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Monitoring the Impacts of Urbanisation on Environmental Sustainability Using Geospatial Techniques: A Case Study in Colombo District, Sri Lanka

Subasinghe, S.^{*a}, Nianthi, R.^a, Rajapaksha, G.^b, Gamage, I.^c

^a Department of Geography, University of Peradeniya, Peradeniya 20400, Sri Lanka

^b Postgraduate Institute of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka.

^c Graduate School of Humanities and Social Sciences, University of Tsukuba, 111 Tennodai, Japan

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ABSTRACT

In recent years, a critical understanding of the sustainable urban environment has become central to many urban studies, leading numerous scholars to employ geospatial tools and techniques to examine the sustainability of growing cities in the developing world. In this study, the Colombo district where the capital city of Sri Lanka is located, was selected with the prospect of monitoring the impacts of urbanization on environmental sustainability. The study uses the spectral indices of remote sensing, including the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-Up Index (NDBI), Land Surface Temperature (LST), and Environmental Criticality Index (ECI) to detect the aspects of urbanization and environmental sustainability of the study area. The results show that there has been a dramatic increase in environment criticality from 1997 to 2008, and a slight decrease indicated from 2008 to 2017, coinciding with the government urban planning initiatives. However, the decline of environmental sustainability of the city center and along the transport corridors could be identified in the context of this study. Finally, by drawing attention of the landscape and land use planners, the study emphasizes the aspects that should be considered in future urban planning.

1 Introduction

Urbanization is a spatial and demographic process that refers to people and buildings' concentration in an area known as a city (Clark, 1982; Scott and Storper, 2015; Thapa and Murayama, 2011). The recent statistics indicate the arrival of a tremendous wave of urban growth in history, making cities the key nexus in the people and nature relationship (Estoque and Murayama, 2015; UN, 2018). In 2018, urban centers were hosting over 55% of the global population, and nearly 70% of the world's population is projected to live in urbanized cities in 2050 (United Nations, 2018). The continuous growth in the number and size of urban areas has created many challenges in maintaining human welfare in the cities, while preserving the natural environment, both locally and globally (Haase et al., 2014; Subasinghe et al., 2016).

Unsustainably planned urbanization processes can lead to

negative socio-economic and environmental consequences (e.g. low quality of life, environmental degradation, and unsatisfactory level of water and air quality) (Dahiya, 2012; Estoque and Murayama, 2015). Of all human activities, urbanization is considered to create the most evident impacts on the earth, in terms of greenhouse gas emissions and land-use changes, which directly leads to temperature rise in urban areas than surrounding suburban or rural areas, creating a plethora of challenges on the sustainability of urban environment (Estoque and Murayama, 2017; Ranagalage et al., 2017; Wang et al., 2018).

Most recent studies have extensively employed remote sensing technology in capturing the spatial patterns of urbanization and its impacts on the environment (Ayanlade and Howard, 2019; Estoque and Murayama, 2017; Estoque et al., 2017; Madanian et al., 2018; Wang et al., 2018; Zhang et al., 2017). Notably, the advances in remote sensing technology such as cost-effectiveness with broad area coverage, easy collection of data over various scales, convenience in processing and analysis, etc., have encouraged its usage in environmental analytics (GrindGIS, 2016). The indices developed through remote sensing technology provide a wide range of information to understand the different environmental conditions on the earth's surface (Chen et al., 2006; Estoque and Murayama,

* Corresponding author: S. Subasinghe, Department of Geography, University of Peradeniya, Peradeniya 20400, Sri Lanka.

E-mail address: shyamgeo@pdn.ac.lk, subasinghepgia@gmail.com (S. Subasinghe).

2015; Guha *et al.*, 2018; Ranagalage *et al.*, 2017). Normalized Difference Vegetation Index (NDVI), Normalized Difference Buildup Index (NDBI), and Normalized Difference Water Index (NDWI) are the most commonly used and well-developed indices used in land surface characteristics analyses (Sekertekin and Zadbagher, 2021; Zhang *et al.*, 2009). Later, by improving and combining these indices, several secondary indices such as modified Normalized Different Vegetation Index (mNDVI), modified Normalized Difference Buildup Index (mNDBI), and modified Normalized Different Water Index (mNDWI), etc. have been developed in the field of remote sensing (Bhatti and Tripathi, 2014; Xu, 2008). These indices can be employed to interpret the landscape's characteristics in a specific area (Estoque and Murayama, 2015; Ranagalage *et al.*, 2017; Zhang *et al.*, 2018). NDVI, NDBI, and NDWI are primarily used to determine the vegetation, water bodies, and the built-up area in a selected land surface, respectively (Macarof and Statescu, 2017). Although these are their primary usages, these indices could be developed to understand the landscape composition comprehensively (Estoque and Murayama, 2015; Ranagalage *et al.*, 2017).

