Remote sensing based analysis of urban heat islands with vegetation cover in Colombo city, Sri Lanka using Landsat-7 ETM+ data

I.P. Senanayake *, W.D.D.P. Welivitiya, P.M. Nadeeka
Space Applications Division, Arthur C Clarke Institute for Modern Technologies (ACCIMT), Moratuwa, Sri Lanka

Article info
Article history:
Received 23 February 2013
Revised 5 July 2013
Accepted 24 July 2013

Keywords:
Albedo
Emissivity
Land surface temperature (LST)
NDVI
Thematic mapping
Urban heat islands (UHI)

Abstract
Urbanisation leads to rapid constructions, which use low albedo materials leading to high heat absorption in urban centres. In addition, removal of vegetation cover and emissions of waste heat from various sources contribute to the accumulation of heat energy, leading to formation of urban heat islands (UHIs). UHIs have many adverse socio-environmental impacts. Therefore, spatial identification of UHIs is a necessity to take appropriate remedial measures to minimise their adverse impacts. Satellite remote sensing provides a cost-effective and time-saving methodology for spatio-temporal analyses of land surface temperature (LST) distribution.

In this study, thermal bands (10.40–12.50 μm) of Landsat-7 ETM+ imagery acquired in 3 distinct dates covering Colombo city of Sri Lanka were analysed for the spatio-temporal identification of UHIs. Vegetation cover of Colombo city was extracted by using NDVI method and subsequently examined with the distribution of LST.

A deductive index was defined to identify the environmentally critical areas in Colombo city based on the distribution of LST and availability of vegetation cover. Accordingly, Colombo harbour and surrounding areas were identified as the most critical areas. Remedial measures can be taken in future urban planning endeavours based on the results of this study.

© 2013 Elsevier Ltd. All rights reserved.

* Corresponding author. Tel.: +94 777 976418/11 2651566.
E-mail addresses: indishe@accmt.ac.lk, indishe@gmail.com (I.P. Senanayake), dimuth@accmt.ac.lk, dimuthprasad@gmail.com (W.D.D.P. Welivitiya), nadeekapm@accmt.ac.lk, nadeekarsa@gmail.com (P.M. Nadeeka).
1. Introduction

Widespread industrialisation and migration of rural population to urban areas lead to urban population growth, while expanding the urban sprawls. As of year 2010, 50.5% of the world’s population resided in urban areas implies that majority of the world population lives in urban areas instead of rural areas. In the year 2050, urban population residing in urban sprawls of developing countries is expected to double in number (United Nations, 2011). To accommodate urban population growth, urban infrastructure such as roads, bridges and residential buildings, need to be developed leading to rapid changes in land use patterns.

Vigorous urbanisation has its beneficial and adverse consequences affecting environmental and social aspects of inhabitants. Highly effective supply chains of basic facilities, easy access to quality education, medical and social services, leisure activities, concentration of resources, better economical and job opportunities, etc. can be considered as beneficial aspects of urbanisation. Though urbanisation has significant benefits as previously stated, there are a number of adverse socio-environmental effects as well.

One of the major reasons for these adverse environmental impacts is removal and replacement of vegetation cover by various built-up structures which cause environmental pollution, climate change and breakdown of ecological cycles. Most of these adverse environmental effects can be minimised by identification of problems and implementation of proper urban planning systems with sustainable solutions.

The roof tops and walls of high rise structures with darker surfaces, parking lots, roads and pavements constructed with asphalt and concrete tend to have low albedos. These dark low-albedo surfaces absorb higher amount of solar radiation and convert it to thermal energy. Consequently, excess amounts of heat energy accumulate in the immediate vicinity to above average levels. This phenomenon causes urban areas to have elevated temperatures compared to the surrounding rural areas. This temperature difference forms the land effect called urban heat islands (UHIs) (Comarazamy et al., 2010). These areas tend to have an above average temperature all year around and the temperature difference can be as high as 12 °C. Generally, the temperature difference is highly pronounced at night time than the day time and is noticeable when the winds are weak (Oke, 1987). Removal of vegetation cover is another major contributor to the UHI formation. While lowering land surface temperature (LST) by providing shade; trees and vegetation decrease the ambient air temperature through evapotranspiration process where they release water vapour to the surrounding atmosphere. Conversely, built-up areas consist of elevated temperatures as the vegetation is replaced by the artificial impervious surfaces such as roads, buildings, pavements, parking lots, etc. (Cheng et al., 2010; Gonzalez et al., 2005; Lo et al., 1997; US Environmental Protection Agency, 2008). Properties of the materials utilised in construction of urban structures, such as solar reflectance, heat capacity and thermal emissivity plays a major role in formation of UHIs. In addition, the waste heat generated by factories, air conditioners and motor vehicles which are ubiquitous in urban areas contribute to the formation of UHIs (Guhathakurta and Gober, 2007; Khan and Simpson, 2001; Sailor and Lu, 2004; Weng, 2010).

