Chapter 4
The Changing Urban Landscape and Its Impact on Local Environment in an Indian Megacity: The Case of Delhi

Richa Sharma and P.K. Joshi

Abstract This chapter presents urbanizing scenario of the megacity, Delhi. The changing land use land cover (LULC) and various environmental variables are discussed using the conjugation of space remote sensing inputs, geospatial analysis and statistical analysis. The two vital components of LULC viz., urban land use and fraction of green cover are important to demonstrate changing urban landscape and its impact on environmental quality. The environmental quality variables like greenness, imperviousness due to built-up intensity, moisture intensity, and bareness can be retrieved from remote sensing data. A general trend of diminishing greenness, especially along the peripheral areas with depleting moisture intensity of the city surface is a common phenomenon. The new industrial developments in the northern and urban expansion in the south-western parts of the city results in drastic and slight decline in moisture respectively. This is accompanied with increase in imperviousness and bareness in some cases in the same areas. The chapter explains the complex interactions between different land uses over the progression of urbanisation explaining the process in details taking Delhi as an example. Eventually the basis for environmental degradation and formation of Urban Heat Island (UHI) in the city is also explained using LULC and environmental variables and their change statistics. The chapter thus presents the process and impacts of urban land transformations in the metropolitan city of a developing nation, India in this case.

Keywords Developing nation • Environmental variables • LULC • Urban Heat Island • Urbanization

R. Sharma
Department of Natural Resources, TERI University, New Delhi 110070, India

National Institute of Urban Affairs, New Delhi 110003, India

P.K. Joshi (✉)
Department of Natural Resources, TERI University, New Delhi 110070, India
e-mail: pkjoshi@teri.res.in; pkjoshi27@hotmail.com

R.B. Singh (ed.), *Urban Development Challenges, Risks and Resilience in Asian Mega Cities*, DOI 10.1007/978-4-431-55043-3_4

4.1 Introduction

Contemporary patterns of urbanization have resulted in the present era to be referred as ‘Urban Age’. Urbanisation per say is a phenomenon that is not new but a paced up growth in urban centres of developing countries of Asia is relatively new. Such urbanization is being characterized by rapidly rising population in cities with concomitant rise of new cities from smaller towns. Currently, nearly half of the world’s population resides in cities (Grimm et al. 2008). This fraction is expected to increase several folds in recent future, the case is particularly true for developing countries (Firdaus and Ahmad 2011). This has made ‘*urbanization*’ one of the most serious issues of global concern attracting greater attention from planners and policy makers from world over. The existing scale of urbanization is resulting in impacts that are not local but global in nature. In spite of acquiring mere 2–3 % of global land surface (Lambin et al. 2003), urban areas consume approximately 75 % of world’s resources. Urban areas thus tend to have multi-scale multiple impacts on environment, such as; fragmentation and degradation of natural habitats, loss of agricultural lands, increased CO_2 emissions (Zarzoso and Maruotti 2011), alter urban climates (Zhang et al. 2004), affecting surface hydrology (Carlson and Traci Arthur 2000; Chelsea Nagy et al. 2012) to mention a few.

Situation in India is no different from other developing countries. The country has an urban population of more than 377 million comprising approximately 31 % of the total Indian population (GoI 2011). The urban population in India has been increasing faster than expected with villages turning into towns and towns into cities at very swift pace (Table 4.1). As a result, urban population increase is higher in comparison to rural increase which possesses huge connotations for supply of infrastructure and other civic facilities in urban areas. The urbanization in India is thus, often termed as *over-urbanisation* or *pseudo-urbanisation* (Sastry 2009). Cities in India are experiencing such disproportionate increase in urban population compared to infrastructural growth, which is resulting in collapse of urban services and impact on local urban environment (Chakrabarti 2001). Hence, a regular monitoring and a thorough understanding of such environmental changes are imperative to deal with such issues.

Delhi, the capital of largest democracy, is increasingly attaining majuscule eminence among some of the greatest global cities (Taubenböck et al. 2009). It is the third largest city of the country and the largest metropolis by area (Government of Delhi 2011; United Nations 2012). In terms of population, Delhi is the second largest metropolis in India and stands third in terms of percentage of geographical

Table 4.1 Number of villages, towns and UA in India over the years (1971–2011)

	1971	1981	1991	2001	2011
UA	231	276	381	384	475
Towns	2,921	4,029	4,689	5,161	7,935
Villages	556,561	556,014	579,688	593,732	608,789

UA Urban agglomeration

area under tree cover. The city thus needs special focus from planning perspectives. But the current relatively ill-planned or even un-planned trends of growth and development are indicting negative bearings on the environment and straining the available natural resources (Firdaus and Ahmad 2011; Mohan et al. 2013). This jeopardizes the sustainability of the city's development. The city thus presents an ideal case for studying impacts of urbanization.

4.2 Delhi: The City Profile

Delhi is located in the fertile alluvial plains of Northern India as a riparian city of the River Yamuna, extending from 28°23′17″ N to 28°53′00″ N and 76°50′24″ E to 77°20′37″ E. It nestles at cross boundaries of two neighbouring states, Haryana and Uttar Pradesh covering an area of 1,483 km^2. Indo-Gangetic plains in north and east, Thar Desert in west and Aravallis in the south bind the city. The presence of such diverged geological features conveys variation to the city's altitude which ranges from 213 to 305 m.

4.2.1 Climate

The city has a remotely inland location and weather is more of continental type experiencing extreme summers and severe winters. The city is characterized by semi-arid climate with stark contrast in day and night temperatures, high saturation deficit and low to moderate rainfall. There are four major seasons during the year, the summers (March–June), monsoons (June–September), post-monsoons transition (October–November) and winters (November till March). An important attribute of Delhi's climate is the temperature extremes that the city experiences (Fig. 4.1a). The temperature during intense hot summers reaches 47 °C (mean maximum being 40.3 °C) while during winters the temperature may plunge as low as 2 °C (mean minimum is around 18.7 °C). City receives 75 % of this rainfall during the monsoonal months of July, August and September (Fig. 4.1b); IMD 2011; Government of NCT of Delhi 2013a).

4.2.2 Environment and Natural Resources

Out of a total of 1,483 km^2, 85 km^2 is under forest cover (FSI 2011) covered by the Northern Tropical Thorn Forest type (Champion and Seth 1968). Of this, 92 % is reserved and rest 8 % is protected. The city boasts of possessing few a network of protected areas; ranging from Najafgarh Jheel and city forest, Jahanpanah Forest Reserve and Asola Bhatti wildlife sanctuary. Native flora of the ridge includes

