Chapter 17
Monitoring and Modelling of Urban Sprawl Using Geospatial Techniques—A Case Study of Shimla City, India

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Abstract Urban Sprawl, a burning global phenomenon, refers to that extent of city or urbanisation, which may driven by industrialisation, population growth, settlement on the periphery of the city and large-scale migration. India, with population of over one billion, which is one-sixth of the world's total population, phenomenon of Urban Sprawl is affecting its natural resources like never before. This results in multiple problems such as unmanageable transportation, unemployment which results in poverty, illegal housing colonies, slums, etc. This study illustrates the use of Geospatial and Statistical Techniques to highlight the extent of Urban Sprawl in Shimla Municipal Corporation, Himachal Pradesh, India; at a detailed level. In the present work, four temporal satellite images of Landsat Thematic Mapper have been used over a period of nearly two decades (i.e. 1991–2011). Landsat imageries of two time periods (Landsat Thematic Mapper (TM) of 1991 and 2011; and ETM+ (Enhanced Thematic Mapper) 2001), were used and quantified for studying the decadal change in land use/land cover. Supervised classification methods have been employed using Support Vector Machine in ENVI 5.0 and ERDAS 2014. The study area is categorized into five different classes, viz. water bodies, forest area, built-up area, agriculture and open space. The results indicate that built-up area is the major land use in study area. During the period 1991–2011, the area under built-up land has increased by 529.65 ha (26.48)% due to construction of new buildings on forest land, agricultural land and open spaces. As a result, the area under vegetation (forest), open space and water bodies decreased by −361.71 ha (−18 09%), −178.02 ha (−8.90%), 0.36 ha (0.02%) respectively. Urban built-up density was calculated in percentage (%) for 25 wards

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of the city for 1991, 2001 and 2011. Depending on the density levels, it categorized as low, medium and high density. The process of urban expansion in the Shimla City during 1991, 2001 and 2011 are further studied by examining a distance decay concept from a major road. The study also highlights the nature, rate and location of change; and the importance of digital change detection techniques in land use planning for sustainable growth of the study area. The Shannon's Entropy Index and Landscape Metrics have been computed in order to quantify the urban growth using built-up area as a spatial unit. Further, Stepwise Regression techniques were used to explore the relationship between the urban growth and its contributory factors. Further, Stepwise Regression was used to study the impact of Independent Variables (population density, female literacy rate, road density, total workers, sex ratio, α-population, number of HH, β-population) and Dependent Variables (percentage of built-Up area) factors on urban growth. The result shows that the growing population triggers the increase in built-up area in study area. This study also demonstrates the potentials of geospatial data in mapping, measuring and modelling the urban sprawl, which could be helpful to decision makers to form/make particular decision support system for sustainable growth of hilly urban areas or in making Smart City planning.

Keywords Urban sprawl · SVM · Digital change detection · Built-up density · Shannon's entropy · Stepwise regression · Shimla city

17.1   Introduction

The world urban centers are growing very faster in terms of the extent geographical area and density of population. Moreover, the urban areas change a rapid rate in developing countries and are experiencing stress. According to the United Nations (2014) report, the trend of global urbanization shows that 66% of the world's population is projected to be in urban area by 2050, with 90% of this expansion being anticipated in developing countries. In 2050, most of the urban population living of the world will be combination in Asia (52%) and Africa (21%). In India, the percentage of urban population to the total population has been steadily increasing since Independence. India is the 2nd largest urban organization in the world with more than 30% of urban population. The half of India's population will become urban has been estimated by 2025. The urban population of Indian cities is highly concentrated in large cities which are growing rapidly compared to small urban centres. The most Indian cities population is highly concentrated in large which are growing rapidly compared to small CBD (Central Business District) centers.

Urbanization drives the change in land use/land cover pattern. Actual information on the extent of urban growth is of great interest for the various purposes such as developmental activities like urban planning and management, land and water resource management, service and marketing analysis, etc. Urban local bodies are required to dedicate more time, effort and attention to able to use of land resources in order to accommodating the growing population or other urban land uses (Jat et al.

2008). The traditional surveying and mapping techniques are time-consuming and also expensive for the estimation of urban sprawl. Therefore, more research interest is being focused on mapping and monitoring of urban growth using Remote Sensing and GIS techniques (Epstein et al. 2002). Several researches on urban sprawl have been attempted by many scholars (Batty et al. 1999; Torrens and Alberti 2000; Barnes et al. 2001; Hurd et al. 2001; Jantz and Scott 2005; Yang and Liu 2005).

Urban sprawl usually takes place on the border area of the city or along the highways. Some studies of urban sprawl (The Regionalist 1997; Sierra Club 1998) was carried out in developed countries (Batty et al. 1999; Torrens and Alberti 2000; Barnes et al. 2001, Hurd et al. 2001; and Epstein et al. 2002) as well as in developing countries such as China (Yeh and Li, 2001; Cheng and Masser 2003) and India (Jothimani 1997; Lata et al. 2001; Sudhira et al. 2003). To quantify the urban sprawl, built-up is considered as a defining parameter (Torrens and Alberti 2000; Barnes et al. 2001; and Epstein et al. 2002), which used to be delineated using standard toposheets. Remote Sensing and GIS systems played important role in quantifying, monitoring, and subsequently predicting urban sprawl phenomenon. On spatial scale, GIS assist in determining the landscape properties in terms of structure, function and change (ICIMOD 1999; Civco et al. 2002). Modelling of the spatial dynamics mainly cover the LULC change studies (Lo and Yang 2002). In predicting the situation of Ipswich watershed, USA, in terms of its land use change, Pontius et al. (2000) carried out future land use changes prediction based on validated model for 1971, 1985 and 1991. Further, the Cellular Automata (CA) technique was extensively used in the urban growth models (Clarke et al. 1996) and in simulating urban sprawl (Torrens and O' Sullivan 2001; Waddell 2002).