Though, the disparity of temperature is not large, it can cause several noteworthy socio-environmental problems in urban areas. UHIs adversely affect the air quality in the region due to the production of pollutant gases such as ozone. Chemical reactions between volatile organic compounds and various oxides of nitrogen (i.e. NO and NO₂) prevalent in warm weather and sunlight produce this toxic ozone gas (Cardelino and Chameide, 1990; US Environmental Protection Agency, 2012). Further, it affects the water quality by increasing the temperature of the water bodies through heated storm water runoff draining into the water bodies in the area, consequently stressing aquatic ecosystems (US Environmental Protection Agency, 2012). In addition to the anomalies in temperature, heat waves generated by the UHI effect can change the climatic patterns including rainfall and wind characteristics of urban areas (Baik et al., 2000; Tan et al., 2010). UHIs indirectly increase the consumption of energy of buildings by raising the requirement for air-conditioning in urban areas. As a result, power plants emit more pollutant gases in the process of generating the required extra electricity (Akbari et al., 2001; Devanathan and Devanathan, 2011) and this effect continues as a positive feedback loop degrading the environmental quality even further.
Elevated temperature levels and air pollution which are consequences of UHIs have adverse effects on human health. These health effects range from general discomfort, respiratory problems, heat strokes and cramps, exhaustion and even heat-related deaths (Devanathan and Devanathan, 2011; US Environmental Protection Agency, 2012).

These adverse effects UHIs can be significantly controlled through sustainable development coupled with mitigation measures. Widespread planting of trees and vegetation in urban areas is one of the most effective methods to reduce the effects of UHI formation. Vegetation cover increases the evaporative cooling while providing shade reducing solar radiation from heat exposed ground. Strategic planting of trees around buildings and establishment of urban forests are excellent sustainable solutions for UHIs. In addition, vegetation cover contributes to enhance the air quality as well (Akbari et al., 2001; Devanathan and Devanathan, 2011).

Another method of reducing heat built up in an urban area is gradually increasing the albedo of the area. This can be done by introducing high albedo reflective materials including light colour coatings for roofs, buildings, roads and pavements replacing darker low albedo surfaces (Akbari et al., 2001; Rosenfeld et al., 1995; Synnefa and Santamouris, 2007; Taha, 1997). Cool roofs (roofs having high solar reflectance and thermal emittance) have been identified as an effective mitigation method for UHI effect (Urban and Roth, 2010). Cool roof coatings and roofing materials can be used to reduce the temperature of the surrounding area (California Energy Commission, 2008).

In this context, green roofs can be identified as an excellent alternative for low albedo roofing materials. Vegetation promotes the evaporative cooling, consequently regulating the temperature of buildings and surrounding areas (Devanathan and Devanathan, 2011; Oberndorfer et al., 2007; Takebayashi and Moriyama, 2007). Road and roof sprinkling systems can promote evaporative cooling to reduce the effects of UHIs as well (Gartland, 2008).

In order to implement mitigation measures against UHI formation, it is important to identify the LST distribution in urban areas and determine areas with anomalous high temperatures. Satellite remote sensing provides an excellent cost-effective and time-saving methodology to analyse spatially and temporally distributed LST, since the coverage of satellite imagery extends over a large area.