Among the remote sensing satellite data, the Landsat images are the most commonly used and reliable imagery tools that have provided the longest temporal records about the earth's surface (Huang *et al.*, 2016). Many studies employed the Landsat images in land surface temperature (LST) calculation, which is one of the essential parameters in climate change, evapotranspiration, urban climate, vegetation monitoring, and other thermal analyses (Ibrahim and Rasul, 2017; Li *et al.*, 2013). The knowledge of LST is useful to examine how human activities alter the natural environment (Estoque *et al.*, 2017). It is an accepted fact that the decrease in green spaces and the increase of human-made surfaces increase the LST in any area (Estoque and Murayama, 2015; Ranagalage *et al.*, 2017). A positive difference in LST between an urban environment and a rural area is called the Urban Heat Island (UHI) (Estoque *et al.*, 2017; Ranagalage *et al.*, 2017; Zhang *et al.*, 2017). The UHI effects have been attributed to having negative impacts on cities' environmental sustainability (Chen *et al.*, 2006; Guha *et al.*, 2018; Mallick *et al.*, 2013).

Spatial sciences play a key role in the strengthening of environmental sustainability (Alshuwaikhat and Aina, 2006). The increasing number of studies have brought the application of spatial technologies as a part of spatial sciences to the forefront of sustainability-related studies (Senanayake *et al.*, 2013; Xu and Coors, 2012). Environmental sustainability in cities requires achieving a balance in environmental protection, economic development, and urban society's social well-being (Riffat *et al.*, 2016). Urbanized communities change their living style environment through their land, water, and energy consumption. In turn, the balance of the living atmosphere has been negatively affected, leading to problems in the urban population's health and quality of life (PRB, 2004). In such a context, detecting the urban environment's criticality spatiotemporally is essential to address urban sustainability-related issues (Sasmito and Suprayogi, 2018;

Senanayake *et al.*, 2013). Previous studies have shown that the Environmental Criticality Index (ECI) is an efficient method in determining an urban environment's criticality spatiotemporally (Ranagalage *et al.*, 2017; Senanayake *et al.*, 2013). Characterizing the environment's criticality through urban-rural gradient provides a comprehensive indication of how the sustainability of urban areas varies spatially through an urban landscape (Ranagalage *et al.*, 2017).

Colombo district of Sri Lanka – the country's capital city, shows a mixture of urban and rural land-use patterns (Divigalpitiya *et al.*, 2007; Subasinghe *et al.*, 2016). During the past two decades, the Colombo district has developed as the country's cradle of power, which accounted for more than 80% of its industrial outputs and about 50% of its Gross Domestic Product (GDP) (Emmanuel, 2005; Subasinghe *et al.*, 2016). As a result, the entire Colombo district experiences several challenges in balancing its rapid urban development and protecting its environmental sustainability. However, limited studies have addressed the environmental sustainability of Colombo city and its surrounding under the land-use changes due to urbanization (Senanayake *et al.*, 2013; Subasinghe *et al.*, 2016). Hence, the main objective of this study is to monitor the impact of urban land use changes on the environmental sustainability of the Colombo district using geospatial tools and techniques. The study employs remotely sensed data and various geospatial approaches, including urban-rural gradient, LST, and spectral indices to achieve its objective. In our discussion, the policy changes that could be taken to reduce the environmental stress are heightened based on the finding of this study.

2 Study Area, Methodology, and Index Mapping

2.1 Study Area

Sri Lanka is a tropical island nation in South Asia with ~ 65,610 km² of land area, ~ 21 million population, and 25 administrative districts (DCS, 2012; Sangakkara and Frossard, 2016). The Colombo district (Fig. 1), is the administrative, industrial, and commercial hub of Sri Lanka, located on the west coast of the country facing the Indian Ocean, containing all government and private sectors' headquarters. The most recent census report (2012) indicates that the Colombo district's total population is 2.3 million (DCS, 2012; Subasinghe *et al.*, 2021). It occupies an approximate area of 700 km² in flat terrain situated in coastal plains topographically. The landscape of the district is a mosaic of urban and rural land usage patterns (Divigalpitiya *et al.*, 2007; Subasinghe *et al.*, 2016). The district's urban core, Colombo city, the country's commercial capital, has been expanding towards the inland rapidly in all directions.

