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Determination of urban heat island phenomena in a small-scale city, based on Landsat 8 data; a case study of Gampola urban area, Sri Lanka

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Abstract

Urban areas generally reflect less and absorb more of the sun's energy due to the surface materials of the urban settings. This absorbed heat increases surface temperatures and contributes to the formation of atmospheric and surface urban heat islands (UHI). Atmospheric UHI can measure, based on air temperature, and surface UHI can calculate based on land surface temperature (LST). High (LST) is normally found within the urban heat islands and therefore, variations of high LST can be used to determine the UHI phenomena of an urban area. Remote sensing (RS) data like Landsat 8 images and geographic information system (GIS) techniques can be used to determine and understand the relationship between LST and urban landscape composition and pattern**.** The normalized difference vegetation index (NDVI), normalized difference built-up index (NDBI) and urban thermal field variance index (UTFVI) are among the most commonly used landscape indices for examining the spatial and temporal variations of LST. Therefore, in this research, those indicators have been used to determine the LST of the research area. Various studies have been conducted to identify the UHI situation in Sri Lanka. However, most of these studies have focused on either Colombo metro area or Kandy city area. Since small cities are also generating UHI, Gampola has been selected as the research area and this study examines the relationship between LST and some important landscape variables such as NDVI, NDBI and UTFVI and the possibility of occurrence of UHI in Gampola urban area. According to the study, strong evidences have been identified to prove the existence of the UHI within the Gampola city.

Key words: *Urban Heat Islands (UHI), Land Surface Temperature (LST), Landsat 8, Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), Urban Thermal Field Variance Index (UTFVI)*

1. Introduction

Many urban and suburban areas experience elevated temperatures compared to their outlying rural surroundings; this difference in temperature is what constitutes an urban heat island (UHI)(Oke,1997). The UHI, a phenomenon of the higher atmospheric and surface temperature of urban and suburban areas occurring compared to rural surroundings, was first described in 1818**(**Howard,1818).

One major environmental problem caused by a rapid and a not well-planned urbanization is the decrease of vegetation cover in urban regions due to the expansions of impervious surfaces such as building, parking lots, pavements and other constructions. Impervious surfaces consist of artificial structures that are covered by impenetrable materials such as asphalt, concrete, brick, stone, and rooftops (Estoque et al., 2017). These buildings, roads, and other infrastructure replace open land and vegetation. Surfaces that were once permeable and moist generally become impermeable and dry (USEPA,2008).

Urban areas typically have surface materials, which have a lower albedo than those in rural settings. As a result, built up communities generally reflect less and absorb more of the sun's energy. This absorbed heat increases surface temperatures and contributes to the formation of surface and atmospheric urban heat islands (Estoque et al., 2017). Except these agents, evapotranspiration, and increased anthropogenic heat production also caused to generate the urban heat island (UHI) (Stone et al., 2010).

With this process and reradiating the trapped heat in the night time (Arsiso et al., 2018), the mean annual air temperature of a city with one million people or more can be 1–3 ºC warmer than its surroundings in the daytime, and, on a clear, calm night, the temperature difference can be as much 12 ºC (Oke,1973). Even smaller cities and towns will produce heat islands, though the effect often decreases as city size decreases (Oke,1982).

The heat island effect arises due to the changing nature of our cities, and is the result of a reduction in vegetation and evapotranspiration, a higher prevalence of dark surfaces with low albedo, and increased anthropogenic heat production (Stone, Hess and Frumkin2010).

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The UHI can be classified into two categories: (i) atmospheric UHI, which is measured based on air temperature, and (ii) surface UHI (SUHI), which is calculated based on land-surface temperature (LST) **(**Estoque et al., 2017). Land surface temperature (LST) is a fundamental variable controlling the surface energy balance, and it is involved in physical, chemical, and biological processes of the Earth surface (Oke,1982).

Surface urban heat islands are typically present day and night, but tend to be strongest during the day when the sun is shining (Estoque et al., 2017). High LST is normally found within the urban heat islands and specifically, within the urban hot spots (UHS) **(**Subhanilet al., 2018).

Studying the UHI based on air temperature is a challenging task due to the lack of ground-level data, especially in developing countries (Oba,2017). Many studies have estimated the relative warmth of cities by measuring the air temperature, using land-based observation stations. This method can be both expensive and time consuming and lead to problems in spatial interpolation (Mallick et al., 2008).