Colombo, the commercial capital of Sri Lanka is located between Northern latitudes 6°55′–6°59′ and Eastern longitudes 79°50′–79°53′ extending over 37 km² of area. Since ancient times, Colombo port has been one of the most important harbours in South Asia due to its central location in the Indian Ocean. This significant location in the East–West trade route has made Colombo city popular among the traders as a business hub since Colonial era. As a result, urbanisation of Colombo has commenced few centuries ago. Contemporary urban development and planning projects have converted Colombo into a highly urbanised city in South Asian region, with a resident population of 637,865 and a floating population of nearly 100,000 (2001 census data) encompassing the highest population density in the island. With the high rate of urbanisation, vegetation cover is diminishing rapidly and it is being replaced by buildings, roads, parking lots, pavements and other constructions. In addition to that, high vehicle density of the region contributes to emission of waste heat and pollutant gases. For these reasons previous research works have identified Colombo as the most polluted city in the island (Liyanage, 2003). As a consequence of these causes, there is a huge potential for the formation of UHIs within the Colombo city limits.

This study focuses on identifying the LST distribution pattern and temperature anomalies in the Colombo city by analysing Landsat-7 ETM+ satellite imagery obtained during 2000–2001. Objectives of this study were to spatially identify the UHI formations in Colombo city, identify the relationship between vegetation cover and LST distribution and to develop an Environmental Criticality Index based on the LST and availability of vegetation. The results of this study can be effectively utilised in future urban planning projects in order to take appropriate remedial measures to minimise the adverse effects of UHIs in Colombo city.

2. Methodology

USGS/NASA Landsat-7 Enhanced Thematic Mapper Plus (ETM+) satellite data was utilised in this study. Landsat-7 ETM+ data are obtained in 3 resolution levels. Bands 1–5 and 7 are acquired in
30 m resolution whilst thermal band (band 6) is acquired in 60 m resolution. Band 8 (panchromatic) has a resolution of 15 m. Landsat-7 ETM+ images were utilised in this analysis, obtained on 23rd January 2000, 14th March 2001 and 6th September 2001. These satellite images have undergone Standard Terrain Correction (Level 1T) processing. The processed images were geo-referenced using WGS84/UTM Zone 44 N projection system. The resampled images pose a resolution of 30 m in bands 1–7 and 15 m in band 8 (NASA, 2012).

The thermal bands (band 6) of the 3 Landsat images were analysed to identify the LST distribution pattern of Colombo city using remote sensing and image processing techniques. Wavelength of band 6 ranges from 10.40 to 12.50 μm of the electromagnetic spectrum. Landsat 7 Science Data Users Handbook describes the retrieval method of LST from the thermal band of an image (NASA, 2012). The digital number (DN) values of the thermal bands of the 3 images were converted to spectral radiance values by using offset (bias) and gain values of the images as shown in Eq. (1):

\[ L_i = (\text{Gain} \times Q_{\text{DN}}) + \text{Bias} \]  

where \( Q_{\text{DN}} \) is quantised calibrated pixel value in DN and \( L_i \) is the spectral radiance of the sensor in \( \text{Wm}^{-2} \text{Sr}^{-1} \mu\text{m}^{-1} \). Gain and bias can be calculated using Eqs. (2) and (3):

\[ \text{Gain} = \frac{L_{\text{max}} - L_{\text{min}}}{Q_{\text{CALmax}} - Q_{\text{CALmin}}} \]  

\[ \text{Bias} = L_{\text{min}} - (\text{Gain} \times Q_{\text{CALmin}}) \]

where \( L_{\text{min}} \) is minimum spectral radiance, \( L_{\text{max}} \) is maximum spectral radiance, \( Q_{\text{CALmin}} \) is the minimum quantised calibrated pixel value (corresponding to \( L_{\text{min}} \)) in DN and \( Q_{\text{CALmax}} \) is the maximum quantised calibrated pixel value (corresponding to \( L_{\text{max}} \)) in DN (Haibin et al., 2010; Li et al., 2012; NASA, 2012). \( Q_{\text{CALmax}}, Q_{\text{CALmin}}, L_{\text{max}} \) and \( L_{\text{min}} \) values can be obtained from the header (metadata) files of the images.