Historical unplanned urbanization and current rapid urban and population growth can be seen throughout the district, particularly the Colombo city area's environmental sustainability is being challenged by various ongoing and forthcoming developments. As the hub of the country's prosperity, the Colombo district, and its heart, Colombo city

Fig. 1: (a) Map of South Asia showing the location of the Study area; (b) Colombo district and its immediate surrounding districts; (c) Landsat images used in this study displayed in a false-color composite.

has been focused on multiple economic, industrial, and social development initiatives (Van Horen, 2002). Among them, infrastructure developments such as highways, residential and commercial constructions are dominant in the district, threatening its livable atmosphere (Subasinghe *et al.*, 2016).

Climatically, the average annual air temperature for the year is about 28 °C and the average annual rainfall is about 2,230 mm (Herath *et al.*, 2016). The average temperature of the warmest month, April, is 29°C (Climate-data.org). The coolest month is January, with an average temperature of 27 °C (Climate-data.org; Ranagalage *et al.*, 2017). The month with the highest precipitation on average is October with 353 mm of rainfall, while the least rainfall on average is in February at an average of 63 mm (Climate-data.org; Subasinghe *et al.*, 2021).

2.2 Data

We used Landsat-5 images captured on 7 February 1997 and 4 November 2008, and Landsat-8 image captured on 13 January 2017 (Table 1). The Landsat data sets were downloaded through United States Geological Survey (USGS) Earth Explorer website (<https://earthexplorer.usgs.gov/>). According to the USGS

description, the spatial resolution of the multispectral bands of Landsat-5 TM data is 30 m and the spatial resolution of its Thermal band (band 6) is 120 m. Due to this reason, we resampled the thermal band of Landsat-5 into a 30 m spatial resolution. The spatial resolution in multispectral bands of Landsat-8 data is also 30 m. Its panchromatic band (band 8) has a 15 m spatial resolution and thermal bands (band 10 and 11) have 100 m spatial resolution. Due to the difference in spatial resolution, we resampled the thermal band of Landsat-8 into a 30 m spatial resolution.

Table 1: Description of Landsat images acquired.

Sensor	Acquisition Date	Time (GMT)	Season
Landsat-5 TM	7 February 1997	04:18:38	Dry
Landsat-5 TM	4 November 2008	04:37:19	Dry
Landsat-8 OLI/TIRS	13 January 2017	04:54:05	Dry

2.3 Index Mapping

The indices such as NDVI, NDBI, and NDWI are widely used in the studies which focus on the urban land use mapping and LST calculations (Estoque and Murayama, 2017; Macarof and Statescu, 2017; Ranagalage et al., 2017; Guha et al., 2018).

2.3.1 Normalized Difference Vegetation Index (NDVI)

The difference between near-infrared (NIR) (with strongly reflecting vegetation) and red light (with absorbing vegetation) is used in NDVI calculations, which indicate the nature of vegetation (Eq. 1) (Ranagalage et al., 2017; Zhang et al., 2017). Accurate assessment of vegetation cover is essential in the measurement of sustainability in cities (Chen et al., 2021). In the NDVI image, negative or close to zero values usually indicate the water bodies, and low positive values are associated with bare soil, while larger positive values indicate vegetation (Albarakat and Lakshmi, 2019).

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \quad (1)$$

where;

ρ_{nir} = band 4 (for Landsat TM – wavelength 0.76–0.90 μm) and band 5 (for Landsat OLI – wavelength 0.85–0.88 μm) and

ρ_{red} = band 3 (for Landsat TM – wavelength 0.63–0.69 μm) and band 4 (for Landsat OLI – wavelength 0.64–0.67 μm).

2.3.2 Normalized Difference Built-Up Index (NDBI)

The difference between mid-infrared (MIR) and NIR used in NDBI calculation, is one of the commonly used indices for analysis of urban pattern or built-up area (Eq.2) (Estoque and Murayama, 2015; Guha et al., 2018; Macarof and Statescu, 2017). In NDBI image, negative values usually indicate the water bodies, and zero values indicate the vegetation, and positive values indicate the built-up. The concentration of built-up features such as buildings, roads, and runaways by exceeding the carrying capacity of landscape, negatively impacts to the sustainability of the cities (Dissanayake et al., 2019). These also retain a higher level of heat, which alleviates computability and environmental balance in the urban areas (Smith and Levermore, 2008).

$$NDBI = \frac{\rho_{swir} - \rho_{nir}}{\rho_{swir} + \rho_{nir}} \quad (2)$$

where ρ_{swir} = Band 5 (for Landsat-5 TM) and Band 6 (for Landsat 8) and ρ_{nir} = Band 4 (for Landsat TM) and Band 5 (for Landsat 8) (Kikon et al., 2016).