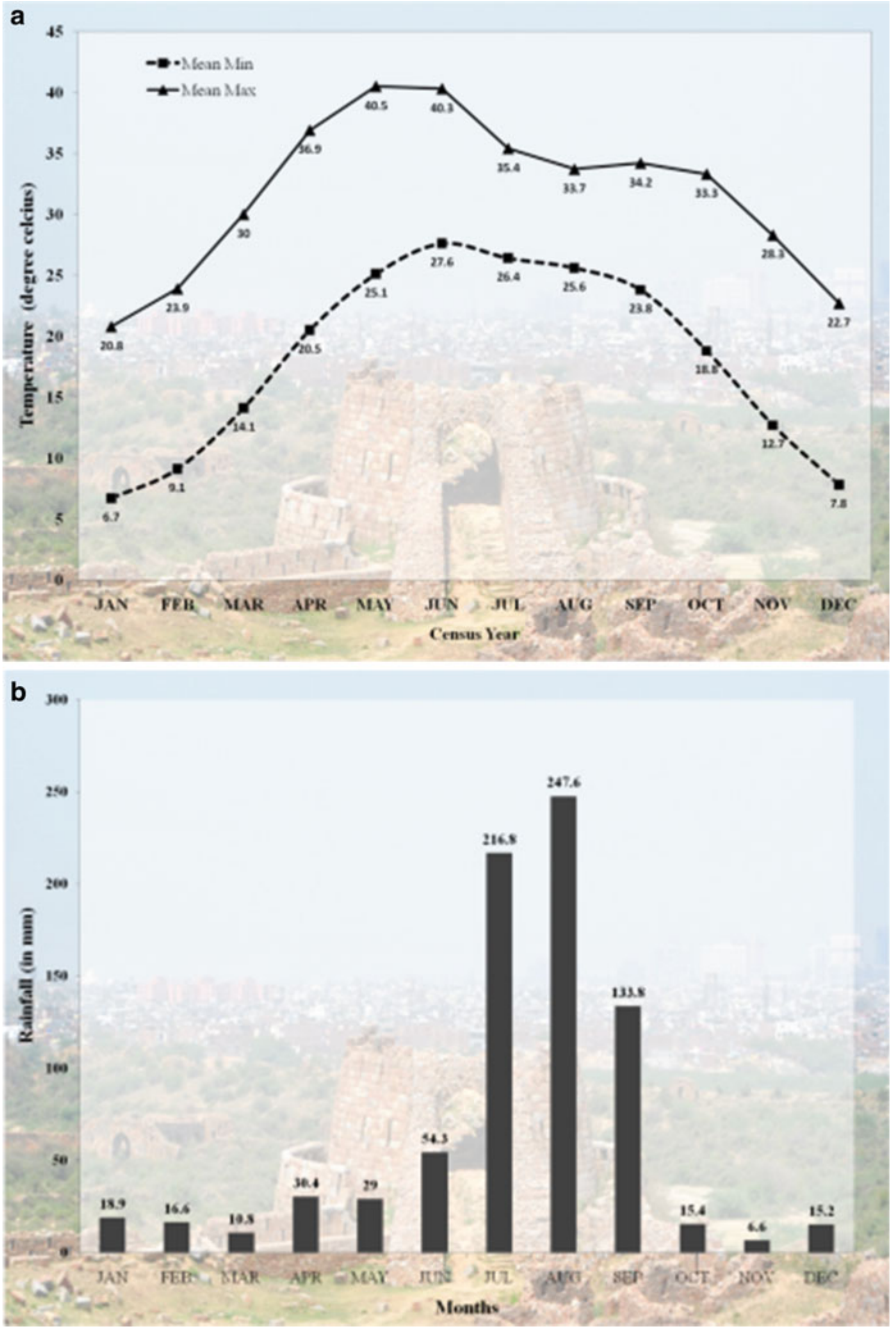

Fig. 4.1 (**a**) Month-wise mean air temperature (**b**) month wise average rainfall of Delhi (1956–2000)

Anogeissus pendula, *Ziziphus mauritana*, *Ehretialaevis*, and *Balanites aegyptiaca* that have been severely invaded by *Prosopis juliflora*. More than 400 bird species have been so far identified in Delhi, including rare ones such as *Pelecanus crispus*, *Leptoptilos javanicus* and *Rynchops albicollis* (Urfi 2003). Of these some 250 species have managed to live through the adversity of urban alterations in the environment. Apart from these, Delhi also has a lot of migratory avian visitors during winters such as ducks pintails, shovellers, common teal, garganey, leaf warblers, lesser white throats, and red starts. Developmental activities such as construction and operation of metro, airport, mobile towers in ecologically sensitive areas are creating havoc to avifaunal diversity in the city. The Ridge forms an important part of the forest cover in Delhi. It is an extension of Aravallis into the city. Delhi ridge, often referred as green lungs (Mann and Sehrawat 2009), has been adopted as an integral component for almost all development plans of the city. There are four extensions of the ridge inside the city. The ridge is collaboratively managed by different governmental agencies which include Delhi Development Authority (DDA), Municipal Corporation of Delhi (MCD), Central Public Works Department (CPWD), Land and Development Office (LDO) and the Forest Department of Delhi (Government of Delhi 2011).

Yamuna provides major proportion of surface water supply in Delhi, which constitutes nearly 86 % of the total water supply. Delhi only shares 4.6 % of river's resources as per the interstate agreements. The cleanliness of the river is a major concern for the government as industrial waste gets accumulated in the river. Ground water resources have been important source of water in some of the administrative blocks of Delhi, e.g. Alipur, Najafgarh, Kanjhawala, etc. Delhi is poor in its mineral resources. The ridge mainly comprises of quartzite rocks. Some deposits of building and road making materials, Kaolim, Quartzite rocks and China clay.

4.2.3 Demography

The population of Delhi was less than a million during pre-independence times. But after the independence and partition, there was massive immigration into the city with millions of immigrants taking the refuge. These were the times (1941–1951) when the annual average exponential growth rate for population was highest (6.63 %). This resulted in a sudden jump in the population of the city during the post-independence era. Delhi has been exploding with population since past few decades. The city recorded a population of 9.42 M in 1991, which increased by 0.85 million in 2001, finally reaching 16.7 million in 2011. Though the decadal population growth for the city has dwindled from 90 % in 1951 to 20 % in 2011, but the rapid population growth has shot up its population density from 6,352 persons/km^2 in 1991 to 9,340 in 2001 and to 11,297 in 2011 (Government of NCT of Delhi 2013a, b, c).

4.3 Urbanization and Delhi

Delhi has been expanding as a city since seventeenth century when it was called Shahjahanabad called the Walled City. In 1913, the British announced New Delhi as the capital city, and changed its face to that of a well-planned urbanized city. Next major event is history of Delhi's urbanization took place during 1947 when partition of India was done. With influx of partition refugees in huge numbers, the city's urbanization got immensely pushed up (Figs. 4.2 and 4.3). Afterwards, the city became the centre for employment opportunities and people started migrating into the city from neighbouring states of UP, Haryana and Rajasthan. 52.76 % of total population in Delhi was urban in 1901, which has increased to 97.5 % in 2011. The urban area in Delhi on the other hand has increased from 22 % in 1961 to 62.5 % in 2001 (GoI 2011).

The urban expansion of city over the years is firmly established by gradual engulfment of several villages by the city. The number of villages has decreased from 231 in 1981 to 165 in 2001 to 112 in 2011 (Mishra 2011). The expansion within Delhi has been well represented by development of sub-cities like Rohini and Dwarka (MDP 2013). Other than that million plus cities in adjoining states such as Faridabad, Gurgaon, Ghaziabad and Noida also symbolize the expansion of city beyond its borders (Dutta and Bandyopadhyay 2011).

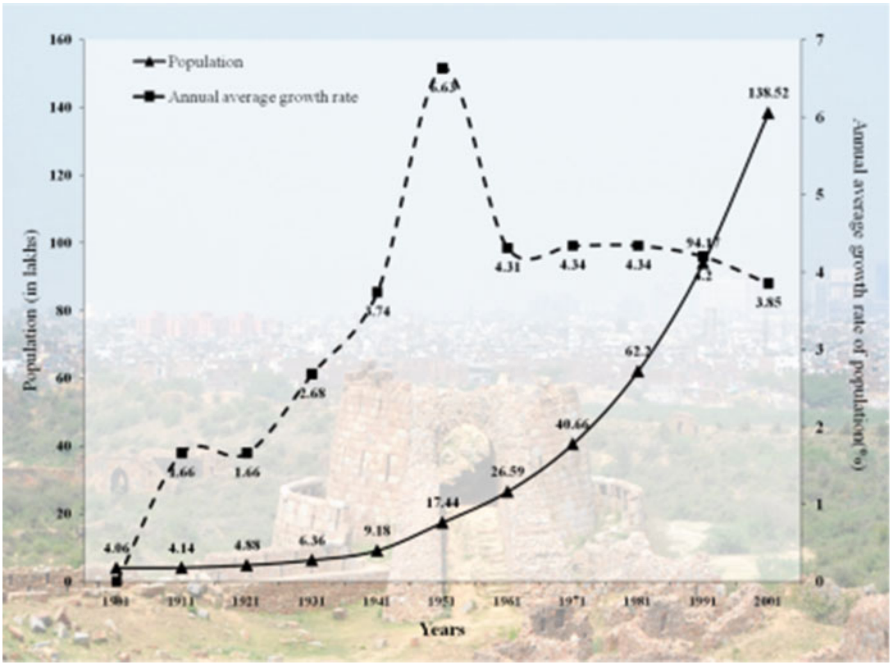

Fig. 4.2 Annual average growth rate and population increase (GoI 2011)