Subsequently, the calculated radiance values can be converted to effective at-satellite temperature in Kelvin \( (T_B) \) by applying the inverse of the Planck function as shown in Eq. (4) (Aniello et al., 1995; Chen et al., 2006; Li et al., 2012; NASA, 2012; Shahmohamadi et al., 2010; Weng et al., 2004):

\[ T_B = \frac{K_2}{\ln \left( \frac{K_1}{\lambda} + 1 \right)} \]

where \( K_1 \) and \( K_2 \) are pre-launch calibration constants (\( K_1 = 666.09 \text{ Wm}^{-2} \text{Sr}^{-1} \mu\text{m}^{-1} \), \( K_2 = 1282.71 \text{ K} \)) and \( L_i \) is the spectral radiance of the sensor in \( \text{Wm}^{-2} \text{Sr}^{-1} \mu\text{m}^{-1} \).

Since the output \( T_B \) values are black body temperatures, it is necessary to make the corrections using emissivity values of land use classes to estimate the real LST. In order to do this, Landsat-7 ETM+ true colour composites (RGB composition of 3-2-1) were classified using maximum likelihood classification method (supervised classification) to identify the land use classes in Colombo city. Subsequently, water bodies, vegetated areas, bare lands and built-up areas were assigned with the emissivity values of 0.990, 0.985, 0.950 and 0.946, respectively (modified from Ramachandra and Kumar, 2009). The emissivity corrected LST values were then computed by using Eq. (5):

\[ T_s = \frac{T_B}{1 + (\lambda \times T_B/\rho) \ln \varepsilon} \]

where \( T_s \) is the emissivity corrected LST in Kelvin (K), \( T_B \) is the black body temperature in Kelvin (K), \( \lambda \) is the wave length of emitted radiance (\( \lambda = 11.5 \mu\text{m} \)), \( \rho = \text{hc}K^{-1} (1.438 \times 10^{-2} \text{ mK}) \), \( h \) = Planck’s Constant (6.626 \times 10^{-34} \text{ J s}^{-1}), c is the velocity of light (2.998 \times 10^8 \text{ m s}^{-1}) and \( K \) is Boltzman constant (1.38 \times 10^{-23} \text{ J K}^{-1}), \( \varepsilon \) is surface emissivity (Li et al., 2012; Markham and Barker, 1985; Weng et al., 2004).

The calculated temperature values in Kelvin were converted to Celsius degrees by using Eq. (6) for the clarity in data interpretation:
The LST of Colombo city computed using the 3 Landsat ETM+ images were classified into 6 classes as illustrated in Fig. 1 in order to identify the LST distribution pattern in the city. The highest temperature value class assigned with black colour indicates the regions where higher LSTs are accumulated; hence can be considered as the possible UHI formations in Colombo city. The lowest temperature class assigned with yellow colour indicates the sea and water bodies, which creates bizarre deviated peak in each of the histograms.

Subsequently, the layers were reclassified by assigning grid code values 0–5, from the highest to the lowest LST class respectively. The 3 reclassified raster layers were summed together through a raster arithmetic operation. The pixel values of the resultant layer vary from 0 to 15, where lower pixel values tend towards higher combined LST values while higher pixel values tend towards lower LST values. The areas belong to the highest LST class in each of the 3 reclassified layers (i.e. areas with grid code value 0 in all 3 layers) obtain pixel value of 0 in the resultant layer, hence can be identified as persistent UHIs in Colombo city. The UHI map of Colombo city (Fig. 2) was subsequently generated by extracting the pixels with 0 values.

Since removal of vegetation cover plays a major role for the formation of UHIs as described in the introductory section, vegetation cover of Colombo city area was analysed using ‘Normalised Difference Vegetation Index’ (NDVI) method. Visible light in the wavelength range of 400–700 nm is strongly absorbed by chlorophyll inside plant cells, in order to carry out photosynthetic reactions. Conversely, Near Infrared (NIR) light in the wavelength range 700–1100 nm is strongly reflected by cell structures in green leaves, because absorption of NIR can damage the plant tissues by overheating. Due to this differential absorption and reflection of radiation, plants appear dark in visible range of the spectrum while they appear bright in the NIR wavelength range (Gates, 1980). Water bodies tend to absorb NIR radiation strongly than absorption of visible radiation and hence appear brighter in visible range than the NIR region. Bare ground and other features such as buildings absorb and reflect both visible and

\[
T(C^0) = T(K) - 273.15
\]
NIR radiation equally and hence appears similar in both visible range and NIR range. This discrepancy between the absorption and reflection characteristics of various features in visible and NIR radiation is used to distinguish between these features, namely vegetation cover, bare ground and water bodies (Gates, 1980).