In this study, we used mNDWI to identify the water bodies. The threshold values of water bodies were manually calibrated using ancillary data.

2.3.3 Modified Normalized Different Vegetation Index (mNDVI),

We used mNDWI to detect the water bodies of the area. The mNDWI was calculated using (Eq. 3).

$$mNDVI = \frac{\rho_{green} - \rho_{swir1}}{\rho_{green} + \rho_{swir1}} \quad (3)$$

where

ρ_{green} = Band 2 (for Landsat-5 TM – wavelength 0.52–0.60 μm) and Band 6 (for Landsat 8 – wavelength 0.53–0.59 μm) and ρ_{swir1} = Band 5 (for Landsat TM – wavelength 1.55–1.75 μm) and Band 5 (for Landsat 8 – wavelength 1.57–1.65 μm).

2.3.4 Land Surface Temperature (LST) Retrieval

The retrieval of LST is essential in determining environmental sustainability (Ranagalage et al., 2017; Zhang et al., 2017). As a standard method of retrieving LST, we convert raw Landsat images' digital values to radiance values (Chander et al., 2009; Estoque et al., 2017; Zhang et al., 2018). Subsequently, the radiance values were converted into satellite brightness temperature. The resampled thermal bands, which contain satellite brightness temperatures expressed in degrees Kelvin, were used to derive the land surface emissivity (ε) value (Eq.4).

$$\varepsilon = mP_v + n \quad (4)$$

where $m = (\varepsilon_v - \varepsilon_s) - (1 - \varepsilon_s) F\varepsilon_v$ and $n = \varepsilon_s + (1 - \varepsilon_s) F\varepsilon_v$, where ε_s and ε_v are the soil emissivity and vegetation emissivity, respectively. In this study, we used $m = 0.004$ and $n = 0.986$ according to Sobrino et al. (2004). The proportion of vegetation (P_v) was derived from NDVI (Eq. 5).

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

where NDVI is the Normalized Difference Vegetation Index (Eq.1). We used the minimum ($NDVI_{min}$) and maximum ($NDVI_{max}$) values of the NDVI in calculating P_v . Once the emissivity images were derived for each year, the emissivity-corrected LST values were retrieved (Eq. 6) (Artis and Carnahan, 1982; Weng et al., 2004).

$$LST = T_B / 1 + (\lambda \times T_B / \sigma) \ln \varepsilon \quad (6)$$

where T_B = at-satellite brightness temperature in degrees Kelvin; λ = wavelength of emitted radiance ($\lambda = 11.5$) μm for Landsat-5 TM band 6, and 10.8 μm for Landsat-8 OLI/TIRS band 10;

$\rho = h \times c / \sigma$ (1.438 $\times 10^{-2}$ mK), σ = Boltzmann constant (1.38 $\times 10^{-23}$ J/K), h = Planck's constant (6.636 $\times 10^{-34}$ Js), c = velocity of light (2.998 $\times 10^8$ m/s), ε is the land surface emissivity (Sobrino et al., 2004). The retrieved LST values were converted from Kelvin to degrees Celsius ($^{\circ}\text{C}$).

2.4 Environment Criticality Index (ECI)

To identify the environmentally critical areas, we derived the ECI for each time point. The ECI is the ratio between LST and NDVI (Eq. 7) (Ranagalage et al., 2017; Senanayake et al., 2013).

$$ECI_{(LST-Veg)} = \left(\frac{LST_{stretched\ 1-255}}{NDVI_{stretched\ 1-255}} \right) \quad (7)$$

where $ECI_{(LST-Veg)}$ Environmental Criticality Index is based on LST and availability of vegetation cover; $LST_{stretched\ 1-255}$ and $NDVI_{stretched\ 1-255}$ are stretched values of LST and NDVI. We used the histogram equalization method in standardizing the LST values and NDVI values. In calculating the ECI, the water bodies which were derived by the mNDWI were excluded.