The Geo-spatial techniques, such as Remote Sensing and GIS plays vital role in quantifying and modelling urban landscape which is otherwise not possible or time consuming by mapping through traditional methods. Remote Sensing have proven its usefulness in mapping urban areas and as a data sources (spatially and temporarily) for modelling of urban sprawl as well as in studying LULC (Batty and Howes 2001; Clarke et al. 2002; Donnay et al. 2001; Herold et al. 2001; Jensen and Cowen 1999). Therefore, more often, it is used for the analysis of urban sprawl (Sudhira et al. 2004; Yang and Liu 2005; Haack and Rafter 2006). The integration of Remote Sensing with GIS and database management systems helps in quantifying, monitoring and modelling the urban sprawl phenomenon. This has reflected in extensive research efforts made in last three decades for urban change detection studies using remotely sensed images (Gomarasca et al. 1993; Green et al. 1994; Yeh and Li 2001; Yang and Lo 2003; Haack and Rafter 2006).

Sudhira et al. (2004) used geospatial techniques in modeling simulation of future urban sprawl. Kumar et al. (2007) carried out similar study in Indore city of India using three temporal satellite Remote Sensing data (1990–2000). In Ajmer city (India), Jat et al. (2008) analyzed the urban sprawl using eight multi temporal satellite imageries of duration 1977–2005. They found that the built-up development in Ajmer city is more than three times the population growth. The spatial extent and patterns of systematic/random changes in urban development in Haridwar city (India) was studied by Jha et al. (2008) for developing future plans. In applying Entropy

approach, Punia and Singh (2012) conducted study on Jaipur city (India) to quantify urban sprawl. This study reveals that the rate of built-up growth in Jaipur city have outstripped the rate of population growth. Based on study using satellite data from 1990 to 2010, Rawat and Kumar (2015) found that there is sharp increase in built up area in Almora town of Uttarakhand state in India, which is attributed to construction of new buildings on agricultural and vegetation lands.

Apart from the research work of land use/land cover change detection, there are studies in which uses statistical techniques with geospatial technology to quantify, estimate, map & model urban sprawl (Jat et al. 2008). Shannon's Entropy is based on information theory. One of such statistical techniques is Shannon's Entropy which used as a mathematical estimation of Urban Growth that occurs in a disorganized way. Shannon's Entropy (Hn) is used to measure the degree of spatial concentration or dispersion of geophysical variables (Xi) among 'n' spatial units/zones. In quantifying urban forms, Shannon's Entropy has been used by Joshi et al. (2006).

Changes in urban structures and pattern can be obtained using landscape metrics, which gives information about the configuration of the land cover classes and the landscape, are algorithms used to describe and quantify the spatial characteristics of patches, class areas and the entire landscape (Cabral et al. 2005; Herold et al. 2002). GIS helps in calculating the urban landscape metrics, like patchiness and density in order to characterize landscape properties in terms of spatial distribution and change (Trani and Giles 1999; Yeh and Li 2001; Civco et al. 2002, Sudhira et al. 2004). However, the analysis of the sprawl pattern and the configuration of landscape metrics correlate with each other, and cannot be seen apart. With the identification of the pattern a first impression of the pattern is obtained, the landscape metrics provide statistical insight of the configuration of the urban sprawl.

In present study, an attempt has been made to investigate the usefulness of the Remote Sensing and GIS techniques along with Shannon's Entropy (Hn) and landscape metrics for urban sprawl dynamics and monitoring of spatial and temporal variability of Shimla city, Himachal Pradesh, India from 1991 to 2011. Variation of urban sprawl (spatially and temporally) is considered for identifying the relationship between urban sprawl and some its contributory factors such as (independent variables) population density, female literacy rate, road density, total workers, sex ratio, α-population, number of household's (HH), β-population, using Stepwise Regression Analysis. In order to quantify and measure the urban growth, Shannon's Entropy, Built-up Density, Landscape Metrics and Spatial Dynamic of urban sprawl were calculated. The landscape metrics were used to enhance understanding of the urban forms. Computation of these parameters helps in understanding the process of urbanization at a landscape level. An attempt has also been made in the study for mapping the status of land use/land cover of Shimla Municipal Corporation, Himachal Pradesh (India) for detecting the land use rate and the change that have taken place during 1991–2011 using Remote Sensing and Geographic Information System (GIS) technique.