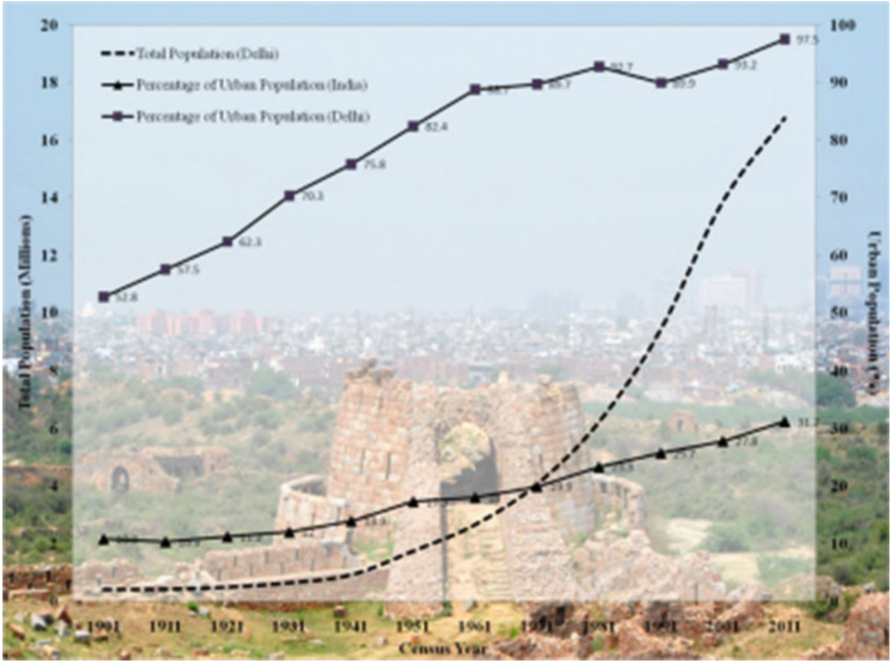

Fig. 4.3 Urbanization in India vs. Delhi (GoI 2011)

Table 4.2 Trends of migration in Delhi

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Migration (lakhs)	0.55	0.62	0.6	0.56	0.67	0.76	0.77	0.67	0.8	0.78

The increase in Delhi's population is not only due to natural increase but nearly 25 % increase is due to migration (Table 4.2). More than 50 % of migration takes place from neighbouring states of Uttar Pradesh (UP) and Haryana. Another 14 % of total migration is from Bihar, 3 % from West Bengal and 2 % from Madhya Pradesh. Punjab and Rajasthan each contribute 5 % each to the migration in Delhi. UP is the leading contributor adding migrating population to the city.

4.4 The Changing Landscape of Delhi

Urbanization in Delhi is achieving unprecedented pace and enormity modifying the city's landscapes massively. The most important manifestation of such alterations is changes in land use and land cover (LULC) across the city (Sharma and Joshi 2012; Sokhi et al. 1989). LULC changes across globe have direct and indirect implications on the ecosystem. Some explicit impacts of LULC change include fragmentation and degradation of forests resources (Freitas et al. 2010) due to conversion to urban or agricultural uses of land. Further implied repercussions of such LULC changes include contribution to soil degradation (Tolba and El-Kholy 1992), affecting biodiversity (Sala et al. 2000), and affecting regional climate altering the earth system functioning (Zhang et al. 2010). All such factors cumulatively tamper the ecosystem functioning and thus affect the ecosystem's capability to support human needs (Vitousek et al. 1997). Monitoring, mapping, studying and documenting LULC changes thus becomes imperative for managing natural resources (Loveland and DeFries 2004) and dealing with altering micro-climate of the cities (Carlson and Traci Arthur 2000). In the present scenario, two important components of LULC transformation considered are; conversion to urban land use (Seto et al. 2010) and proportion of green or vegetation cover (Jiang et al. 2006).

Interpretation of satellite remote sensing inputs [Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+)] for 1998, 2003 and 2011 were used for explaining the annual LULC. Season (rabi, kharif and zaid) data based on prevailing cropping practices are useful to extract the insights in LULC pattern. Additional information about elevation, slope and aspect derived from ASTER GDEM data was also used. These LULC classes namely agriculture, forest, plantation, scrub, sparse built-up, dense built-up, exposed area and water are shown in Table 4.3. The information on these eight class seasonal information was combined together to form annual composite map consisting of eleven LULC classes (Fig. 4.4). Table 4.3 presents the classification scheme followed for mapping annual LULC maps. The change detection for the three annual maps provides statistics for from-to changes in LULC.

The built-up area in 2003 (504 km^2) increased by 15 % from 1998 (440 km^2) and again in 2011 (521 km^2), it further increased by 17 km^2. Forest lost by 5 % area from 1998 (122 km^2) to 2003 (116 km^2), and again by 32 % (37 km^2) from 2003 to 2011. Agriculture suffered major loss of 17 % from 1998 to 2003 but gained very little (4 km^2) during 2003–2011 phase. Overall agriculture was found to decrease from 1998 to 2003 and then slightly improve from 2003 to 2011. Huge dynamics was observed within agricultural classes; Double crop (DC), Rabi crop (RC), Kharif crop (KC) and Zaid (ZC). Double and rabi crop exhibited very complex mutual dynamics with marked inter-conversions. From 1998 to 2003, classes that had maximum gain from rabi crop lands are exposed land (32 km^2) and kharif crop (7 km^2). Kharif's loss was mainly due to conversion to sparse built-up lands (28 km^2). This is the category that contributed the biggest chunk of land to sparse built-up. Zaid crop has no major contribution to any other class during this time period. But it suffered major loss at hands of sparse built-up (10 km^2). The trend during 2003–2011 was more or less similar to previous years, except a few cases. The mutual interchanges of double crop and rabi crop were observed similar to previous 1998–2003 analysis. Sparse built-up and Kharif crop were major gainer from rabi crop. Each class increased by 21 and 23 km^2 respectively due to rabi crop. Kharif crop's loss during this phase is mainly to double cropping (6 km^2). Kharif and zaid crop did not act as major contributors to any category. But zaid suffered major loss at hands of other two agricultural classes; double and kharif crops (7 km^2 each).