Many of the previous studies have also shown the usefulness of using remote sensing and geographic information systems (GIS) techniques to understand the relationship between LST and urban landscape composition and pattern (Ranagalage et al., 2017).

Remote sensing might be a better alternative to the aforesaid methods. The advantages of using remotely sensed data are the availability of high resolution, consistent and repetitive coverage and capability of measurements of earth surface conditions (Owen et al., 1998).

When comes to remote sensing data, Landsat data has free access and it has various bands for different applications. Landsat 8 (formerly the Landsat Data Continuity Mission - LDCM) was launched in 2013. Combined with other Landsat series, it provides continuity with the more than 40-year-long Landsat land imaging data set (Wulderet al., 2016). The thermal infrared sensor (TIRS) with two thermal infrared channels was added to the Landsat 8 payload to support the detection of the urban heat island and there are many algorithms to retrieve the LST from Landsat 8 data (Meng et al., 2019).

The normalized difference vegetation index (NDVI) and the normalized difference built-up index (NDBI) are among the most commonly used landscape indices for examining the spatial and temporal variations of LST. (Kumar & Shekhar,2015)**.** Except those indexes, some researchers have used urban thermal field variance index (UTFVI), since it is important to determining the ecological comfort level of a city is a very important task (Subhanilet al., 2018).

Various studies have been conducted to identify the UHI situation in Sri Lanka. However, most of these studies have focused on either Colombo metro area (Manawadu&Liyanage,2008) (Ranagalage et al., 2017) (Samanmali & Siriwardane,2015) (Senanayake et al., 2013) or Kandy city area (Dissanayake et al., 2019).

Sri Lanka is an Island nation with limited land resources. Even though, Sri Lanka ranks as the fifth least urbanized during the period 1995-2017, urban area grew by 6.42 % year, which is a remarkably high figure even by global standards**(**http://unhabitat.lk/news**).** Since small cities are also generating UHI, (Oke,1982) as a developing country with limited land resources, it is very important to study the UHI situation in other urban areas in Sri Lanka also.

In this research, it is expected to find any evidence of UHI phenomenon in small scale urban area. Gampola has been selected as the research area and moreover, this study examines the relationship between LST and some important landscape variables such as NDVI, NDBI and UTFVI.

2. Materials and Methods

2.1 Study area

Gampola city, which is located within the Kandy district, central province of Sri Lanka and stands 300 – 500 m in altitude, has been selected as the study area. It is one of Municipal and urban area in Kandy district and according to the population and housing census, 2012. population of the Gampola urban area was 37871 (DCS,2012).

Geographically, this region belongs to the highland complex of Sri Lanka. Mean annual rainfall is in between 3000 – 3500 mm and mean annual temperature is in between 20-25°C (SDSL,2007).

Historically, Gampola was an important city since it was a capital city of the Sri Lanka, in between 1314-1415 AD.

This particular topography features led to the selection of the Gampola urban area as the study area of this study.