17.2   Study Area

Shimla is a capital of Himachal Pradesh. The population of Shimla city is 1,69,578 (Census of India 2011). Shimla city, located between 31°3′ and 31°8′ N latitudes and between 77°7′ and 77°13′ E longitudes (Fig. 17.1). It has an average altitude of 2195 m above mean sea level and extends along a ridge with seven spurs. The city is spread over an area of 30 km². Population of Shimla city has increased from 1,42,555 (in 2001)–1,69,578 (in 2011), accounting for 18.96% decadal growth. Population growth in percentage (%) has increased from 39.51% (in 2001) and 18.95% (in 2011).The climate in Shimla is mostly cool during winter months and moderately warm during summer months (Cwb), under Koppen climate classification, with three distinct seasons—summer, rains and mild winter. Shimla has an average temperature of 19 °C–28 °C during March to June (in summer) and average temperatures in winter season (November–February) ranges from 03 °C–09 °C. As a result of north-west monsoon, the city receives an annual rainfall of 1577 mm between July–October. The warmest month of the year is June.
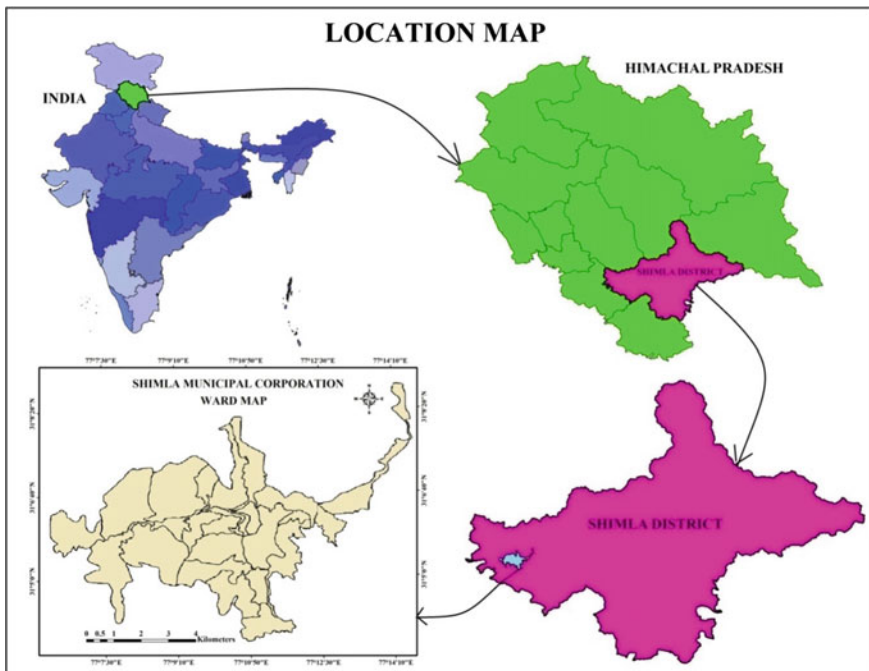

Fig. 17.1   Location Map of the study area

Table 17.1 Data used for study

Data	Date of acquisition	Spatial resolution & scale (m)	Sources
A. Satellite images			
Landsat TM	16–11–1991	30 m	Earth Explorer
Landsat ETM+	18–10–2001	28.5 m	Earth Explorer
Landsat TM	22–10–2011	30 m	Earth Explorer
B. Additional data			
Toposheet (53E/4)	–	1:50,000	Survey of India
SMC Map (Ward)	2011	–	SMC
Demographic data	1991, 2001 and 2011	–	Census of India
Road layers	2011	–	Google Earth

17.3 Database and Methodology

17.3.1 Data Used

Primary and secondary data sources have been used for present study (Table 17.1).

17.3.2 Methodology

Cloud Free Landsat satellite data of multi-temporal image of three years: 1991, 2001 and 2011 were selected for analysis. The freely available Landsat images were downloaded from Global Land Cover Facility (GLCF) and Earth Explorer website of United States Geological Survey (USGS). All the data are preprocessed and projected to the Universal Transverse Mercator (UTM) projection system. Another reason for selecting these images was their availability at similar resolution.

Using bands 2, 3 and 4 of the preprocessed images, map of land use/cover pattern was prepared by Supervised Classification using the Support Vector Machine (SVM) classification algorithm of Envi (Environmental Visualization Imagine) 5.1 and ERDAS 2014 (Earth Resource Data Analysis System) software. ArcGIS 10.2.2 software was also used for spatial analysis and generating thematic layers. To study the built-up change detection especially in the land use/cover over the period of two decade (from 1991 to 2011), unsupervised and supervised classification was used. In the ERDAS 2014, indices such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Normalized Difference Built up Index (NDBI) were also applied to classify the Landsat images at a spatial resolution of 30 m of 1991 and 2011, ETM+ at a spatial resolution 28.5 m of 2001. The Error Matrix and Kappa coefficient method were used to assess the mapping accuracy. Five Land use/cover types have been identified and used in this study, namely (i) Water Body(ii) Forest Area (iii) Built up Area (iv) Agriculture Area (v) Open Space

Table 17.2 Description of land use/land cover classes

Land use/land cover categories	Description
Urban or built-up	Residential, commercial, services and industrial, roads and playground, others means of transportation and other urban feature and Recreational areas also included
Forest area (Vegetation)	Vegetation areas, grass land and green parks and Forest, scattered trees
Agriculture Area	Production of food and fiber, This includes cropped areas, fallow lands and plantation (Apples and pears orchards and nurseries)
Water bodies	River, lakes, tank, ponds, reservoirs etc
Open space/land	Exposed soil, landfill sites, polder area of active excavation, open space in the built-up land etc

(Table 17.2). A change matrix (Weng 2001) was build using ERDAS 2014 and ArcGIS 10.2.2 software. The quantitative areal data of land use/land cover changes and its gains and losses in each categories from 1991 to 2011, were compiled.