Table 4.3 Comprehensive LULC classification scheme

LULC classes mapped		Description
Agriculture	Double crop	Land under agriculture that is cropped two or more than two times a year
	Rabi/winter crop	Areas under cropping during November/December and February/March months
	Kharif/summer crop	These lands are cropped during south-west monsoon season, from months of June/July to September/October
	Zaid/monsoon crop	Zaid crop areas are areas cultivated during summers, from April to August/September
Exposed area		Exposed lands include categories of land covered by sand (e.g. river beds), barren rocky area, current fallow lands etc., which are bright due to high reflectance
Vegetation	Forest	Forest area includes dense tree vegetation e.g. areas of central and northern ridge in Delhi
	Plantation	These include areas under tree crops of agricultural or non-agricultural significance (part of policy and management processes) and tree vegetation along the roads as well
	Scrub	Scrub lands are mainly dominated by scrub (shrubby) vegetation and are highly erosion prone areas and are often mixed with cropped lands
Built-up	Sparse	Area that is mainly covered with human settlements and built-ups but has some proportion of vegetated and open lands in between. Thus these areas have relatively lesser density of built-up
	Dense	Areas that have higher density of built-up and are characterised by lesser proportion of vegetation or open lands
Water		Water bodies like river or smaller impoundments in form of tanks or reservoirs

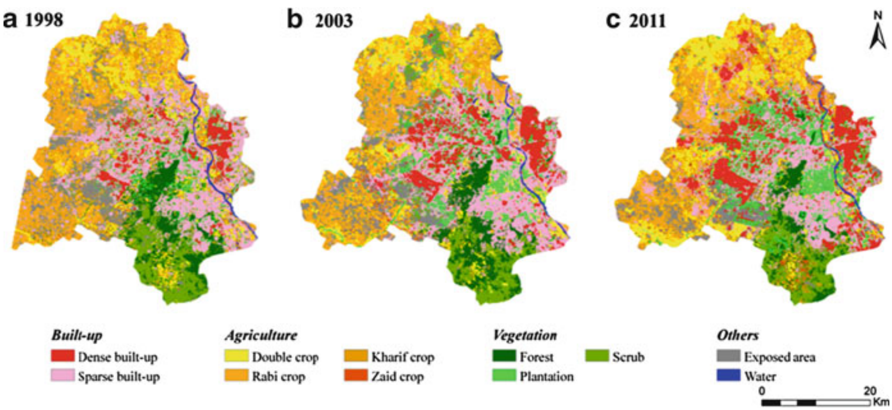

Fig. 4.4 Land use land cover results for (**a**)1998, (**b**) 2003 (**b**) and (**c**) 2011 (Sharma 2013)

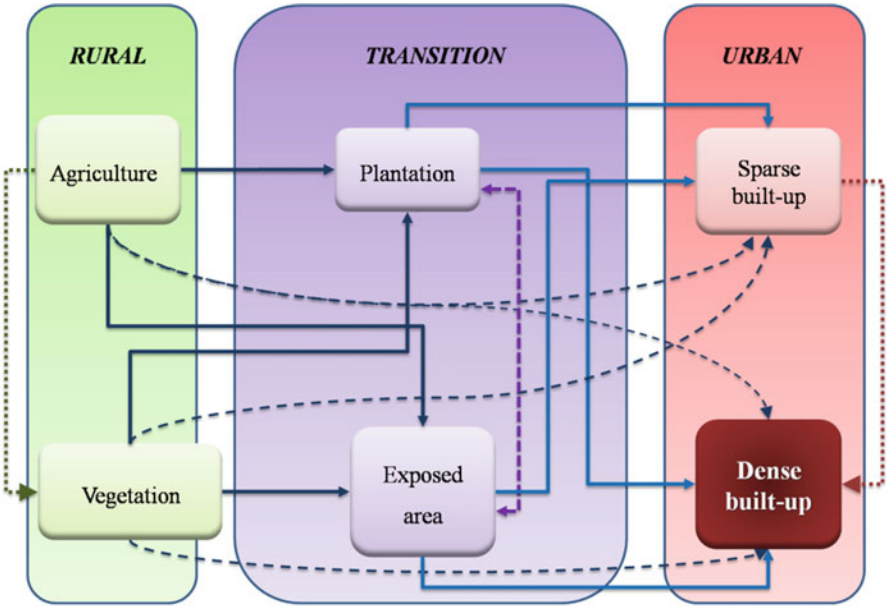

Fig. 4.5 Urbanization—the process and dynamic implications for overall LULC pattern (Sharma 2013)

Vegetation (comprising of forest, plantation and scrub) is another class that exhibited within subclass dynamics. The class increased in area by 13 and 7 % during each interval. Forests decreased by 6 and 37 km^2 during each time period. Similarly 8 and 11 % fall was observed for scrub class. Plantation was the only vegetation class that kept expanding during both intervals by 94 and 66 % due to massive spread in the horticultural plantation on Yamuna river beds and also rise in sparse built-up area which is characterised by scattered vegetation like roadside plantation and small community parks.

Dense built-up was found to double up from 1998 to 2003 and further increased by 44 %. Sparse built-up initially increased slightly by 3 km^2 and then it fell down by 40 km^2. Exposed area initially did not exhibit any change but it decreased by 29 % during 2003–2011 interval. Water covered area shrivelled by more than one-fourth during 1998–2003, and further diminished by 4 % from 2003 to 2011. These statistics support the complete tract of land conversions and inter-conversions acting in the course of urbanisation (Fig. 4.5). Process of urbanisation has been split in three phases; Rural, Transition and Urban. Rural phase comprises of two classes, viz., agriculture and vegetation. The vegetation class is not restricted to rural only as it includes forest and scrub, both. The forest part is restricted to rural phase while scrub spans across from rural phase to transition phase. Transition phase covers plantation and exposed area. Built-up classes strictly fall under urban phase.

The diagram (Fig. 4.5) explains the complex interactions between different land uses over the progression of urbanisation. It is illustrated that agriculture gets converted to vegetation (scrub), plantation, and exposed area entering the transition phase. Apart from this, agriculture also contributes directly to urban phase (built-up classes). Another rural phase class vegetation (forest) is conducive to urbanisation by getting transformed to transition (plantation and exposed area) and urban (sparse built-up and dense built-up) phases. Thus, the land cover flow from agriculture to vegetation is ultimately flowing into transition and urban phases. The transition phase demonstrates conversion of plantation to built-up. Intra-stage land transformation is illustrated by exposed area and plantation. The final stage is urban stage, where sparse built-up engulfs massive land masses from transition phase (plantation and exposed area) and rural phase (agriculture and vegetation). Along with other classes, sparse built-up also contributes to dense built-up. Dense built-up is thus the final category where all '*to*' land use transformations occur culminating the process of urbanisation.

4.5 Urbanizing Delhi and the Changing Environment of City

The environment of an area is governed by a myriad of factors and processes displaying an inter-play at hierarchical scales of space and time. LULC is one such prime factor that has its influence at all spatial scales from global to regional or local levels. Considering the case of cities, the local scale, LULC and land surface temperature (LST) plays imperative role in shaping of the environment due to pronounced anthropogenic activities and their entrenched impacts (Mallick et al. 2008). Thus it is only a prudent step to monitor LULC, LST and their relationships to keep a track of any implied changes in the environmental status of the region.

Land use in cities is characterised by built-up covers. More specifically in cities of developing nations, Delhi in this case, apart from built-up cover, LULC is also characterised by the presence of agricultural lands in peripheral parts and some forest patches in the city. This indicates that vegetation represents another important land use category in the cities. The crucial balance of built-up and vegetation in the city determines the status of LSTs and other variables of environmental quality. The proportion of green or rural and built-up or urban cover governs the city's thermal environment and hence governs its urban heat island distribution. 'Urban Heat Island' or UHI is the area of city or city itself ('*Urban*') where the temperature is relatively higher ('*Heat*') than their surrounding comparatively rural or green environs ('*Island*').

Environmental quality is viewed as a latent characteristic that is synergistically determined by a number of variables. Thus, for monitoring environmental quality, apart from LST, four other prominent indicators were chosen; greenness, imperviousness, moisture intensity and intensity of bareness. Of these, *greenness* was estimated using NDVI or Normalised Difference Vegetation Index (Gallo et al. 1995; Goetz 1997; Maxwell and Sylvester 2012; Weiss et al. 2004; Zhou et al. 2004), Normalised Difference Built-up Index (NDBI) was used to assess imperviousness, Normalised Difference Water Index (NDWI) was used to estimate moisture intensity and finally intensity of bareness was assessed using Normalised Difference Bareness Index (NDBaI). LST retrieval was retrieved using Qin et al's monowindow algorithm (Qin et al. 2001; Sun et al. 2010). NDVI based emissivity estimation method was employed for emissivity correction (Zhang et al. 2006).