In order to compute NDVI, red band representing the visible spectrum and the NIR band are utilised. Eq. (7) describes the method of calculating the NDVI (Cracknell, 1997; Goward et al., 1985):

$$NDVI = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}}$$

(7)

where $\rho_{\text{NIR}}$ and $\rho_{\text{RED}}$ are the radiance in reflectance units of NIR and RED bands respectively.

NDVI values range from $-1$ to $+1$. Water bodies tend to have minus NDVI values. Bare ground exhibits NDVI values close to 0, whilst green vegetation exhibits NDVI values close to $+1$.

NDVI layers of the 3 Landsat scenes used in this study were generated utilising band 3 (visible-red) and band 4 (NIR) of the images. Fig. 3 illustrates the generated NDVI layers of Colombo City which
shows the temporal variation of NDVI on 23rd January 2000, 14th March 2001 and 6th September 2001. Subsequently, the layers were classified to extract the vegetation cover of Colombo city using appropriate break values. The extracted vegetation cover layers were spatially verified by visual comparison with the natural colour composites of the relevant Landsat-7 ETM+ imagery used in the study.

Thereafter, LST contours of Colombo city were derived from the LST layers of the area on a GIS platform. The LST contour layers were superimposed with the vegetation cover layers, in order to identify correlations between LST distribution pattern and vegetation cover of the Colombo city (Fig. 4).

Vegetation cover plays an important role in minimising environmental issues in urban centres. Conversely, removal of the vegetation cover leads to environmental criticality in urban sprawls whilst acting as a major contributor for the formation of UHIs (Foley et al., 2005; Wong and Yu, 2005). Consequently, the availability of vegetation cover is considered as an indicator of ecological sustainability in an urban community. Therefore, proper management of vegetation cover has become an integral part in any sustainable urban development endeavour (Bernatzky, 1982; Senanayake et al., 2013a,b).

Since, both removal of vegetation and elevated LST can adversely affect the surrounding environment, it is essential to identify the combined environmental criticality in Colombo city based on elevated LST and lack of vegetation cover. Identification of the combined environmental criticality based on elevated LST and lack of vegetation cover provides insight in future urban greening endeavours and development projects in order to take appropriate remedial measures for UHI effect. With the view of accomplishing this, a deductive index was defined using LST and NDVI values in order to identify the combined environmental criticality in Colombo city based on elevated LST and lack of vegetation cover. NDVI values range from −1 for non vegetated areas to +1 for dense vegetation (Batista et al., 1997). Hence, highest environmental criticality can be observed at low NDVI values whilst high NDVI values indicate higher environmental quality based on vegetation density. On the other hand, higher LSTs including UHIs contribute to adverse environmental conditions, whilst moderate LSTs contribute to
better environmental conditions in tropical cities like Colombo where temperature does not drop down to extremely low levels. Accordingly, LST and NDVI have directly and inversely proportional relationships respectively, with the environmental criticality level of Colombo city. Based on this fact, a deductive index was defined as shown in Eq. (8) to identify the level of combined environmental criticality in Colombo city on the basis of LST and availability of vegetation cover. The LST layers and NDVI layers used in Eq. (8) were stretched using histogram equalisation method from 1 to 255 pixel values to enhance the clarity and contrast of the resultant layer and to avoid erroneous infinite Environmental Criticality Index values caused by the presence of 0 stretched-NDVI values in the calculation:

$$ECLI_{(LST-Veg)} = \frac{LST_{(Stretched \ 1-255)}}{NDVI_{(Stretched \ 1-255)}}$$

where $ECLI_{(LST-Veg)}$ is Environmental Criticality Index based on LST and availability of vegetation cover, $LST_{(stretched \ 1-255)}$ and $NDVI_{(stretched \ 1-255)}$ are LST and NDVI values histogram stretched from 1 to 255 pixel respectively.

