo harbor jetty are constructed with dark albedo materials like asphalt.

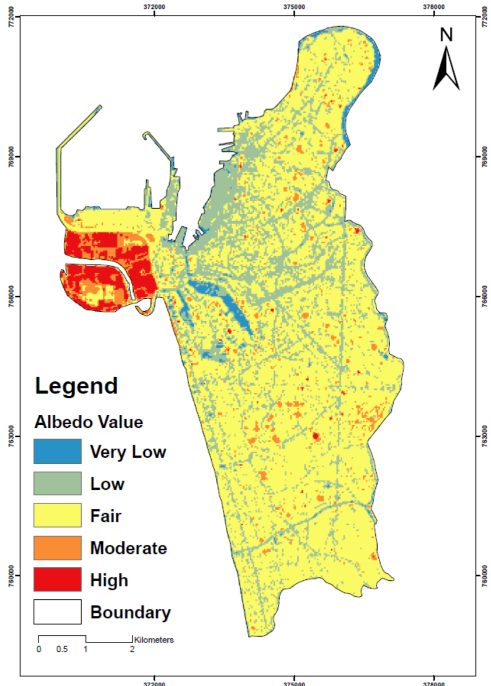


*Figure 7: Albedo map of Colombo city*

### 3.7 Ecological Evaluation of Colombo City

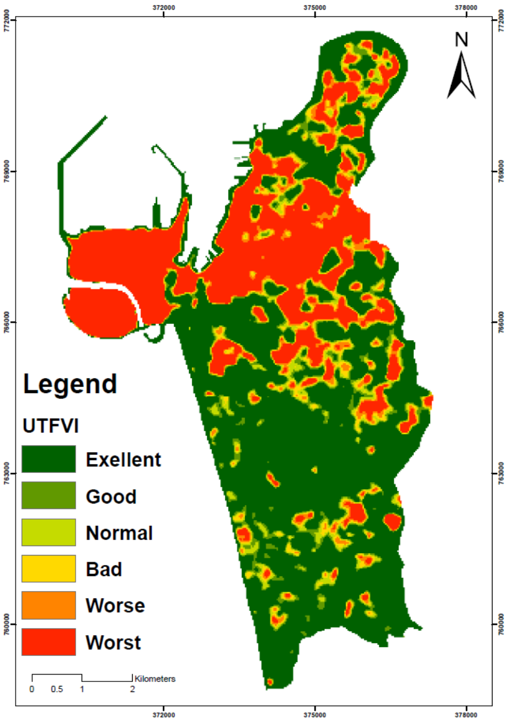


*Figure 8: UTFVI Map of Colombo City*

The quantitative ecological evaluation of UHI effect in Colombo city is shown in the Figure 8. Generally Urban Thermal Field Variance Index is a measurement of the urban ecological quality of life in terms of the degree of thermal comfort with respect to the UHI effect. According to Figure 8 the Colombo city mainly experienced two extremes such as areas with healthy microclimate (53.85%) and areas with worst heat stress (27.50%).

## 4. Conclusions

We have found that LULC patterns ware significantly changed during 2001 – 2019 due to rapid urbanization of the city. 2019 it has been expanded into Western, Eastern, Northern, Central and some part of the Southern regions. Correlation analysis revealed that vegetation cover can reduce the effect of UHI while the built-up area can strengthen UHI effect. Low albedo materials can accelerate UHI phenomenon due to high absorption of heat. According to UTFVI, Colombo city experiences both extreme conditions of thermal comfort 53.85% of the area experiences optimal thermal conditions while 27.50% of that experiences worst conditions indicating that the need of well-designed urban planning system and UHI mitigation strategies. As some of the mitigation measures, use of cool roofs, pervious pavements and more tree plantation near urban communities can be recommended.

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