2.5 Urban-rural Gradient Analysis

The concept of "Urban" is fuzzy and inconstant (Subasinghe et al., 2021; Taubenböck et al., 2012; Zhang et al., 2014). One country can define urbanity based only on built infrastructure (e.g. the existence of paved streets or water supply systems), while another may define urbanity by population density, livelihoods (e.g. percentage of agricultural workers), economic characteristics, administrative function (for example regional districts or capitals), and/or administrative limits (Christenson et al., 2014). A sizable number of remote sensing studies have used built-up land use derived from NDBI to identify the urban areas (Hegazy and Kaloop, 2015; Moghadam and Helbich, 2013). The concept of gradient is commonly applied in landscape ecology (Boone et al., 2012; Bunting et al., 2002; Subasinghe et al., 2016). In this study, we performed the gradient analysis to identify the urban-rural gradient of LST, built-up (derived using NDBI), and the environmentally critical areas (ECI) for each time point (1997, 2008, and 2017). The multiple ring buffers were

created from the city center with a distance interval of 2,000 m (2 km). The changes of these average values were compared with the gradient distance to the city center. The city center of Colombo district was defined encircling the Fort Clock tower at the base near the president's house—the zero-road distance point (6° 56' 5" N, 79° 50' 34" E). Literature revealed that a city center is defined using a landmark place of a city by representing the highest urban concentration (Wang, 2006).

2.6 Linear Regression Analysis

LST's relationships with NDVI and NDBI were analyzed by fitting a simple linear regression (SLR) equation. For the analysis, 500 sample points were randomly created, and then the LST, NDVI, and NDBI values were extracted corresponding to the random points to calculate the SLR.

3 Results

3.1 Spectral Indices

In Fig. 2, we present the maps of NDVI and NDBI for 1997, 2008, and 2017. The NDVI values ranged from -1.00 to 0.84 in 1997, -0.34 to 0.78 in 2008, and -0.32 to 0.77 in 2017. The mNDVI was used only for the exclusion of water bodies in the ECI calculation process.

In order to interpret the NDVI results, the classification developed by Zaitunah et al. (2018) has been used. According to the Zaitunah et al. (2018), NDVI values < 0 = non-vegetation; 0-0.15 = lowest dense; 0.15-0.3 = lower dense; 0.3-0.45 = dense; 0.45-0.6 = higher dense; >0.6 = highest dense. The NDVI values of non-vegetation mainly represent the water bodies, while lowest dense, lower dense of vegetation represent the urban and urban-mixed landscape, where they are mainly accumulated in the western part of the study area.

Fig. 2: NDVI (top) and NDBI (bottom) maps of Colombo district in, left to right, 1997, 2008, and 2017.

Fig. 3: LST maps of Colombo district in, left to right, 1997, 2008, and 2017(bottom).

Additionally, the dense, higher dense, and highest dense vegetation is mainly distributed in the eastern side of the area in all the time points.

NDBI values further strengthen the results derived by NDVI. The NDBI values ranged from -1.00 to 0.42 in 1997, -1.00 to 0.51 in 2008 and -0.72 to 0.63 in 2017. The high NDBI value indicates urban and mixed-urban landscapes. It shows the spatial diffusion of urbanization from the western part where the center of Colombo city is situated, to the eastern part of the Colombo district. It is noteworthy that the increasing density of urban landscape towards northern and southern directions, along the coastal belt and along the transport lines, becoming significant.

3.2 Land Surface Temperature

The LST maps of Colombo district for 1997, 2008, and 2017 are shown in Fig. 3.

On February 7, 1997 (04:18:38 GTM), the LST in the study area ranged from 21.5 °C to 34.9 °C with a mean value of 26.5 °C. On November 4, 2008 (04:37:19 GTM), the LST ranged from 16.1 °C and 38.7 °C with a mean value of 27.4 °C. On January 13, 2017 (04:54:05 GTM), the LST ranged from 20.2 °C and 33.8 °C with a mean value of 27.0 °C. This result shows that the Colombo district experienced an increase of mean LST by 0.5 °C from 1997 to 2017. However, it is noted that this area experienced a decrease in mean LST by 0.4 °C from 2008 to 2017.

In 1997, the proximity center of Colombo city and Ratmalana airport are identified as main hotspots (>30 °C), while along the coastal belt a higher LST (around 29 °C-30 °C) was observed, compared to the adjoining areas. In

addition, the surrounding areas of Oruwala Steel Corporation, Panagoda industrial zone, Seethawaka export processing zone, and Slawa army camp areas could be identified as being outside the hotspot from the main urban cluster of Colombo district. Meanwhile, Labugama – Kalatuwawa forest reserve area shows the lowest LST among other areas of the Colombo district.

