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Assessing the impacts of urbanization on the thermal environment of Ranchi City (India) using geospatial technology

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ABSTRACT

Understanding, monitoring and mitigating the effects of increasing urbanization on the environment is essential for sustainable development. The objective of this study is to find out how and at what extent the spatio-temporal dynamics of Land Surface Temperature of Ranchi, Jharkhand (India) is affected by urbanization. In this study, the temporal Landsat images were used to derive the land use/land covers (LULC), Land Surface Temperatures (LST) and the spatio-temporal dynamics of urban expansion and Urban Heat Island Intensity (UHII) for three dates of 1992, 2001 and 2013. The impact of urbanization to the UHII is assessed using land use trajectories from 1992 to 2013. The results show that, with the urban built up growth of 251.89% in between 1992 to 2013, the increase in UHII is as high as 1.42 K. This is an alarming signal of deteriorating thermal environment of the city which happens to be cooler due to its relatively higher altitude. The result shows that in Ranchi, the Contribution to UHII (CUHII) of different urbanization trajectories are different and by 2013, the land transformed from agriculture to urban has highest CUHII than any other types of transformations. The results provide valuable insights into the effect of urbanization on thermal environmental and are very useful for decision making and planning of Ranchi, to make it an environmentally smart city.

1. Introduction

Urbanization is an inevitable consequence of this globalized twenty-first century. Currently as much as 50% of total world population inhibits in urban areas. By the end of the first half of the twenty-first century, it is assessed that nearly 66% of the global population would be dwelling in cities (United Nations, 2014). In India, according to the census of 2011, as much as 31% of the population resides in the urban area. Revision of world urbanization prospects of 2014 by Department of Economic and Social Affairs (UN), notes that the major urban growth will take place in India, China, and Nigeria and will account for 37 percent of the increase in the world's urban population between 2014–2050.

One of the characteristics of urbanization is that it causes the alteration of natural land cover by increasing the amount of impervious surface cover. Remote Sensing Satellite data makes it convenient to map the spatio-temporal dynamics of impervious surfaces at medium to coarser resolutions. Built-up indices are being developed for automatic built-up feature mapping, with the advantage of spectral reflectance properties at different wavelength regions (Zha et al., 2003; Xu, 2010). At the global scale, impervious surface cover products are derived from MODIS, and DMPS-OLS data (Schneider et al., 2009; Shao and Liu, 2014) whereas LANDSAT data is suitably used for regional level mapping (Gao et al., 2012). Recent work of Wang et al. (2017) on Continuous Field Impervious Surface Change (ISC) mapping of India using LANDSAT data has reported an ISC of 2274.62 ± 7.84 Km^2 between 2000 and 2010 at 95% confidence level. This trend is continuing and will further increase in coming years.

The urbanized and urbanizing land cover has significant impacts on the ecosystems and environment. The trends of climate change are widely driven by urbanization and industrialization which are responsible for alteration of land surface and atmospheric components (Grimm et al., 2000). Sand, asphalt, concretes etc. which are the elements of this impervious surface have unique thermal properties by which they absorb and radiate energy quickly. The higher solar radiation absorption and greater thermal capacity and conductivity are mainly found in urban areas (Voogt and Oke, 2003). Due to this increasing urbanization, there has been a significant increase in global night minimum temperatures leading to decrease in the diurnal temperature range (Jones et al., 1999; Wang and Dillon, 2014; Qu et al., 2014). Apart from these global effects, the urbanized and urbanizing landscape also experiences an amendment in its local thermal

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environment. Due to high heat store during daytime and heat release at night in the city area, it experiences higher temperature than surrounding rural area. Urban Heat Island (UHI) concept is popularly used to quantify this phenomenon for a city. It has been commonly referred to as higher thermal conductivity and radiation heat budget (Howard, 1818; Rosenfeld et al., 1998; Grimm et al., 2008; Tan et al., 2010) over urban areas when compared with the countryside, because of the presence of densely artificial surfaces (Landsberg, 1981). In his recent work, Hausfather et al. (2011) has shown this spatial pattern of Land Surface Temperature (LST) for rural and urban areas and highlighted a difference in the trends of an anomaly to be 0.03 °C per decade. UHI evidently leads to changes in urban microclimate such as solar radiation absorption, land surface temperature, atmospheric temperature, evapotranspiration, water vapor and air pollutant concentration which are directly linked to human health (Changnon et al., 1996; Simsek and Sengezer, 2012). Hence, understanding the dynamics of UHI over an urban landscape is an essential part of sustainable urban planning.

Earlier the intensity of UHI was being calculated from discrete data of near-surface air temperature (Howard, 1818). With the advent of thermal remote sensing, now the Land Surface Temperature (LST) is being used widely (Rao, 1972; Gallo et al., 1993; Weng, 2001, Sabrino and Romaguera, 2004, Zhao et al., 2010, Schwarz et al., 2011; Wang et al., 2012; Xiong et al., 2012; Balcik, 2014). Many studies have been conducted using thermal band of Landsat TM/ETM+, ASTER and MODIS data (Aniello et al., 1995; Weng, 2003; Weng et al., 2004; Kato and Yamaguchi, 2007; Xiong et al., 2012; Liu and Zhang 2013; Balcik, 2014). However, with its consistent global coverage with proper spatial, spectral and temporal resolution USGS's Landsat data has been proved most effective in studying the land surface temperature at the regional scale.