The correspondent stretched values of mean LST and NDVI break value used to differentiate vegetation were substituted into Eq. (8) in order to define approximate threshold values for the resultant Environmental Criticality Index layers. The area below this threshold values were distinguished as the non-critical areas based on LST and availability of vegetation cover and the rest of the area was classified into 3 criticality classes using quantile classification method.

Although, water bodies and clouds produce lowest NDVI values, they do not represent environmentally critical areas. Hence, areas covered by water bodies and clouds had to be excluded from this analysis. Therefore, normalised Difference Water Index (NDWI) method was employed to identify water bodies in Colombo city area from Landsat-7 ETM+ imagery. Reflectance values from NIR channel
around 0.86 μm (band 4) and Mid-IR channel around 1.24 μm (band 5) were utilised in computing NDWI. NDWI is defined in Eq. (9) (Chen et al., 2006; Gao, 1996):

$$NDWI = \frac{\rho_{\text{NIR}} - \rho_{\text{MidIR}}}{\rho_{\text{NIR}} + \rho_{\text{MidIR}}}$$  

(9)

where $\rho_{\text{NIR}}$ and $\rho_{\text{MidIR}}$ are the radiance in reflectance units of NIR and MidIR bands respectively.

By means of Eq. (9), corresponding NDWI layers of Colombo city were generated using Landsat-7 ETM+ data acquired on 23rd January 2000, 14th March 2001 and 6th September 2001. Subsequently, water bodies and clouds were differentiated from land area utilising appropriate break values. Thereafter, the extracted water bodies were superimposed over the Environmental Criticality Index layers as illustrated in Fig. 5 to avoid the presence of ambiguous Environmental Criticality Index values caused by water bodies.

The extracted land areas were used as a mask to omit water bodies and clouds from the 3 Environmental Criticality Index layers. To compute the combined environmental criticality of the 3 resultant layers (excluding water bodies and clouds) were reclassified by assigning pixel values 0–3 to the 4 drought severity levels shown in Fig. 5 (from lowest to highest) and subsequently the layers were multiplied together using a raster arithmetic operation. The resultant combined environmental criticality layer consists with 11 value classes vary from 0 to 27. Areas with 0 value class in the resultant layer were identified as non-critical areas and assigned with white colour, whilst areas with rest of the 10 value classes (i.e. environmentally critical areas based on LST and available vegetation cover) were reclassified into 3 classes with equal intervals as illustrated in Fig. 6.
3. Results and discussion

While examining the histograms of the LST distribution layers of Colombo city (Fig. 1), some noteworthy features were observed. As depicted by the arrowheads in Fig. 7, all 3 histograms of LST distribution layers exhibit an anomalous peak in the low LST end, instead of having a normal distribution. Examination of this anomalous peaks revealed that the pixels responsible for creating this anomalous peak belong to the temperature distribution of the ocean. This feature is a result of the dichotomy of heat capacity between oceans and land masses. Oceans pose a higher heat capacity relative to land masses and hence heats up relatively slowly in the daytime while absorbing solar radiation. Due to this reason the sea surface temperature is always significantly lower than the LST at daytime. Since Landsat images used in this study have ocean-land interfaces, this temperature difference creates anomalous peaks in the histograms of the LST distribution maps.

UHIs are persistent zones with above average LSTs. For the purpose of identification and classification of these persistent features, a temporal analysis requires to be employed to exclude short-term
temperature anomalies such as temporary heat producing entities. In order to satisfy this condition, Landsat-7 ETM+ images captured in 3 distinct dates were utilised to identify UHIs in the study area. Consequently, high LST zones common to all 3 satellite images were designated as UHIs in Colombo city.

Examining the UHI map of the Colombo city (Fig. 2) reveals some notable facts. According to the UHI map, UHIs are concentrated in and around Colombo harbour area (WGS 84/UTM Zone 44 N, 373390mE, 768186mN). The largest heat island covers the jetty and the container storage area of Colombo harbour. The adjacent vicinity of Colombo harbour (i.e. Colombo Fort and Pettah) is considered as the heart of Colombo where the central bus terminal, central railway station, head offices of main banks, companies and government departments are located. Hence, this area encompasses high build-

Fig. 7. Histograms of land surface temperature distribution maps of Colombo city, Sri Lanka on (a) 23rd January 2000 (b) 14th March 2001 and (c) 6th September 2001.
ing density comprising high and medium rises. In addition, this area consists of constructions such as roads, pavements, parking lots and railways constructed with low albedo materials.