In 2008, the Colombo district experiences an increasing spatial coverage of high LST areas. Mainly, the high LST values diffuse from the main urban cluster toward the eastern area, where previously low LST values were observed, while the LST along the coastal belt increase. Specifically, the size of previous LST hotspots around Oruwala steel corporation, Panagoda industrial zone, and Seethawaka export processing zone have amplified. In addition to that, new hotspots have emerged such as Hanwella and Padukka,

In 2017, the spatial coverage of high LST areas was further increased while the size of high LST hotspots outside augmented. However, the places including Seethawaka botanical garden, Diyawanna-oya Park where recent urban beatification planning was introduced, showed a slight decrease in LST. However, areas associated with recent development projects such as NSBM green university project and Athurugiriya housing project have experienced an increasing trend of LST.

3.3 Relationship of LST with NDVI and NDBI

Fig. 4 shows the correlation of LST with NDVI and NDBI for all three-time points.

Fig. 4: Scatter plots between, left to right, LST and NDVI, and LST and NDBI, in, top to bottom, 1997, 2008, and 2017.

LST negatively correlate with NDVI, while they were all statistically significant ($p < 0.001$) across all the time points as disclosed by the results. In 1997, the beta value of -0.455 describes that the impact of NDVI changes on LST is moderate. The regression analysis between LST and NDBI in 1997 indicates a strong and positive correlation (0.68) between LST and NDBI. In 2008, the correlation between LST and NDVI is strong and negative (-0.63), while the correlation between LST and NDBI proves to be strong and

positive (0.76). In 2017, the correlation between LST and NDVI is strong and negative (-0.68), while it is strong and positive (0.82) between LST and NDBI. It can be noted that the decrease of vegetation cover and increase of the built up areas have intensely impacted on amassing of the LST in 2008 and 2017. The R^2 show an increasing trend from 1997 to 2017. This indicates that the explanatory or predictive power of NDVI on the spatial variations of LST became stronger when urbanization increased. Similar to the

Fig. 5: Environmental Criticality in, left to right, 1997, 2008, and 2017 (bottom).

Fig. 6: Patterns of, left to right, NDVI, NDBI, and LST along the urban-rural gradient in 1997, 2008, and 2017.

relationship between NDBI and LST, the relationship between NDBI and LST strengthened from 1997 to 2017 due to the cumulative trend of urbanization in the area.

As previous studies have shown, regression analysis results also indicate that the spatial pattern of NDBI values is highly correlated with the spatial pattern of LST values.

3.4 Changes in Environmental Criticality

The derived ECI maps of Colombo district in 1997, 2008, and 2017 are shown in Fig. 5. The results show that the environment criticality areas are mainly concentrated in close proximity to the city center (where the CBD is

located) in all the time phases. The environmentally critical areas were 1%, 4%, and 3% of the total landscape in 1997, 2008, and 2017, respectively. Although there was a dramatic increase in environmental criticality from 1997 to 2008, a slight decrease was indicated from 2008 to 2017.

3.5 Gradient Analysis

Fig. 6 shows the spatial distribution of NDVI, NDBI, LST, and ECI along the gradients of the city center of Colombo district.

The gradient analysis shows that in terms of less vegetation cover, concentration of built-up area, and higher level of

LST, the central area (0-6 km) shows an extreme level of urbanization compared to the surrounding areas. The decrease of vegetation cover, increase of built-up area and increase of LST along the gradient distance is identical from 1997 to 2008. From 2008 to 2017, it can be observed that while the built-up area increased, there is a slight increase in vegetation cover and decrease in surface temperature in the study area. This situation is clearly identical in the close proximity of city center area.

4 Discussion

4.1 Urbanization and its challenges

According to the prior revelation, the city's geographical location, historical factors, economic dominance, infrastructure development, and government policies have fuelled Colombo to gain the status of primate city in the country with the highest level of urbanization (77.6% in 2011) (DCS, 2012). In 2012, Colombo district accounted for approximately 11% of the total population with 2.3 million total inhabitants (DCS, 2012). On the other hand, Colombo district shows the highest population density among other districts of the country, which accounts for 2,605 persons/km² in 1981, which has increased to 3,330 persons by 2001, and has increased further to 3,438 persons by 2012 (DCS, 2012). In addition to that, the Colombo city limit shows a much higher population density compared to the Colombo district population as a whole. At present, Colombo city limit accounts for 20,182 persons/km², making it one of the highly populated capital cities among the South Asian countries (Table 2).