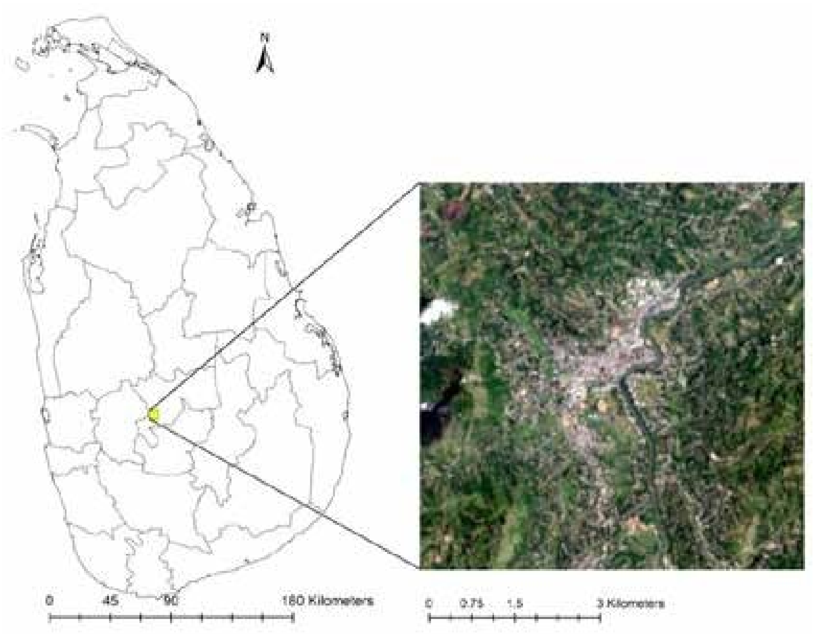

Figure 1. Location of the study area study area

In the study, a geographical grid was selected as a study area which bounded by 7°7’52.32” N to 7°11’34.15” N latitude and 80°36’4.68” E and 80°36’4.50” E longitude from the eastern side while 7°7’51.97” N to 7°11’33.96” N latitude and 80°32’25.30” E and 80°32’25.03” E longitude from the western side, while extend of the area is 46 km^2. Whole Gampola city was comprised into that grid (Figure 1).

2.2. Data set and data processing

For this study, Landsat Level 1(Landsat 8 OLI/TIRS C1 level-1) data provided by the United States Geological Survey (USGS) were used. For the Landsat-8 OLI/TIRS data, the multispectral bands (bands 1–7 and 9) also have 30 m spatial resolution. Its panchromatic band (band 8) has 15 m spatial resolution, while its thermal bands (band 10 and 11) have 100 m spatial resolution, which have also been re-sampled to 30 m by the USGS (https://landsat.usgs.gov).

In the data selection stage, daytime dry-season data, cloud-free images (< 10%), and pre-geo referenced by using Universal Transverse Mercator (UTM) zone 44 north projection data have been extracted.

Table 1. Key metadata of the Landsat image used

Sensor	Scene ID	Acquisition date	Time (GMT)	Season	Cloud cover (%)
Landsat-8 OLI/TIRS	LC81410552019083LGN00	24-03-2019	04:53:29	Dry	8.23

2.3 Retrieving LST from Landsat thermal band

As first step, TOA (Top of atmospheric) spectral radiance was calculated using below equation (1) (Artis & Carnahan,1982).

$$TOA(L) = M_L \times Q_{cal} + A_L \quad (1)$$

Where, M_L is Band specific multiplicative rescaling factor from the metadata and Q_{cal} Corresponds to band 10. In addition, A_L is band specific rescaling factor from the metadata.

Then TOA to brightness temperature conversation has been calculated using the following equation. (2) In the same step, to obtain results in Celsius (°C), the radiant temperature was adjusted by adding the absolute zero temperature which is -273.15°C.

$$BT = \left(\frac{K_2}{\ln\left(\frac{K_1}{L}\right)+1}\right) - 273.15 \quad (2)$$

Where, K_1 and K_2 are calibration constants. For Landsat 8 K_1 value is 774.8853 and K_2 value is 1321.0789.

Once the brightness temperature conversation calculated, to retrieve the LST values, the land surface emissivity (ε) values Equation (3) (Sobrinoet al., 2004) has been derived.

$$\varepsilon = m\,PV + n \quad (3)$$

Where m = (ε − ε) − (1 − εσ) Fεv and n = εs + (1 − εs) εs and εv are the soil emissivity and vegetation emissivity, respectively. For this study, m and n value has taken 0.004 and 0.986 respectively (Sobrinoet al., 2004). PV is the proportion of vegetation, (4) extracted from the NDVI Equation (6).

$$PV = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2 \quad (4)$$

Where NDVI is the normalized difference vegetation index derived in Equation (4). The $NDVI_{min}$ and $NDVI_{max}$ are the minimum and maximum values of the NDVI, respectively. The emissivity-corrected LST values were then retrieved using Equation (5) **(**Ranagalage et al., 2017).

$$LST = \frac{TB}{1} + (\lambda \times \frac{TB}{\rho})\ln\varepsilon \qquad (5)$$

Where TB = Landsat 8 Band 10 (adjusted by the equation (1) and (2)); λ = wavelength of emitted radiance (λ = 10.8 μm for Landsat TIRS Band 10); ρ = h × c/σ(1.438 × 10 – 2 mK), σ = Boltzmann constant (1.38 × 10 − 23 J/K), h = Planck's constant (6.626 × 10 − 34 Js),c = velocity of light (2.998 × 108 m/s), ε is the land surface emissivity **(**Ranagalage et al., 2017).