In determining qualitative as well as quantitative aspects of the changes from 1991 to 2011, classified image pairs of respective time frame were compared using cross-tabulation. In order to produce the change information on pixel basis and interpreting the changes more efficiently, a pixel-based comparison was performed. A change matrix (Weng 2001) and Land Encroachment map was produced using ERDAS Imagine 2014. The matrix showed the respective gains and losses in land use/cover category during 1991–2011. Field data were collected for two reasons: first, to acquire GPS data for ground verification of doubtful areas; and secondly, to calculate the mapping accuracy of the classified images (Table 17.3). The ground control points were used to correct the misclassified areas using recode option in ERDAS Imagine 2014 software. To assess the classification accuracy of all the produced outputs a reference dataset of randomly selected 200 pixels were used. Land use/land cover for these pixels was determined with the help of urban settlement map, and data collected from other secondary maps. In order to avoid the errors in the reference dataset for sensitive classes such as vegetation, which is temporal in nature; the original satellite data was used for better assessment in its accuracy. Some of the ground truth data that have been used in present study essentially includes urban settlement map and

Table 17.3 Description of land use/cover mapping accuracy

Land use/land cover	Overall accuracy (%)	Kappa coefficient
1991	92.00	0.714
2001	97.00	0.926
2011	96.00	0.920

Sources: Landsat TM and ETM+ satellite data for 1991, 2001 and 2011

geographical locations of some of the features, location-wise type of vegetation, buildings, play grounds, permanent water bodies, and road network.

Urban sprawl over a period of two decade (1991–2011) is obtained from the classified images. To understand and model the urban sprawl pattern, different Landscape Metrics (Shannon's Entropy, Stepwise Regression, Map density and Buffering along major roads) were calculated using the demographical and built-up area statistics. Shannon's Entropy (H_n) is mostly used for ascertaining the urban growth phenomena. This method is basically used from information theory which acts as a measure of uncertainty of conveyed information over a noisy channel (Jat et al. 2007; Bailey 2009). The greater value of Shannon entropy imparts higher uncertainty in the information conveyed (Bailey 2009). High Entropy leads to high occurrence of phenomena that contributes to disorder. This is probably same for urban sprawl. Thus, Shannon entropy has been computed to quantify the decay of sprawl. The Shannon entropy H_n is given by (Yeh and Li 2001).

$$H_n = \sum_i^n P_i \log_e \frac{1}{P_i} \tag{17.1}$$

where, P_i is the proportion of occurrence of a phenomenon ith spatial zone out of n zones (wards). This is given by

$$P_i = \frac{x_i}{\sum_i^n x_i} \tag{17.2}$$

where, x_i is the area of built up at the ith zone.

The value of entropy varies between 0 to $\log_e n$. The value closer to 0 indicates concentrated or compact distribution of the built up while value closer to $\log_e n$ revels dispersed distributed pattern. However, high value of entropy indicates the occurrence of sprawl.

Apart from the whole study area, entropy model has been also applied to different administrative wards in the study area to detect the form and type of urban growth phenomena (Punia and Singh 2011). For ward wise calculation of Shannon entropy, each ward has considered as an individual spatial unit, and is given by

$$H_i^n = \sum_i^n P_i \log_e \frac{1}{P_i} \tag{17.3}$$

where, P_i represents proportion of land use/land cover class in ith ward, n denotes total number of land use/land cover classes. The range of Entropy values is minimum of 0 to $\log_e n$ representing upper limit of entropy which is equal to $\log 25 = 1.3413$.

In developing the relationship of percentage built-up (dependent variable) with causal factors (independent variables) of sprawl, Stepwise Regression analysis was carried out. In this study, independent variables are Population Density (PD), α-Population Density (α-PD), β-Population Density (β-PD), Total workers (TW), Road

density (RD), Female literacy rate (FLR), Sex ratio, (SR) and No of Household's (HH). In order to identify the probable relationship of percentage of built-up (PB) (dependent variable) and individual causative factors, different distributions (Linear, Polynomial, Logarithmic, and Exponential) have been calculated and documented.

In present study, eight spatial metrics indices, i.e., Class Area (CA), Number of Patches (NP), Largest Patch Index (LPI), Edge Density (ED), Euclidian Mean Nearest Neighbour Distance (ENN_MN), Area Weighted Mean Patch Fractal Dimension (AWMPFD) and Contagion (Table 17.10), were used for quantify the spatial characteristics of urban landscape. The changes in urban landscape were measured and analysed using the FRAGSTATS software. The process of urban expansion in the study area during the period of two decade (1991–2011) was examined by evaluating a distance decay concept from major roads. In an obvious phenomenon like density of land development declines rapidly as the distance from roads increases, the National Highway No.—NH 22, National Highway No.—NH 88, summer hill roads, Bharari road, Mall road and Ridge road, etc., have been considered for present urban sprawl analysis, where four buffer zone were created along the roads with 0–50 m each.

17.4 Result and Discussion

17.4.1 *Image Analysis*

The spatial analysis was performed beyond the Shimla Municipal Council's administrative boundary. The classified images for land use/land cover in 1991, 2001 and 2011 are shown in Figs. 17.2, 17.3 and 17.4 respectively. The extent of land use/land cover during 1991, 2001 and 2011 comprised built-up area with 361.05 ha, 646.92 ha, 890.7 ha respectively. Similarly, the extent of non-built-up area comprising open land, forest area and water bodies were 2329.47 ha, 2106.72 ha and 1968.12 ha during 1991, 2001 and 2011 respectively. The LULC change analysis was carried out based on the differences in land use/land cover on spatial scale and temporal variation. During 1991–2011, it was observed that the extent of built-up area has increased by 26.48%. Here, the extent of increase in built-up area only describes the magnitude of change but without the pattern of this transition. The cross-tabulation for the studied classified images was performed in order to analyze the probable LULC change from various non-built-up classes to Built-up class. It was found that during 1991–2011, the land use change from open land into Forest area was significant. The open land-use class was found to be a major land use that contributed to the increase of built-up area. Similarly, during 1991–2011, the Forest Area was the major land use/land cover that was lost (by almost 361.71 ha) due to changes into built-up areas.