Table 2: The population density of capital cities in South Asia (Source: <http://worldpopulationreview.com/>)

Country	Capital city	Population density (per km ²)
Maldives	Malé	27,000
Bangladesh	Dhaka	23,234
Nepal	Kathmandu	20,288
Sri Lanka	Colombo	20,182
India	New Delhi	11,900
Afghanistan	Kabul	4,500
Bhutan	Thimphu	4,015
Pakistan	Islamabad	2,089

Furthermore, it is noticeable that the urbanization of Colombo district, which owns the location of the administrative capital - Sir Jawardhanapura Kotte, the commercial capital - Colombo city, and the country's only metropolitan area-Colombo metropolitan area, is very low compared to other capital cities of the South Asian region. The average annual population growth rate of the Colombo district is 0.35%, while it is 4.2% in Dhaka, 4.0% in Kathmandu, and 5% in Karachi (UN, 2018). The slothful

urbanization in Colombo is mainly associated with the absence of social infrastructure throughout the country, slower population growth (1.1% in 2017), and high cost of housing in Colombo district, and recent improvement of connectivity between Colombo and other areas of the country (Ellis and Roberts, 2015).

Upon the conclusion of the 30 years civil conflict in 2009, the Colombo district entered into a new era possessing a larger number of development projects such as 'Colombo Beautification Project', 'Port City Project', and highway projects. In addition to that, Foreign Direct Investment (FDI) inflow proliferated in the Colombo district. As a result of recent economic upliftment, the primacy of Colombo reached the apex of the country's urban system. From an economic point of view, the recent GDP contribution of the Colombo district is very high compared to other districts of Sri Lanka (40% of Sri Lanka's GDP), although it accounts for only 5.7% of the country's geographic area and 25% of the national population (CBSL, 2017). Meanwhile, it has also recorded the lowest poverty headcount ratio of 0.9% by grabbing 80% of industries of the country (DCS, 2015).

Our analysis reveals that the Colombo district had undergone dramatic urbanization in the past two decades (1997-2017). The results further visualize the ribbon type urbanization, which radiates out from the city center along the routes of main transportation. The dominance of transport corridors in the urban expansion in the Colombo district is visible in the spatial pattern of NDBI calculation. Previous literature, such as Ellis and Robert (2015), Subasinghe *et al.* (2016) have identified and proved the ribbon-type urban expansion of the Colombo district. This ribbon-type urban expansion is considered as a kind of "messy" urbanization, which creates many challenges in sustainable urban planning initiatives and lead to missed economic opportunities (Ellis and Roberts, 2015). Specifically, lands adjacent to the transport corridors are developed, but those without direct access remain in rural uses. The ribbon-type urban expansion takes place beyond the urban planning boundaries, and the planning authorities (i.e. urban development authority) have no jurisdiction over administratively defined rural areas - even if these areas contain high concentrations of urban features along the transport corridors. Gradient analysis shows that the main urban cluster remains in a very limited area while outward areas show rural characteristics. It has been argued that growing a city in a limited space creates many disadvantages, such as traffic congestion and pollution, limited open space, and crowded services (Evans, 2004).

According to the finding of this study, the environmental criticality and LST has increased from 1997 to 2017. Indeed, these situations are mainly driven by the increasing trends of urbanization. In all time points, the higher level of environmental criticality is concentrated in close proximity to the city center. The lack of vegetation cover in this area contributed a higher level of LST values and increased environmental criticality. On the other hand, along the western coast where the major urban nodes (i.e. Dehiwela and Moratuwa) and the main transport corridor are located, could be identified as some other environmentally critical areas. Since this main transport corridor serves as

the main connectivity line of Colombo district, commercial buildings and other constructions have sprung up along this road and its vicinity. Our NDVI maps show that the vegetation cover is also scarcely distributed in these areas. Meanwhile, the LST of these areas shows a higher value compared with other parts of the study area.

However, recently there is a harbinger of environmental sustainability under Colombo district urbanization. Our results show that there is a slight decrease in environmental criticality and LST values from 2008 to 2019. The main reason for this improvement is the implementation of recent urban planning projects (i.e. the beautification project of Colombo) which enhanced the green space coverage of Colombo city and its suburban areas. Specifically, implementation of the Colombo Metropolitan Regional Structure Plan - 1998, Western Megapolis Plan - 2002, and Western Province Master plan have improved the green space in the Colombo main urban cluster (NPPD). In general, the green spaces play a critical role in cooling cities, and also improve the well-being of people living and working in cities. The recent green space enhancement of Colombo city has led to a decreasing level of the environmental criticality and LST in the last decades in Colombo district. However, it is noticed that the city center area and the western coastal line remain as environmentally critical areas. The concentration of commercial centres in the city central area and tourism function-based developments - e.g., hotels and commercial activities - and residential function developments concentrated along the coastal area have articulated these environmental vulnerabilities in this area. It is clearly observed that the overall transformation of the Colombo district in the last two decades has made the central area and western coastal line as a higher vulnerable area in the aspect of environmental criticality and LST values. The concentrated urban footprint in the western part of the Colombo district has preserved most of the natural and rural environment of the eastern part. As a result, the eastern part of the Colombo district is not an environment criticality, while it enjoys less LST values. However, few areas associated with industrial zones, export processing zones, and locations of industries in even in the eastern part shows higher LST values and are associated with environmental criticality than its vicinity.