2.4. Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-Up Index (NDBI)

The NDVI is a major indicator of urban climate and its values range from −1 to 1, with positive values representing vegetated areas and negative values representing non-vegetated areas (Zhang et al.,2009). The NDVI is derived by using the surface reflectance of the red band (band 4 in OLI of Landsat 8) and the surface reflectance of the near-infrared band (band 5 in OLI of Landsat 8) Equation (6) (Estoque et al., 2017).

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (6)$$

Where NIR = band 5 for Landsat 8 OLI; wavelength 0.85–0.88 μm) and RED = band 4 (for Landsat 8 OLI; wavelength 0.64–0.67 μm) (Ranagalage et al., 2017).

The NDBI, is an index for identifying and classifying built-up areas or impervious. The positive values of the NDBI indicate built-up areas and those close to 0 indicate vegetation, while the negative values represent water bodies (Zhang et al.,2003. The NDBI was calculated using below equation (7).

$$NDVI = \frac{MIR - NIR}{MIR + NIR} \qquad (7)$$

Where MIR = band 6 for Landsat 8; wavelength 1.57–1.65 μm and NIR = band 5 (for Landsat 8 OLI—wavelength 0.85–0.88 μm) (Ranagalage et al., 2017).

2.5 Urban thermal field variance index (UTFVI)

A number of thermal comfort indices are available for evaluating the UHI impacts on the quality of urban life (Subhanilet al., 2018). The UTFVI has been used for the ecological evaluation of UHI zones of Gampola city area with UHI. UTFVI has been estimated using the following equation (8) (Zhang,2003).

$$UTFVI = \frac{T_s - T_{mean}}{T_{mean}} \qquad (8)$$

Where T_s is land surface temperature (°C) Tmean is Mean land surface temperature (°C).

2.6 Identification of area with UHI

Areas with UHI phenomena can be determined using the Land surface temperature of the study area and UHI was identified by the range of LST determined by the following equation (9) (Subhanil et al., 2018).

$$LST > \mu + \text{þ}\, 0.5 \times \delta \qquad (9)$$

Where μ and δ are the mean and standard deviation of LST in the study area, respectively.

2.7. Statistical Analysis

Scatter plots were created and a linear regression analysis was performed to determine the relationship between LST and NDVI, between LST and NDBI and between LST and UTFVI. To do this, 500 random points were created. The parameter values of these points were then extracted from the LST, NDVI, and NDBI images.

In addition to these, a temperature profile of the area has been generated in order to examine the distribution of the UHI.

ArcGIS 10.5 and QGIS 3.4.13 were used to do the analysis and MS Excel was used to perform the linear regression.

3. Results

3.1 Land surface temperature (LST)

The LST map of Gampola at 2019 is shown in Figure 2 and the descriptive statistics of the retrieved LST values are summarized in Table 2. On 24th March 2019 (04:53:29 GMT), the LST in Gampola area ranged from 21.71–35.26 °C, with a mean of 28.23 °C.

Higher LST values were found mostly the more urbanized part of the Gampola city and high LST were mostly concentrated along with the main road of the city (Figure 2). This situation can be identified north to south of the city (Bothalapitiya to Jayamalapura along the Gampola urban area) where most of commercial activities and dominant infrastructures of the city such as bus stand and railway station are located (Google map).