4.5.1 Changing Distribution of Biophysical Variables and the Dynamics of Their Inter-Relationships

Greenness—NDVI distribution in the city indicates the pattern of diminishing greenness, especially along the peripheral areas. The south-western parts of Najafgarh and Dwarka, north-western suburbs of Rohini and industrial patches of Bawana and Narela noticeably exhibited a degrading vegetation cover that was due to expansion of industrial and residential land uses in these areas. Major agricultural portions of these areas have been converted to built-up for industrial sites. Thus, transitional fall in NDVI is seen providing a direct indication of the diminishing green cover (Fig. 4.6).

Moisture intensity—Water index images illustrate a depleting trend in moisture intensity of the city surface (Fig. 4.6). The peripheral agricultural lands and central and southern ridge areas present better status of moisture intensity as compared to the urban areas. Over the years, drastic decline in moisture status is observed for new industrial developments in northern parts of the city and slight decrease in the gradual south-western urban expansions. With conversion of agricultural land to built-up area, the land loses its vegetation cover, which in turn results in loss of huge amount of moisture. This resultantly brings down the moisture intensity of such transformed land.

Imperviousness—NDBI is computed using difference of band 4 (NIR) from band 5 (MIR), the bands that are sensitive to vegetation and moisture. The southern parts of city are dominated by scrub forest. Such forests are tropical dry forest with xeric shrubland vegetation. Since the forest is an extension of the Aravallis (the mountain ranges running into Rajasthan), at some places, it contains semi-desert soil. Thus, these forest lands have high sensitivity in MIR and low in NIR bands compelling these to exhibit high NDBI in spite of being non-built-up land. With the exception of the southern ridge, high NDBI was observed in built-up areas. NDBI results for the year 1998, 2003 and 2011 indicated an increasing expansion in built-up surface of the city (Fig. 4.6).

Intensity of bareness—Intensity of bareness of the surface was estimated using NDBaI. MIR and thermal bands were used to retrieve information regarding the bareness. The areas that got highlighted are majorly open or exposed lands and to some extent, the scrub forest lands. Huge chunks of land in suburban areas is captured and left exposed for succeeding construction activities. Such lands

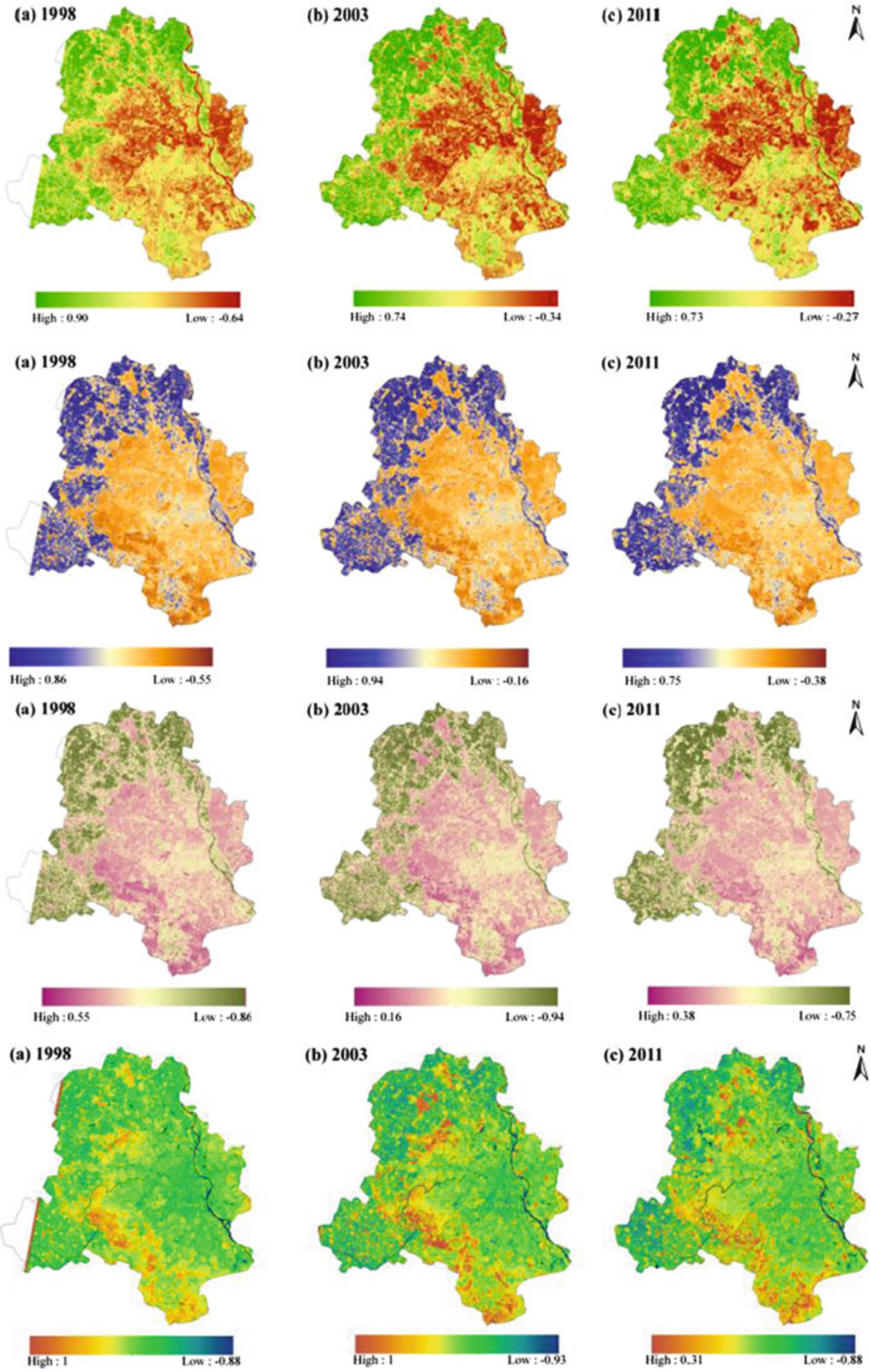

Fig. 4.6 NDVI, NDWI, NDBI, NDBaI and LST maps for 1998, 2003 and 2011 (Sharma 2013)

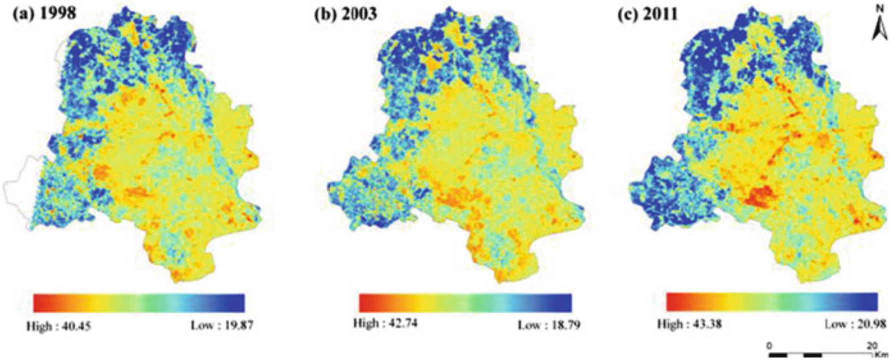

Fig. 4.6 (continued)

illustrate high bareness intensities. But as they get converted to built-up, their NDBaI values fall down. The NDBaI trend for the three images show that bareness was minimum for the year 1998, for 2003 more and more suburban lands exhibited very high bareness intensities, with some of these then subsiding in 2011 after their conversion to built-up areas. Southern scrub forest due to predominance of exposed rocks demonstrated high NDBaI (Fig. 4.6).