The overall accuracy and Kappa coefficient for all the classified images are presented in Table 17.3. For better classification results, random sets of 200 samples were generated and classification results were compared with the true information classes in the reference image. The high level of accuracy was obtained in the present
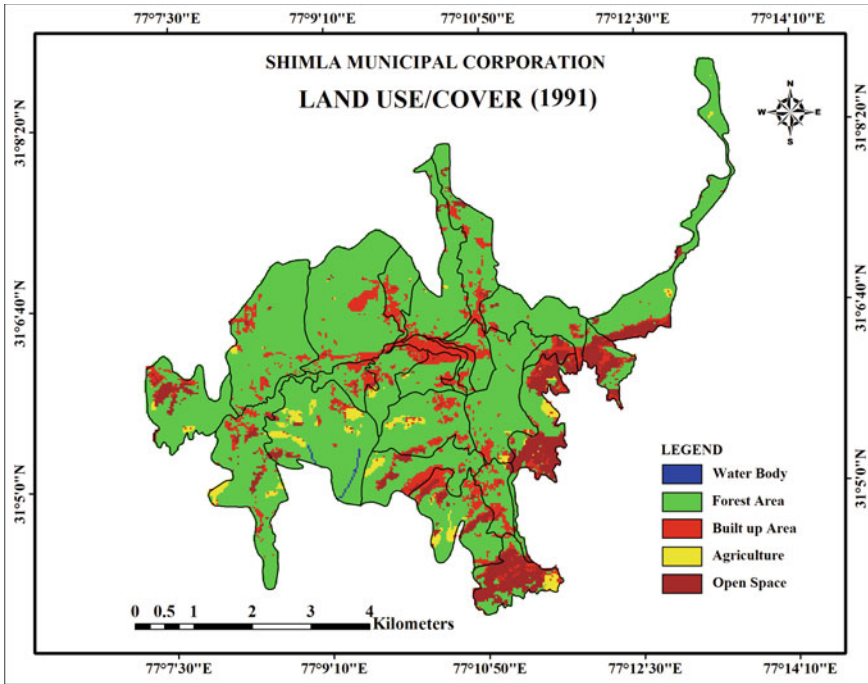
Fig. 17.2 Land use/cover classification of Shimla City (*Source* Landsat TM 1991)

study could be the result of the coarse classification, since only five classes are used. The classified image of original bands using Support Vector Machine (SVM) of Landsat TM (1991 and 2011) and Landsat-7 ETM+ (2001). From the image it is seen that most of the forest area is classified as vegetation due to similar spectral reflectance.

Table 17.4 and Fig. 17.5 reveal that both positive and negative changes occurred in the land use/cover pattern of Shimla city. According to the land use/cover maps produced, the total built-up area for 1991 was 361.05 ha (11.78%). This has increased to 646.92 ha (21.16%) by 2001, and finally reached 890.7 ha (29.06%) in 2011. These figures represent about 26.48% growth in built-up area over a period of time from (1991 to 2011). With respect to forest cover, it is clear that in 1991 it was 2325.6 ha and decreased to 1963.89 ha by 2011. Likewise, open space was about 296.19 ha in 1991 and decreased by 118.17 ha in 2011. The total decrease in forest area and open space during the study period was 18.09% and 8.90% respectively. The decrease in both the land use/land cover is mainly due to over exploitation of land for built-up purpose.

During this period, forest area decreased from 2325.6 ha in 1991–1963.89 ha in 2011 which accounts for −18.09% change (−361.71 ha) of total land cover area. The open space decreased from 296.19 ha in 1991 to 118.17 ha in 2011 which accounts for −8.90% change (−178.02 ha) of the total area. Forest area is decreasing due to
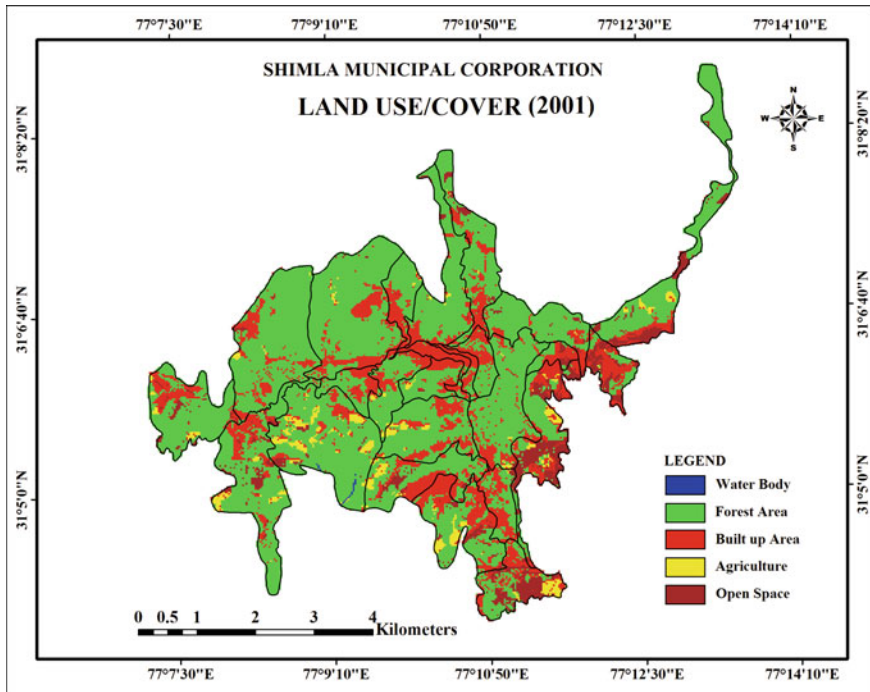
Fig. 17.3 Land use/cover classification of Shimla City (*Source* Landsat ETM+ 2001)

increasing population of the city which required more land for new settlers. Forest land which included both land of different vegetation and also included the grass park and green grass land. The built-up area has increased from 361.05 ha in 1991–890.7 ha in 2011 which accounts for +26.48% (529.65 ha) of the total area (Table 17.5). Built-up area which included both playground and stadium. This dramatic increase in built-up area is due to migrated population problem, rapid growth of local population, tourism development, continuous establishment of national/multinational companies, and development of major and minor's roads, etc. During the study period, it is observed that the fringe area, forest area and open space has change to built-up area in 1991–2011, decrease the forest area and open space is due to increase in the built-up area.