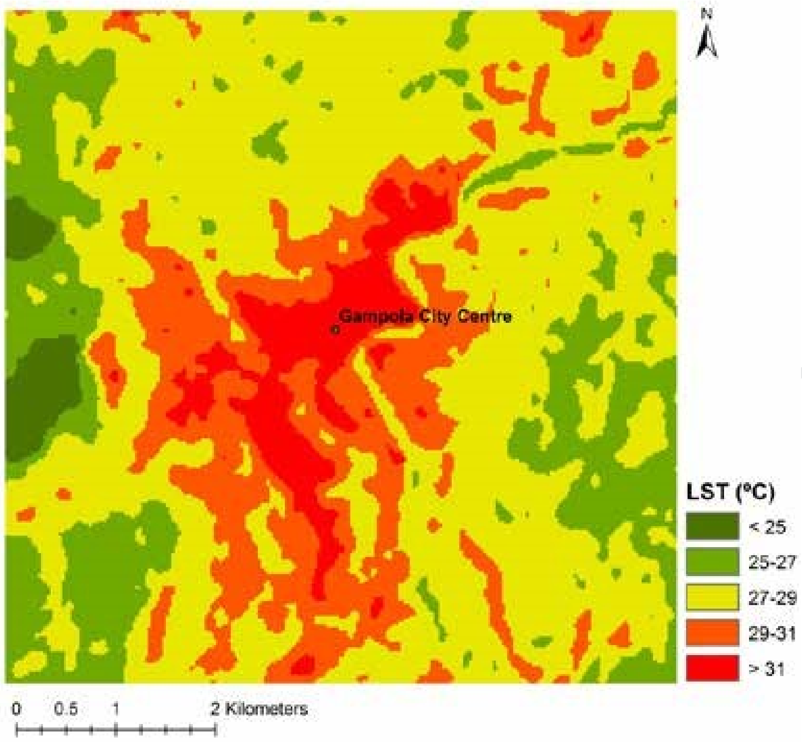

Figure 2.
Land surface temperature (LST) of the study area on 24th March 2019.

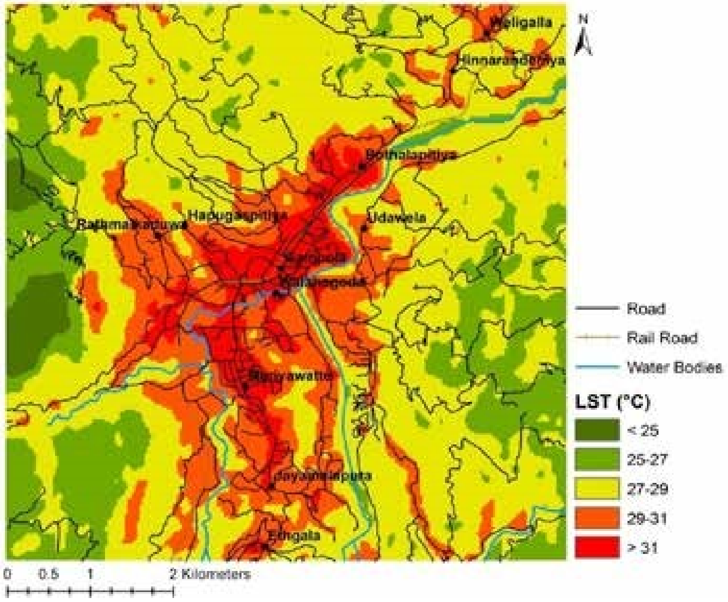

Figure 3.
Land surface temperature (LST) of the study area (with road network and water sources) 24th March 2019

3.2 Normalized Difference Vegetation Index (NDVI)

The NDVI map of Gampola at 2019is shown in Figure 4 and the descriptive statistics of the retrieved NDVI values are summarized in Table 3. On 24th March 2019 (04:53:29 GMT), the NDVI in Gampola area ranged from -0.15 to 0.57, with a mean of 0.39.

Figure 5 shows the scatter plots between NDVI and LST. The regression analysis revealed that LST is negatively correlated with NDVI even though the coefficient of determination (R^2) is 0.262.