Land Surface Temperature (LST)—LST distribution across the city for 3 years (1998, 2003 and 2011) was also mapped. High LST values were found to have spread out from city centres. Very high LST values were observed for 2011 along the major industrial centres and notably in the IGI airport area along with central parts of city that include Old Delhi. Newly built-up patches of Bawana and Narela in north and Dwarka and Najafgarh in south-west exhibited a progressive elevation in LST with increased built-up in these areas over the years (Fig. 4.6). The two areas recorded an increase of about 5–15 °C and ~2 °C respectively.

Strong positive or negative correlations were observed among various variables, except with NDBaI. LST was negatively related to with NDVI and NDWI. LST-NDVI exhibited negative correlation values of −0.75, −0.81 and −0.71 for 1998, 2003 and 2011 respectively. At the same time, the correlation values for LST and NDWI were −0.89, −0.88 and −0.74 during 1998, 2003 and 2011. The relationship for LST-NDVI is directional from NDVI to LST. NDVI represents the abundance and status of health of vegetation, thus higher the NDVI, the better is the vegetation. Vegetation contributes in bringing down the surface temperature in various ways; for example, their shadow results in lesser incident radiation, therefore, less heating while the vegetation cover maintains a more pervious surface which absorbs more moisture, thereby, bringing down the temperatures by evaporation. Evapo-transpiration is an important way by which plants bring about cooling of the surrounding. All these culminate in bringing down the LST. Thus, higher is NDVI, lesser is the LST. However, the NDVI for water is negative but owing to evaporation, it brings about cooling effect. Thus, in spite of negative (very low) NDVI, water has low LST as well. This exceptional phenomenon can be observed in the correlation graph of LST vs. NDVI where, the curve shows minimum NDVI (water) values not for maximum LST but for lower LST values.

Relationship of LST with NDWI is negative with −0.89, −0.88 and −0.74 in 1998, 2003 and 2011. This relationship is apparent from the fact that water causes cooling through the process of evaporation. This relationship is bi-directional unlike relationship of LST with other variables. Thus it is not only NDWI influencing the LST, but LST also controls the NDWI. As LST increases, it evaporates the water available in the surface, bringing down its moisture status, thus lowering the NDWI. LST's correlation with NDBI is similar to NDWI but opposite in direction with correlation coefficient being 0.89, 0.91 and 0.74 for years 1998, 2003 and 2011. NDBI being sensitive to moisture and vegetation highlights built-up areas that are typically devoid of vegetation cover and have very low moisture content due to their imperviousness. Since built-up areas lack both vegetation and do not hold moisture, they tend to exhibit elevated temperatures; therefore, as NDBI moves up or down, the LST moves in lockstep in same direction.

NDBI had a negative correlation with both NDVI and NDWI with high correlation coefficient values for each year. Built-up area is typically characterised by low or no green cover and high or very high imperviousness, a distinctive property of urban materials such as concrete. This explains the negative correlations existing between NDBI-NDVI and NDBI-NDWI. Since vegetation cover lands tend to retain water and also their leaves contain huge amounts of moisture, a high positive correlation is observed between NDVI and NDWI. NDBaI with NDBI and NDWI had respectively positive and negative correlations of the order 0.3. Since NDBaI had neither strong nor any consistent relationship with other variables, NDBaI has not been used for analysing its relationships with LULC.

The complex and dynamic relationship among these biophysical variables helps in identifying both the explicit and implicit impacts of process of urbanisation in Delhi on the environmental quality. The Fig. 4.7 illustrates this phenomenon based on the correlation results and theoretical analysis discussed so far.

For urban sprawl to take place, the first major change in land use is loss of vegetation cover. This brings down the NDVI, as well as NDWI. The negative correlation of NDVI and NDWI with LST suggests that a fall in these two indices results in an increase in LST. The next eventual transition of land is conversion to built-up, which increases NDBI. NDBI's negative correlation with NDWI and positive one with LST insinuates a drop off in NDWI and intensification of LST. Fall in NDWI further implies a rise in LST. Thus urbanisation of an area via dual pathways brings about massive changes in the environmental quality. The figure also explains the development of UHI with context to mere land use changes and also helps to understand the remotely sensed science behind its development. For example, in case of Indira Gandhi International (IGI) Airport (Fig. 4.8), the LST range in 1998 was around 34–36 °C with few patches of higher LST of order of 36–38 °C. In 2003, major portion is covered with higher 36–38 °C LST range. 2011 image reveals, that complete airport area exhibits higher LST of around 38 °C with new patches of highest LST values ranging between 38 and 40 °C. The results clearly demonstrate the impacts of alterations in LULC of Delhi, on surface temperatures and gradual culmination of the city as an island of heat.

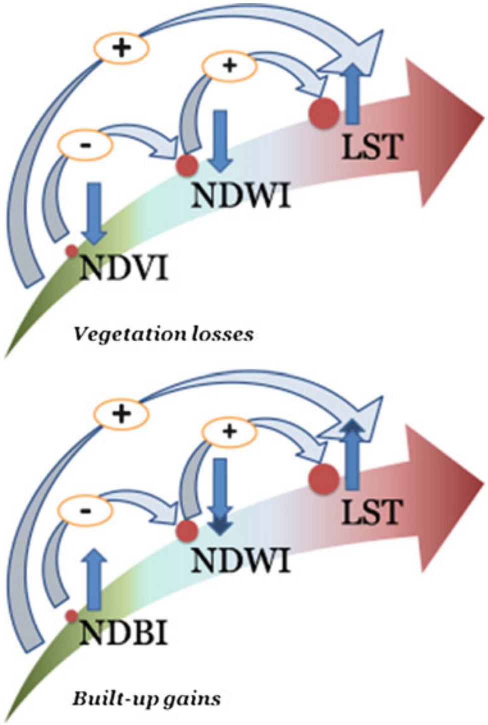

Fig. 4.7 Synergies of environmental health indicators driving the environmental changes in response to process of urbanization (*Minus* represents a negative or diminishing effect, and *plus* represents a positive or elevating effect) (Sharma 2013)

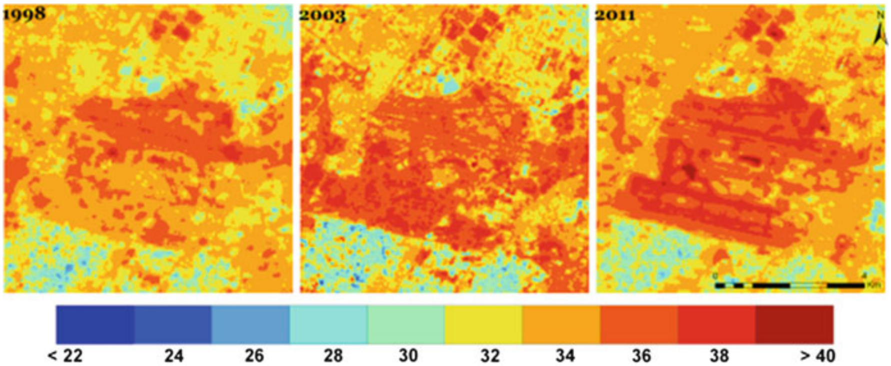

Fig. 4.8 Zoomed in view of LST distribution in and around IGI airport area

4.5.2 LULC (Green Cover and Urban Fraction) and LST

The discussions so far indicate that changing land use of Delhi altered the various biophysical variables determining environmental quality. LULC is a significant governing factor of environmental quality status. Another major highlight of the discussion is that, all the variables that were altered had their additive impact on

LST distribution patterns. LST is thus the ultimate receiver of the impacts incurred upon various environmental variables. This eventually elevates the LST culminating in formation of Delhi as an urban heat island.