In order to understand the land conversion into different land categories in two decade (i.e., 1991–2011) a change detection matrix (Table 17.6) was prepared that reveals about 362.52 ha area of forest cover has been converted into built-up area, 48.06 ha into agriculture area, 30.69 ha into open space and 3.78 ha into water body. Similarly, about 55.71 ha area of open space has been converted into forest area, 148.77 ha area converted into built-up area, and 6.21 ha area converted into agriculture area. Likewise, about 24.48 ha area under agriculture area has been converted into forest area, 18.36 ha area converted into built-up area, 1.98 ha area converted into
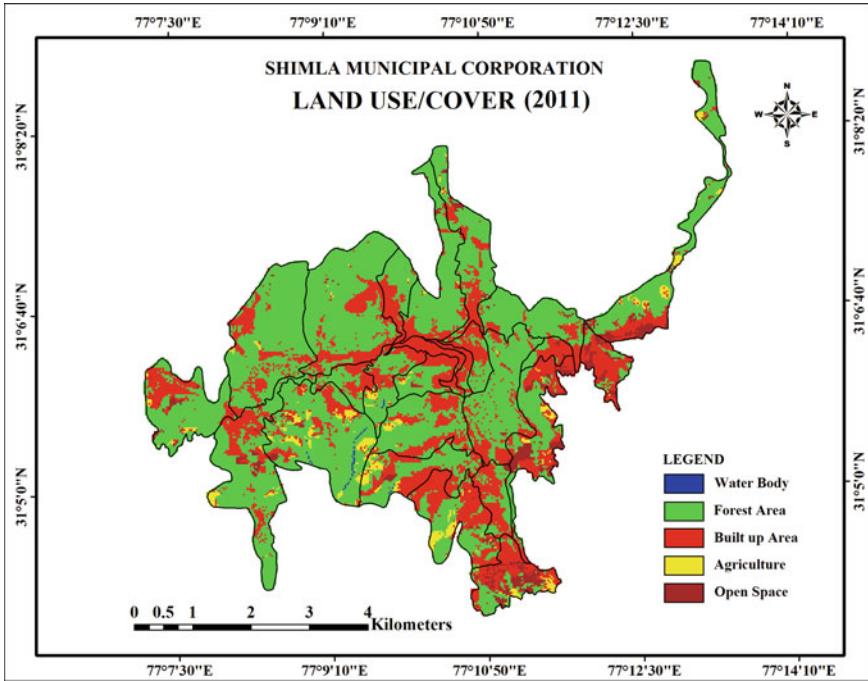
Fig. 17.4 Land use/cover classification of Shimla City (*Source* Landsat TM 2011)

Table 17.4 Status of land use/land cover in all categories in Ha

Land use classes/years	1991(Ha)	2001(Ha)	2011(Ha)
Water bodies	3.87	1.98	4.23
Forest area	2325.6	2106.72	1963.89
Built-up area	361.08	646.92	890.73
Agriculture area	77.85	96.66	87.57
Open space	296.19	212.22	118.17

Sources Landsat TM and ETM+ satellite data for 1991, 2001 and 2011

open space. And, about 3.15 ha area open water body has been converted into forest area and 0.27 ha area has been converted into agriculture area.

17.4.2 Population Growth and Built-up Area

The urban impervious area such as built-up land has increased from 361.05 ha in year 1991–890.7 ha in year 2011. Results in Table 17.7 and Fig. 17.6 reveals that
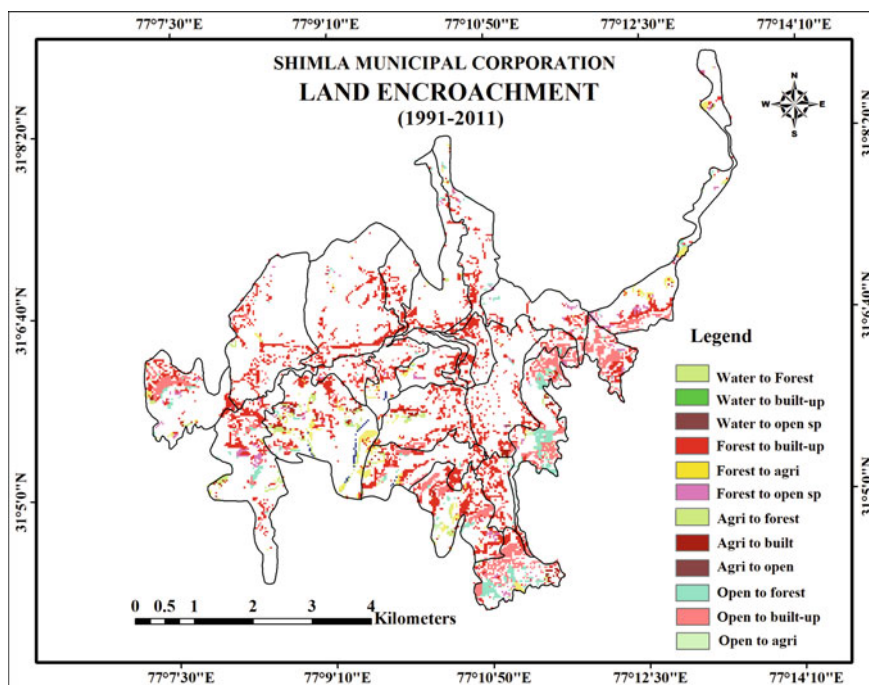
Fig. 17.5 Land Encroachment of Shimla City (*Sources* Landsat TM and ETM+ satellite data of 1991–2011)