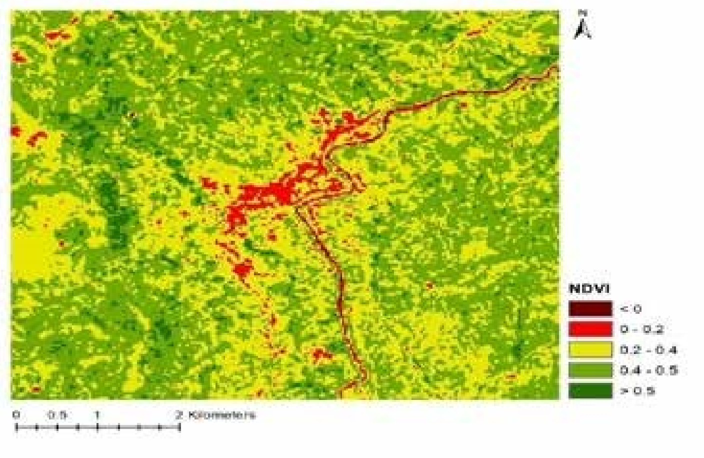

Figure 4.
Normalized Difference Vegetation Index (NDVI) values of study area

24th March 2019

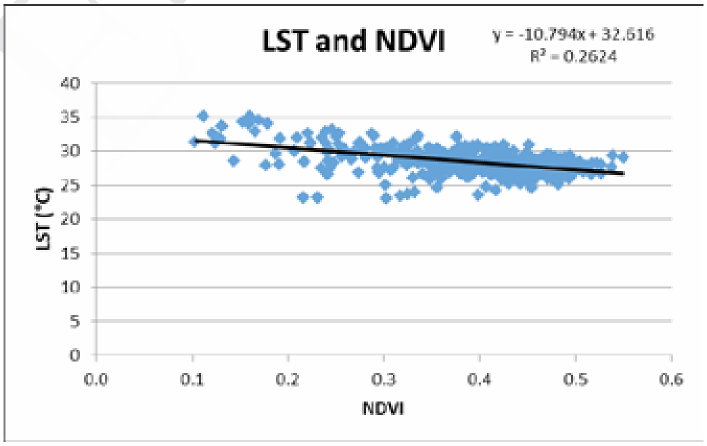

Figure 5.
Relationship between RST and NDVI

3.3 Normalized Difference Built-Up Index (NDBI)

The NDBI map of the Gampola is shown in Figure 6 and their descriptive statistics are summarized in Table 4. The NDBI values ranged from -0.36 to 0.18 in the area. Areas with high NDBI values had greatly distributed from North to South of the city which along with the road network.

The Figure 7 shows the scatter plots between NDBI and LST. When compare with the LST of the area (Figure 2) with the NDBI map, it is clear that those two variables are positively related. Even the scatter plots also indicating a positive linear relationship with R_2 value of 0.327. NDBI has more strong relationship with the LST than the NDVI of the area.

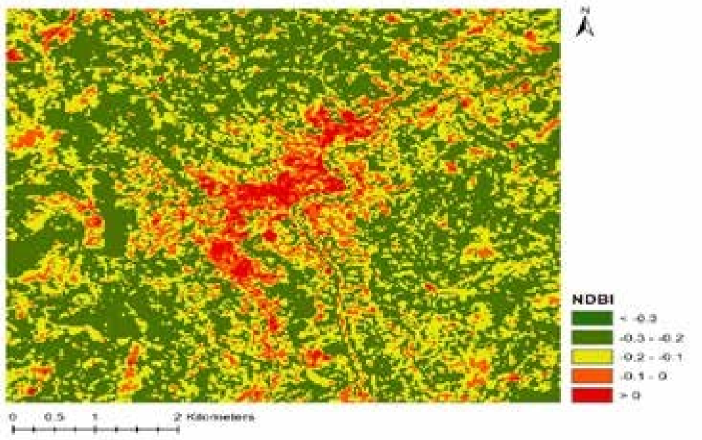

Figure 6.
Normalized Difference Built-Up Index (NDBI) values of study area

24th March 2019

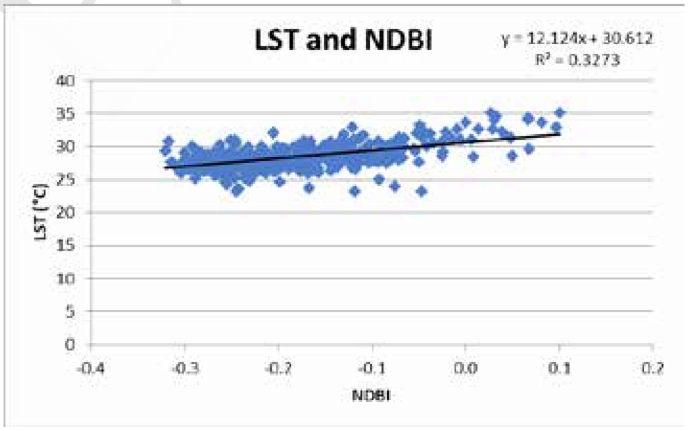

Figure 7.
Relationship between RST and NDBI

3.4 Urban thermal field variance index (UTFVI)

The UTFVI values were divided into six categories according to six different ecological evaluation indices. (Table 5) (Zhang,2003). The UTFVI map of Gampola at 2019 is shown in Figure 8 where areas with high LST has worse ecological evaluation index. There is significant extend of area can be identified in this region, as areas with worst ecological evaluation index.

Table 5. The thresholds of ecological evaluation index.