Since, LST is majorly governed by greenness (NDVI) and imperviousness (as indicated by NDBI and NDWI). Thus, vegetation class (comprising of plantation, forest and all agricultural classes viz., double crop, rabi, kharif and zaid crops) and urban class (sparse and dense built-up) were analyzed to study impact of urbanizing LULC on city's LST. A very high negative correlation was observed for LST with green cover percentage with $r = -0.97$. This indicates that as the proportion of green cover increases, LST follows it in steplock in the same direction. The grids that were covered mainly with water had low green cover percentage as well as low LST. A positive correlation with $r = 0.96$ was observed for LST and urban (built-up) percentage. The plot illustrates that an increase in built-up fractions of the area drag the LST upwards (Fig. 4.9).

4.5.3 'Urban Heat Island' Development in Delhi Over the Decades

Qualitative analysis of urban area coverage versus LST categories revealed that the total area under 32–34 °C has increased over the years from 656 km^2 in 1998 to 660 km^2 in 2003 to finally reaching 774 km^2 in 2011 (Fig. 4.10). Similar trend is observed for built-up area statistics recording an increase in the 32–34 °C category from 236 km^2 (1998) to 274 km^2 (2011). It establishes a convergence of high LST areas with high built-up, and also revealed a simultaneous upward trend for both. This established the fundament for UHI development in Delhi supported by the fact that high heat areas majorly occurred in high urban or built-up lands of the city.

4.6 Conclusion

Land use type greatly influences the quality of the environment in the region. The notion is strengthened by the correlation analysis between different environmental biophysical variables analysed; viz., greenness, imperviousness, moisture intensity, intensity of bareness and surface temperature. This exercise provides an understanding of how LULC changes influence the environment and what are crucial factors that were influenced. This also helped in identification of prime factors governing environmental quality and their inter-relationships. This section quantified the qualitative and quantitative relationship of different environmental biophysical variables and hence gave a better understanding of their fundamentals. In next section, these observations were used in background to analyse LULC change

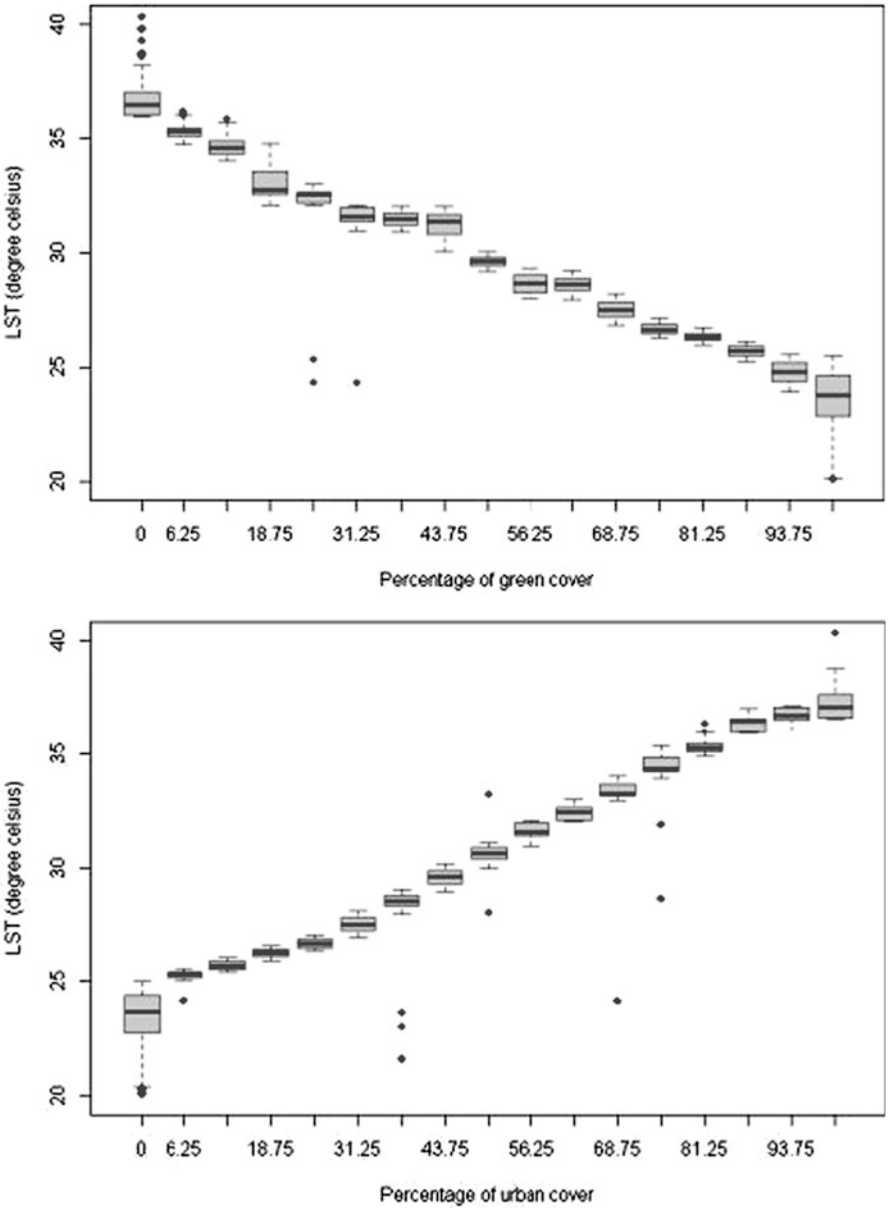

Fig. 4.9 Boxplot curve of green cover & LST and urban cover & LST. (Sharma 2013)

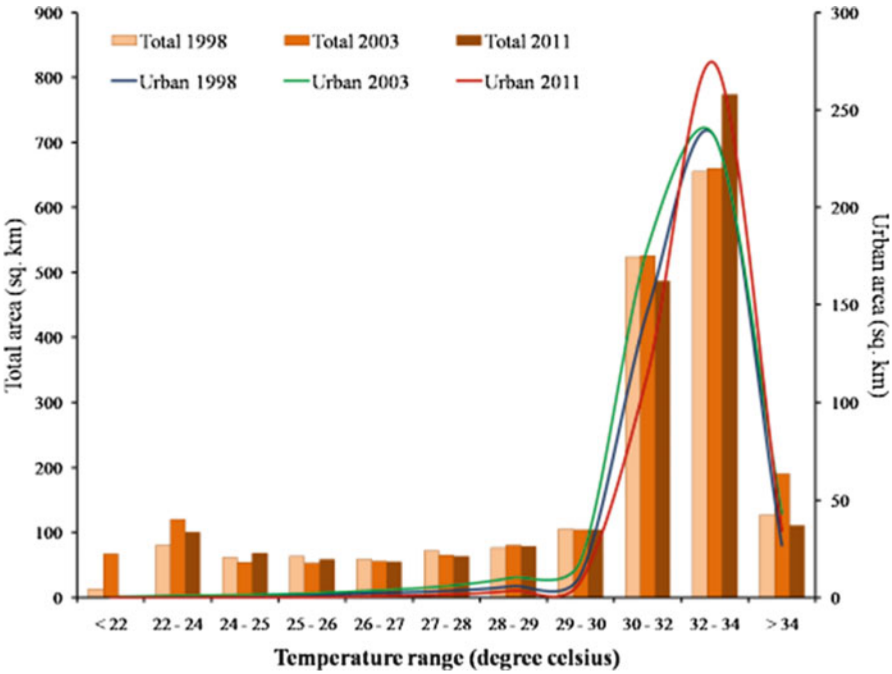

Fig. 4.10 Distribution of urban area by LST categories over the years (1998, 2003 and 2011) (Sharma 2013)

statistics specific to Delhi and their impacts on the environment. The statistics also formed the basis of understanding the progression of UHI in Delhi.