Comparing the UHI map with the natural colour composite image, it is possible to identify various factors which have contributed to UHI formation. Majority of the UHIs have occurred at buildings covering large land areas. Most of these buildings are roofed with concrete or asbestos roofing sheets. It is pertinent to mention here that, same type of buildings with tiled roofs have not developed UHIs around them. Other major UHIs created by large parking lots and the harbour jetty are paved with dark materials such as asphalt.

It is common knowledge that a water body such as the ocean or a large lake will lower the LST of surrounding area through breezes and evaporative cooling. This fact can be clearly seen in the UHI map generated in this study (Fig. 1). According to UHI map of Colombo, most of the UHIs present are located away from shorelines and water bodies. However, when the Colombo harbour area is considered, UHIs have formed adjacent to the sea due to the low albedo materials used in the constructions. If the area of low albedo cover was small, the heat may dissipate effectively into the surrounding area.
environment. Since the area covered by asphalt is much larger, the harbour area tends to accumulate heat more vigorously leading to formation of a large heat island. When the main jetty of the harbour is considered, it is evident that the heat island does not extend all the way to the water's edge, but terminates approximately 50 m from the water front. Furthermore, the heat island boundary has further shrunk inland, where the jetty is surrounded by 2 sides of water (Fig. 8). These anomalies are classic examples of evaporative cooling and sea breeze working in conjunction to reduce the temperature of water front UHI.

The LST contour map was superimposed with the vegetation cover map derived through NDVI (Fig. 4) to analyse the relationships between the LST distribution and the vegetation cover in Colombo city. The LST is always lower in areas covered with vegetation relative to non-vegetated areas. In some instances, there are sharp LST boundaries between regions with high LSTs and regions covered with vegetation. This is another example where vegetation reduces the LST of its surroundings. Vegetation can reduce the surrounding temperature through a number of mechanisms. Green vegetation utilises

Fig. 9. Formation of sizable gap surrounded by UHIs adjacent to the main jetty of Colombo harbour, Sri Lanka due to existence of green vegetation cover.
some of the solar radiation in photosynthesis to produce the nutrients they require. Also, through the same mechanism they scrub out greenhouse gases such as CO₂ in the immediate area, consequently reducing the surrounding temperature.

On the other hand, vegetation also reduces surrounding temperature through evapotranspiration where heat energy is consumed for evaporation of water from leaves, reducing the temperature of the immediate area. Further, shades provided by trees with large canopies prevent solar radiation from heat exposed ground. The fact that vegetation cover is capable of reducing the temperature of surrounding area can be clearly seen in the generated UHI map of Colombo. Inspecting the largest heat island near the Colombo harbour, a sizable gap can be observed adjacent to the jetty of the harbour. Further visual observation with the true colour satellite imagery revealed that this gap is consistent with a large area of green vegetation (Fig. 9). This green space has depressed heat accumulation effect in this area, and prevented the heat island from penetrating into its vicinity, although the surrounding is a severe heat island.

Histograms of LST distributions of Kurunduwatta (WGS 84/UTM Zone 44 N, 374726mE, 764150mN) and Pettah (UTM 84 Zone 44 N, 373340mE, 766904mN) areas were analysed to exemplify the dichotomy between LST distributions of residential areas and commercial areas respectively (Fig. 10). Comparison of histograms reveals that LST of residential areas illustrates nearly normalised distribution; while LST of commercial areas illustrates negatively skewed distribution. Planned residential areas consist of dense vegetation and more open spaces, whereas commercialised areas consist of higher building density and constructions with low albedo surfaces (Senanayake et al., 2013b). Thus, commercialised and highly urbanised areas have comparatively higher LST distributions than in residential and rural areas.