UTFVI	UHI phenomenon	Ecological evaluation index
< 0.000	None	Excellent
0.000-0.005	Weak	Good
0.005-0.010	Middle	Normal
0.010-0.015	Strong	Bad
0.015-0.020	Stronger	Worse
> 0.020	Strongest	Worst

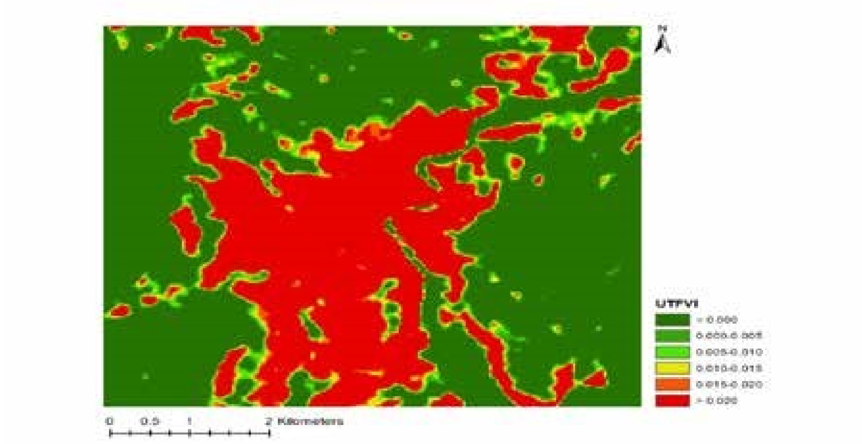

Figure 8.
Urban thermal field variance index (UTFVI) values of study area

24th March 2019

3.5 Urban Heat Island (UHI) situation in the Gampola urban area

Figure 10 shows the distribution of urban heat island phenomena of within the Gampola urban area and figure 11 shows the temperature profile of the study area where can identify the UHI and non UHI areas across the region.