4.2 Prospects for sustainable development

Obviously, Colombo city is the country's most active economic node in terms of commercial activity and population concentration. Further, the western coastal area serves as a long-standing tourist region and provides habitats for many marine ecosystems (Senanayake *et al.*, 2013). Thus, urban development planners must prioritize environmental stress reduction, particularly in the city center area and western coastal area, to achieve sustainable urban development of the city.

To limit the ribbon-type urban expansion, it requires a cooperative effort by legislators, town planners, traffic department, judiciary, and adjacent landowners. Green belts establishment and preservation of lands for forestry, agriculture, and wildlife along the main transport corridors

would help to reduce the adverse effect of ribbon-type growth further. In addition to that, managing urbanization stress in a limited space should be addressed in the urban physical planning framework and administration in Colombo city. The planning should ensure sufficient land to cater to Colombo city's future needs, while maintaining good quality living standards for its population. Functional city zoning is an effective method that could address intensified urban land stress in Colombo city. Educational and administration functions can be diversified into the eastern part of the Colombo district, while Colombo port-based commercial activities remain in the Colombo city area.

Another main challenge in Colombo city in terms of environmental suitability is the existence of slums and degradation of the city. These are mainly associated with the limited income earned by the poor in gainful jobs. Policies designed to increase the employment and wages of urban poor must therefore be given foremost attention. On the other hand, slum dwellers and squatters on the streets have migrated to the city due to landlessness, joblessness, and hopelessness in the rural areas in the country. Therefore government policies should tackle the rural-urban migration, even if it is a small number in the context of the Colombo district experience. Hope (1989) indicated four aspects that must be considered in third world urbanization management: 1) foster the full development of national resources; 2) promote cohesion among regions, especially where there are striking inequities in per capita output; 3) prevent or correct the overconcentration of economic activity in a few urban centers; and 4) create a more efficient, equitable management of growth within cities. Referring to the study outcomes, we suggest more strategic tools need to be developed to control the environmental criticality and LST in the central area of the city. There is a crucial necessity to re-arrange the spatial pattern of urban land use pattern in the area. This result indicated that the location of high-temperature zones also corresponds with the overall pattern of urban development in recent years. Trees and other plants help cool the environment, making green space a simple and effective way to mitigate urban heat island effects. The positive changes that took place in the last decades should be continued in future.

5 Limitation of this study

The main limitation of this study is that satellite images are used to represent the different time ranges of the day. This may impact to the LST calculation of this study. To overcome this limitation, the use of average LST is suggested. In this study, LST was retrieved using the images of the same season (dry season image) to reduce this limitation. We also used only two spectral variables (NDVI and NDBI) in detecting the landscape pattern of the area. The environmental criticality was evaluated based on ECI and LST. Other variables, including socio-economic variables and land use changes, also need to be examined in future studies.

6 Conclusion

The Colombo district has undergone a full-scale urban transformation that encompasses changes in socioeconomic settings and environmental processes. The analysis revealed that the vicinity of the central area shares a progressive change in terms of green space enhancement in last decades, coinciding with the recent urban planning projects. However, as it was shown by the gradient analysis, the main center and along the main transport corridors are still in a stage that is environmentally vulnerable on the basis of ECI and LST values, while the areas away from the city center tend to have better environment quality except for a few growth nodes. Additionally, the long-term sustainability of cities has been slightly acceptable which was clearly shown by environmental criticality decline. For Colombo to be a sustainable city, it must achieve a balance between economic development, social well-being, and environmental protection and conservation. It is high time for government, planners, and policy-makers to plan the urban future of the city by reducing environmental criticality and the city's skin temperature further. Output emanating from this study would support to sustain the city in particular, and the whole district in general.

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Author Contributions

Conceptualization, methodology, analysis, writing original draft preparation, S.S., review and editing, R.N. and I.G., and data processing, G.R. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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