![Histograms of land surface temperature distributions of (a) Kurunduwatta area, and (b) Pettah area of Colombo city, Sri Lanka.](image-url)
The environmental criticality map of Colombo was generated by incorporating both LST and availability of vegetation cover in Colombo city area. As explained in the methodology section, environmental criticality was determined for each of the 3 Landsat images (Fig. 5) and the resultant criticality layers were integrated to generate the final environmental criticality map (Fig. 6). As expected, the highest environmental criticality exists in the Colombo harbour and neighbourhood areas over the North-Western part of Colombo city. Lack of vegetation cover and existence of UHIs contribute to increase the environmental criticality of these areas. When the environmental criticality map is considered, a linear feature with high environmental criticality could be identified in the Western coastal belt extending towards the South of Colombo city. Further analysis revealed that this feature coincides with the Colombo-Galle A2 road and its vicinity. Since Colombo-Galle A2 road serves as the core of North–South transportation of the city, commercial buildings and other constructions have sprung up in its vicinity replacing the vegetation cover. Inspecting the NDVI map (Fig. 3), it is evident that vegetation cover is also absent adjacent to the Colombo-Galle A2 road. Further, rows of medium rises along the borders of Colombo-Galle A2 road and intersecting narrow streets effectively block the sea breeze (Johansson and Emmanuel, 2006). As a consequence, LST of Colombo-Galle A2 road and surrounding area is elevated compared with other regions. Resultantly, environmental criticality of Colombo-Galle A2 road and its vicinity has increased within the study area.

Upon the identification of UHIs and their sources, appropriate remedial measures can be applied to the environmentally critical areas in future urban development and planning projects. Since the environmental critical areas are based on elevated LST and lack of vegetation cover, the results can be effectively utilised as references in urban greening projects to enhance the environmental quality of the city. Further, outcome of this study can provide insights into the authorities and decision makers in implementing rules and regulations for urban construction works.

As identified through this analysis, one of the major sources of UHIs is buildings with large footprints roofed with low albedo roofing material such as asbestos or concrete. This effect can be minimised by following cool/green roof concept as described in the first section of this article. Further, albedo of roads and low albedo open spaces such as harbour jetty and parking lots can be increased by using appropriate methods including strategic planting of trees, sprinkling and using high albedo construction materials.

The methodology used in this study can be adopted in analysing LST distributions in other urban areas; hence an environmentally affable sustainable development can be achieved by introducing appropriate remedial measures and implementing necessary rules and regulations in urban constructions.

4. Conclusion

This study was carried out to identify the UHIs and environmentally critical areas based on LST distribution and availability of vegetation cover in Colombo city, Sri Lanka with the integration of satellite remote sensing and GIS techniques.

LST distribution of Colombo city, Sri Lanka in 3 distinct dates during 2000–2002 were analysed utilising Landsat-7 ETM+ imagery for the spatio-temporal identification of UHIs. NDVI layers of the above Landsat images were created in order to identify the vegetation cover of the study area. The vegetation cover of Colombo city was analysed with the LST distribution to identify the relationship between elevated LSTs and lack of vegetation cover. Subsequently, a deductive index was developed to identify the environmentally critical areas, on the basis of LST distribution and availability of the vegetation cover. Water bodies and clouds were identified using NDWI method and omitted from the final environmental criticality index analysis. Colombo harbour and surrounding areas in the North-Western part of Colombo city were identified as the environmentally most critical region based on LST and availability of vegetation cover. Large areas paved with asphalt such as Colombo harbour jetty, buildings with large footprints with low albedo roofing materials and parking lots were identified as the major sources of elevated LSTs. Further, Colombo-Galle A2 road appears to be an environmentally critical region based on availability of vegetation cover and LST. In addition, analyses of LST with vegetation cover revealed that there is a direct relationship between lack of vegetation cover and the occurrence of UHIs in Co-
Urban climate. Use of satellite remote sensing and GIS provided a time and cost effective methodology for this analysis.

The results of this study can be utilised effectively in future urban development and planning projects as well as a framework for implementing rules and regulations by the authorities for a sustainable urban development through an environmentally affable approach. Remedial measures such as increasing the albedo of the city, proper distribution of vegetation cover and use of cool/green roofs can be introduced to the highly critical areas identified in this study based on elevated LST distribution and lack of vegetation cover in order to minimise the adverse socio-environmental effects of UHIs.

This methodology can be adopted in other urban centres in order to identify the formation of UHIs and consequently can be used as a framework in taking proper remedial measures in urban development and planning endeavours.

References