It is evident from the study that rapid and rampant urbanisation has taken place in Delhi over the years. The process has massively modified the land use and land cover patterns in the city, which in turn have their repercussions on environmental variables. An analysis of the inter-relationship of these variables illustrated that LST is uni-directionally related with other variables, where LST served as the variable which bears the ultimate impacts of the change. It is the most important variable. The crucial factors which designed the LST distribution over the city were built-up and green cover fractions. From 1998 to 2011, Delhi witnessed tremendous increase in built-up and decrease in green cover, which has resulted in high LST patches within the city creating archipelagos of heat.

Acknowledgement This research has been supported by the Department of Science and Technology (DST), Government of India and TERI University, Delhi. The authors are also grateful to anonymous reviewers for their comments. The chapter is part of a doctoral thesis submitted at the Department of Natural Resources, TERI University New Delhi

References

Carlson TN, Traci Arthur S (2000) The impact of land use—land cover changes due to urbanization on surface microclimate and hydrology: a satellite perspective. Glob Planet Change 25:49–65

Chakrabarti PGD (2001) Urban crisis in India: new initiatives for sustainable cities. Dev Pract 11:260–272

Champion HG, Seth SK (1968) A revised survey of the forest types of India. Manager of Publications, Government of India, New Delhi

Chelsea Nagy R, Graeme Lockaby B, Kalin L, Anderson C (2012) Effects of urbanization on stream hydrology and water quality: the Florida Gulf Coast. Hydrol Process 26:2019–2030

Dutta BK, Bandyopadhyay D (2011) Management of Delhi's urban growth and shrinkage. In: Change for stability: lifecycles of cities and regions. Presented at the REAL CORP 2011

Firdaus G, Ahmad A (2011) Impact analysis of urbanization on rural livelihood – an empirical study of an urban centre of Delhi. India Int J Urban Stud 15:147–160

Freitas SR, Hawbaker TJ, Metzger JP (2010) Effects of roads, topography, and land use on forest cover dynamics in the Brazilian Atlantic Forest. Forest Ecol Manag 259:410–417

FSI (2011) The state of the forest report. Forest Survey of India, Ministry of Environment and Forest, Govt. of India, Dehradun

Gallo KP, Tarpley JD, McNab AL, Karl TR (1995) Assessment of urban heat islands: a satellite perspective. Atmos Res 37:37–43

Goetz S (1997) Multi-sensor analysis of NDVI, surface temperature and biophysical variables at a mixed grassland site. Int J Remote Sens 18:71–94

GoI (2011) Census of India 2011 (Census). Government of India, New Delhi

Government of Delhi (2011) Government of India [WWW Document]. delhi.gov.in

Government of NCT of Delhi (2013a) Human development report 2013 [WWW Document]. delhi.gov.in. URL http://www.delhi.gov.in/wps/wcm/connect/DoIT_Planning/planning/misc./index+human+development+report+2013

Government of NCT of Delhi (2013b) Socio-economic profile of Delhi (2010–11). Planning Department, Govt. of NCT of Delhi, New Delhi

Government of NCT of Delhi (2013c) Economic survey of Delhi (2012–13). Government of India, New Delhi

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. Science 319:756–760

IMD (2011) Indian Metreological Department [WWW Document]. imd.gov.in

Jiang Z, Huete AR, Chen J, Chen Y, Li J, Yan G, Zhang X (2006) Analysis of NDVI and scaled difference vegetation index retrievals of vegetation fraction. Remote Sens Environ 101:366–378

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu Rev Environ Resour 28:205–241

Loveland TR, DeFries RS (2004) Observing and monitoring land use and land cover change. Ecosyst Land Use Change Geophysical Monograph Series 153:231–246

Mallick J, Kant Y, Bharath B (2008) Estimation of land surface temperature over Delhi using Landsat-7 ETM+. J Indian Geophys Union 12:131–140

Mann M, Sehrawat S (2009) A city with a view: the afforestation of the Delhi Ridge, 1883–1913. Mod Asian Stud 43:543–570

Maxwell SK, Sylvester KM (2012) Identification of "ever-cropped" land (1984–2010) using Landsat annual maximum NDVI image composites: Southwestern Kansas case study. Remote Sens Environ 121:186–195

MDP (2013) Delhi Master Plan 2021 [WWW Document]. Delhi-Masterplancom

Mishra OP (2011) Policing Delhi: urbanization, crime, and law enforcement. Oxford University Press, New Delhi

Mohan M, Kikegawa Y, Gurjar B, Bhati S, Kolli NR (2013) Assessment of urban heat island effect for different land use–land cover from micrometeorological measurements and remote sensing data for megacity Delhi. Theor Appl Climatol 112: 647–658

Qin Z, Karnieli A, Berliner P (2001) A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel-Egypt border region. Int J Remote Sens 22:3719–3746

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A (2000) Global biodiversity scenarios for the year 2100. Science 287:1770–1774

Sastry GS (2009) A model for sustainable urbanisation: the case of Karnataka. J Soc Econ Dev 11:17–45

Seto KC, Rodriguez RS, Fragkias M (2010) The new geography of contemporary urbanization and the environment. Annu Rev Environ Resour 35:167–194

Sharma R (2013) Development and behaviour of Surface Urban Heat Island (SUHI) in semi-arid conditions of Delhi (Doctoral Thesis). TERI University, Delhi

Sharma R, Joshi P (2012) Monitoring urban landscape dynamics over Delhi (India) using remote sensing (1998–2011) inputs. J Indian Soc Remote Sens 41: 641–650

Sokhi BS, Sharma ND, Uttarwar PS (1989) Satellite remote sensing in urban sprawl mapping and monitoring – a case study of Delhi. J Indian Soc Remote Sens 17:57–69

Sun Q, Tan J, Xu Y (2010) An ERDAS image processing method for retrieving LST and describing urban heat evolution: a case study in the Pearl River Delta region in South China. Environ Earth Sci 59:1047–1055

Taubenböck H, Wegmann M, Roth A, Mehl H, Dech S (2009) Urbanization in India – spatiotemporal analysis using remote sensing data. Comput Environ Urban Syst 33:179–188

Tolba MK, El-Kholy OA (1992) The world environment 1972–1992: two decades of challenge. Chapman & Hall, New York

United Nations (2012) World urbanization prospects: the 2011 revision. Department of Economic and Social Affairs. Population Division, UN

Urfi AJ (2003) The birds of Okhla barrage bird sanctuary, Delhi, India. Forktail 19:39–50

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737–750

Weiss M, Baret F, Smith G, Jonckheere I, Coppin P (2004) Review of methods for in situ leaf area index (LAI) determination: Part II. Estimation of LAI, errors and sampling. Agric Forest Meteorol 121:37–53

Zarzoso IM, Maruotti A (2011) The impact of urbanization on CO2 emissions: Evidence from developing countries. Ecol Econ 70:1344–1353

Zhang X, Friedl M, Schaaf CB, Strahler AH, Schneider A (2004) The footprint of urban climates on vegetation phenology. Geophys Res Lett 31:1–4

Zhang J, Wang Y, Li Y (2006) A C++ program for retrieving land surface temperature from the data of Landsat TM/ETM + band6. Comput Geosci 32:1796–1805

Zhang N, Gao Z, Wang X, Chen Y (2010) Modeling the impact of urbanization on the local and regional climate in Yangtze River Delta. China Theor Appl Climatol 102:331–342

Zhou L, Dickinson RE, Tian Y, Fang J, Li Q, Kaufmann RK, Tucker CJ, Myneni RB (2004) Evidence for a significant urbanization effect on climate in China. Proc Natl Acad Sci U S A 101:9540–9544