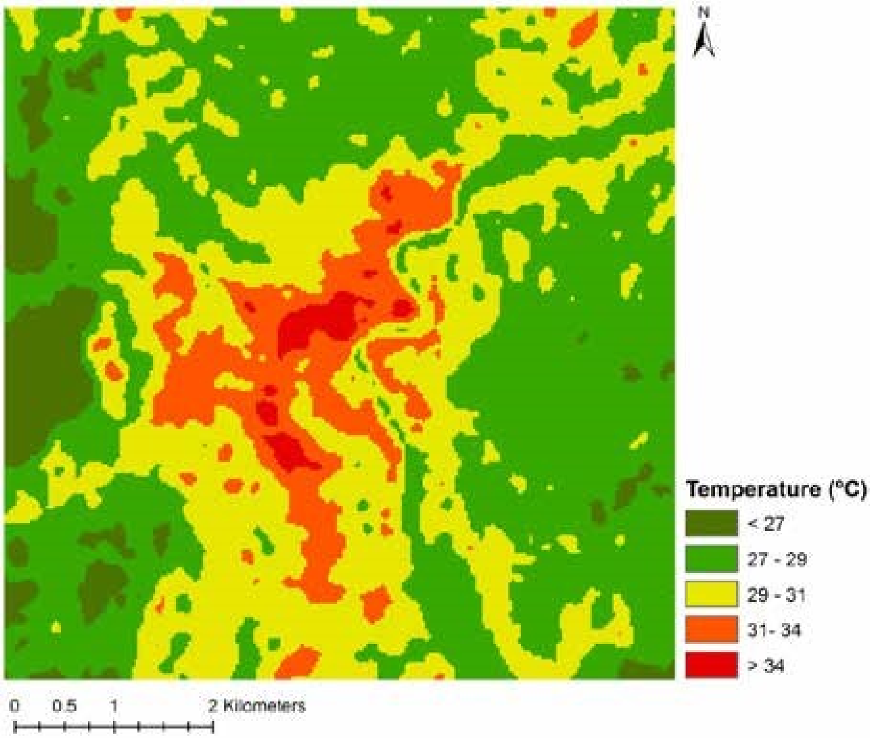

Figure 09.
Distribution of UHI in Gampola urban area

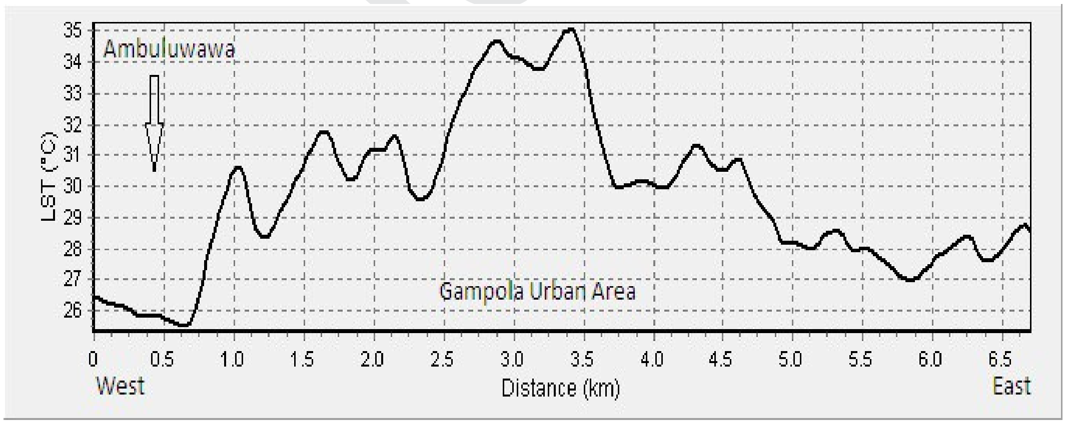

Figure 10.
Temperature profile in Gampola urban area - 24th March2019

In addition to those, extend of areas with different levels of temperature are shown in the Table 06. According to the table 06, area of around 0.99 Km^2 was experiencing temperature which goes more than 34 º C when this image was captured.

Table 6. Extend of areas (in Km^2) with different temperatures - 24th March 2019 (04:53:29 GMT)

Value range (ºC)	**< 27**	**27 – 29**	**30 - 31**	**32 - 33**	**34 >**
Area (Km^2)	1.54	29.59	11.28	2.64	0.99

4. Discussion

In Sri Lanka, Colombo and Kandy urban areas have been examined in terms of the UHI phenomena. Colombo is a coastal city and some studies have indicated that ocean has significant impact on lowering of the LST, which is directly impact with the UHI (Senanayake et al., 2013). Being located in the central high lands, Gampola urban area is placed in different topographic setting than the Colombo city.

However, Kandy urban area is more similar to the Gampola urban area in terms of the climatic conditions and the landscape. Studies have shown that the rapid growth of urbanization is the major cause for the increased UHI situation in the Kandy urban area (Dissanayake et al., 2019).

According to the research results, it is clear that not even in wide spread urban areas like Colombo or Kandy, but also small-scale urban areas can be having UHI situation.

The intensity of UHI may be defined as the difference between the average temperature of UHI and non-UHI) (Subhanil et al., 2018). Gampola urban area is an area with high dense of build-up structures according to the NDBI index (Figure 6). City has spread along with the Peradeniya-Hatton road from North to south with a linier pattern. In addition, NDVI values of the urban area is significantly low (Figure 4) and LST of that area is much greater comparing with the surrounding area (Figure 2 and Figure 11). Ecologically also Gampola urban area is in a worst situation according to the UTFVI values and it also indicating that the city is experiencing UHI for some extend (Figure 8).

According to the satellite data, minimum LST of the area was 21.71 ºC and the Maximum was 35.26 ºC when the satellite image was capturing. Extend of the study area was around 46 Km^2 and even it is a small area, by that time; temperature difference is much greater between the urban center and other suburbs. Around 61.4% from the total land area was experiencing more temperature than the mean temperature (28.23ºC) of the area (Table 6). In addition, when consider about the temperature profile of the area, it is possible to identify considerable temperature incensement within the heart of the city compare with the surrounding area which can be defined as a UHI situation (Figure 11).

Various studies have suggested different mitigation strategies including Enhancing vegetated spaces in urban areas or the concept of the land-use mixture (a mixture of impervious surfaces and green spaces) (Galagoda et al.,2018). Gampola urban area is surrounded by some natural protected areas such as Ambuluwawa. If it is possible to increase the area of dense vegetation within these protected lands, that will be highly effective on reducing the LST within the Gampola urban limits. In addition to that, strategies such as land-use mixture and urban agriculture can be used to reduce the LST in the area and that will be causing to prevent the UHI phenomena in the Gampola urban context.

5. Conclusion

In this study, objective was identifying the UHI phenomena within a small urban area in Sri Lanka with the spatial distribution and the pattern of the LST and Gampola urban area and suburb was selected as the study area.

According to the study, strong evidences have been identified to prove the existence of the UHI even within small-scale urban areas also.

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