The interrelationship between land surface temperature and LU/LC inside major cities have been established by different qualitative and quantitative researchers using remote sensing data (Zhang et al., 2013). Weng et al. (2004) analysed Landsat TM & ETM+ data to extract land surface temperature information for urban heat islands of Indianapolis, Indiana; Yue et al. (2007) investigated the relationship between Normalized Difference Vegetation Index (NDVI) and LST over Shanghai using Landsat 7 data; Zhang et al. (2009) established the dynamics of impervious surface and LST over Nanjing of China; Liu and Zhang (2013) conducted UHI study of Hong Kong; Balcik (2014) studied the correlation between the LST and urban built-up using the Index Based Built-up Index (IBI) inside Istanbul along various transects etc. Feyisa et al. (2014) evaluated the efficiency of parks in mitigating the UHI effects. For planning, prospective landscape matrix was used by Asgarian et al. (2015) to demonstrate the cooling effect of water bodies over the LST. Chen et al. (2016) devised an integrated landscape matrix to predict the potential UHIs. All these studies have established that quantitative analysis of spatio-temporal dynamics of Urban Heat Island Intensity (UHII) and another surface cover can contribute significantly in the process of sustainable urban planning.

In this paper, multi-temporal Landsat data was used to find out the impact of urbanization on the urban thermal environment. The main objectives of the study are: (1) quantifying the process of urbanization using the temporal land cover data developed by supervised classification method (2) quantifying the spatio-temporal dynamics of thermal environment of the study area using Land surface temperature (LST) and Urban Heat Island Intensity (UHII) derived from the thermal bands of Landsat data, and (3) assessing the complex interrelationship between urbanization and urban thermal environment through GIS analysis.

2. Study area

Ranchi, the capital City is situated in the eastern region of India on the Chotanagpur Plateau of Jharkhand state (Fig. 1). With its 37 wards, Ranchi Municipality Corporation covers an area of approximately 177.19 Km^2 extending from latitudes 23° 14′ N to 23° 26′ N and longitudes 85° 15′ E to 85° 25′ E. Over a period of last two decades this region has been experiencing a rapid urban growth especially due to its relatively pleasant climate and as the capital of new state Jharkhand (from 2002).

The city experiences a subtropical climate, which is characterized by hot summer from March to May and well-distributed rainfall during southwest monsoon from June to October. Winter season in this area is marked by dry and cold weather during the month of November to February. Due to the higher elevation of 650 m above means sea level, it experiences pleasant climatic condition, though Tropic of Cancer passes near it. Relative humidity also remains low, so summer season is also not uncongenial. The average annual temperature varies between 18 °C and 29 °C. However, due to global warming, temperature goes high up to 44 °C (IMD, 2016). The data set obtained from Indian Meteorological Department (IMD), Indian Water Portal (IWP, 2017) and local weather stations show that December is the coldest month with mean minimum temperature as low as 10.1 °C and May is the hottest month with mean maximum temperature as high as 39.0 °C. January is the second coldest month with the average daily maximum temperature at 24.3 °C and the mean daily minimum temperature at 10.2 °C. February onwards both day and night temperature increases promptly till May (hottest month of the year with the average maximum temperature at 39.0 °C).

3. Data & methodology

This study implemented a simple methodology whereby Landsat data of 1992, 2001 and 2013 were processed to generate products of LST, NDVI, MNDWI and LU/LC. Then the LST and LULC were integrated using GIS, and raster overlay method was implemented to calculate the change trajectories and CUHII. The flow diagram shown in Fig. 2 illustrates the overall methodology followed in this study. The detailed steps are described below.

3.1. Data resources and pre-processing

Satellite images from Landsat 5 TM (Thematic Mapper) and Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) and Landsat 8 OLI/TIRS sensors (acquired on 1st November 1992, 2nd November 2001 and 11th November 2013 respectively) were used in this research. The L1 Orthorectified images were downloaded from the Global Visualizer (GloVis) of U.S. Geological Survey. The TM, ETM+ and OLI/TIRS data was in resampled 30 m resolution. All the three data sets were co-registered using ERDAS 9.2 and then clipped to Area of Interest using the shapefile of Ranchi city. The GIS software Arc GIS 10 was utilized for all other GIS analysis and creating maps.

3.2. Methodology

3.2.1. Land use classification

Supervised classification with maximum likelihood algorithm was used to develop the land use maps of all three dates. The four top landuse types such as water, urban built up, forest vegetation cover, agriculture, and fallow land were identified and numbered from 1 to 4 respectively for their digital forms.

The classified images further improved using NDVI and MNDWI data. Pixels with NDVI > 0.727 and class different than the forest vegetation cover were reclassified to forest cover, and similarly, pixels with MNDWI > 0 were all classified as water (Qin et al., 2001; Xu, 2005). This reclassification is of particular importance due to the reflectance properties of vegetation and water in the wavelength region used to calculate the indices as described in Section 3.2.2.

The classification accuracy assessment was carried out using historical Google images as reference with selected ground verification for two hundred random sample points as reference data. Then, the