Table 17.5 Area and per cent changes in land use/cover categories (1991–2011)

Land use/cover categories	Area (1991)	Area (2011)	Change (1991–2011)	Area (1991)	Area (2011)	Change (1991–2011)
	Hectares	Percent	Hectares	Percent	Hectares	Percent
Water body	3.87	0.13	4.23	0.14	0.36	0.02
Forest	2325.6	75.89	1963.89	64.08	−361.71	−18.09
Built up	361.05	11.78	890.7	29.06	529.65	26.48
Agriculture	77.85	2.54	87.57	2.86	9.72	0.49
Open space	296.19	9.67	118.17	3.86	−178.02	−8.90

Source Landsat TM and ETM+ satellite data for 1991, 2001 and 2011

the rate of land development in Shimla has exceeded the rate of population growth, from the year 1991–2011. A compound annual growth rate for built-up area for two decade (1991–2011) and average annual exponential growth rate for population of Shimla city has been calculated with considering the logic of population grows exponentially while area does not. In the description of population growth and built-up area from, 1991 and 2001, the highest annual growth rate was observed in both built-up area and population. However, the built-up area growth is much higher

Table 17.6 Land use/land cover change matrix (Ha) of Shimla city

Land use/land cover categories		Year 1991					2011 Total
		Water body	Forest	Built Up	Agriculture	Open Space	
Year 2011	Water body	0.45	3.78	0	0	0	4.23
	Forest	3.15	1880.55	0	24.48	55.71	1963.89
	Built up	0	362.52	361.05	18.36	148.77	890.7
	Agriculture	0.27	48.06	0	33.03	6.21	87.57
	Open space	0	30.69	0	1.98	85.5	118.17
1991 Total		3.87	2325.6	361.08	77.85	296.19	3064.56

Source Landsat TM and ETM+ satellite data for 1991, 2001 and 2011

Table 17.7 Urban growth statistics for Shimla city 1991–2011

Years	Built-up area (Ha)	Percentage increase in built-up area (%)	Projected Population	Percentage growth in population (%)
1991	361.05	–	102,186	–
2001	646.92	79.18	142,555	39.51
2011	890.73	37.69	169578	18.95

Source Landsat TM and ETM+ satellite and census data for 1991, 2001 and 2011
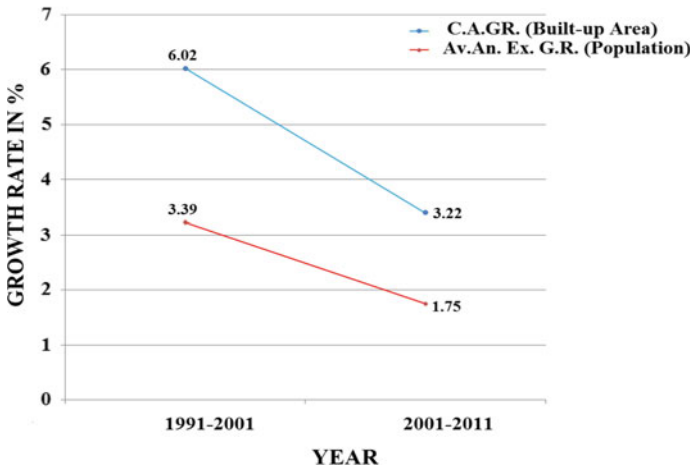

Fig. 17.6 Growth of population and built-up area of Shimla city in last 20 years, 1991–2011 (*Sources* Landsat TM and ETM+ satellite data and Census of India, 1991, 2001 and 2011)

(6.02%) than the growth rate of population (3.39%). This denotes the higher per capita land consumption and the city has been expanded physically with high rate of expansion. In the next period of 2001–2011, it is also observed that built-up area is growing much higher (3.22%) than the growth rate of population (1.75%). It is noteworthy here that with this high base, growth rate of the city is very significant that indicates spatial and temporal growth of the city.

Shimla city is growing fast in the pattern of construction of new building and others factors. Since the inception of Shimla Municipal Corporation (SMC), small pockets of land in parts of the villages were added increasing the area within the jurisdiction of SMC. The border area growth has resulted into the increased residential areas and other facilities such as transportation nodes. The population of Shimla city has increased manifold in the last 20 years and the rate of increase has been very speedy after 1991. The continually increasing population pressure has led to the growth of the adjoining areas and the city has extended outwards filling in spaces between it and the suburbs. The urban expansion has taken place in all directions but more extensively in the eastern, southern and south-western directions. Spatial distribution of ward-wise urban sprawl in last 20 years from 1991 to 2011 is shown in Fig. 17.7. It was found that urban sprawl is faster in outer area of (ward number 20–23) and inner area of (ward number 9–13) along the major roads of the city as compared to central
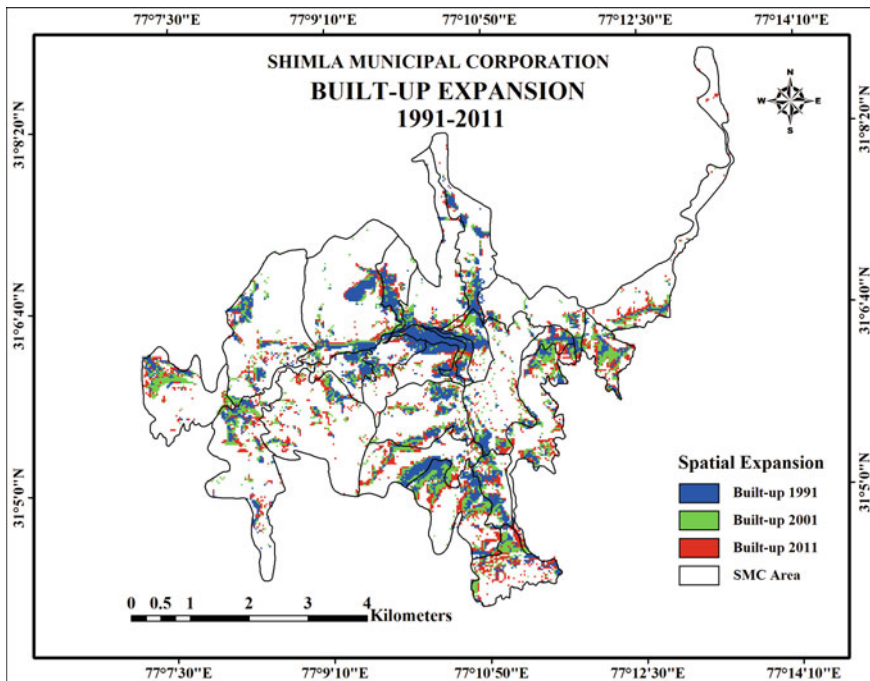

Fig. 17.7   Urban growth of Shimla city from 1991, 2001 and 2011 (*Sources* Landsat TM and ETM+ satellite data for 1991, 2001 and 2011)
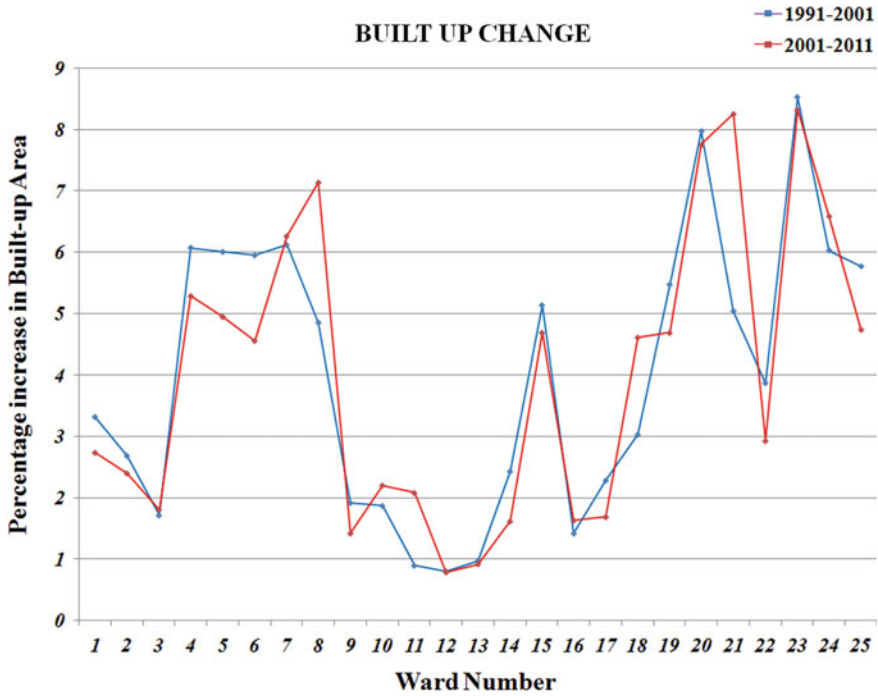
Fig. 17.8 Ward-wise urban growth of Shimla City from 1991 to 2011 (*Sources* Landsat TM and ETM+ satellite data for 1991, 2001 and 2011)

portion, which is also validated by landscape metrics. This is in accordance to the hypothesis which stated that increase in economic conditions among the population and development relates to urban sprawl (Census of India 2011). Highest built up growth was observed in ward number 23 and lowest in ward number 12 (Fig. 17.8).

17.4.3 Metrics of Urban Sprawl

17.4.3.1 Shannon's Entropy (H_n)

In the present study, Shannon's entropy was used in order to measure the extent of spatial concentration or dispersion (homogeneity) of a geophysical variable, impervious (built-up area) among 'n' spatial units/zones (wards).The entropy indicates that there was substantial internal variation in the patterns of urban sprawl among the wards of the study area. Shimla municipal area grew in all the wards has almost reached the threshold value of growth ($\log (n) = \log, (25) = 1.34$). The value of entropy varies between 0–log n. Entropy closer to zero correspond to compact distribution or homogeneity of urban growth; whereas, entropy closer to log n signify the

Table 17.8 Values of Shannon's entropy: Shimla city (1991–2011)

Years	Values of Shannon's entropy
1991	1.30
2001	1.32
2011	1.34

Source Landsat TM and ETM+ satellite data for 1991, 2001 and 2011

dispersed distribution of urban sprawl (specially built-up area). Entropy values have been calculated across all wards, and were summed-up to represent the entropy for the whole urban area. The change in entropy helps identifying whether land development is towards the more dispersal or in compact pattern. For ward wise calculation each ward has considered as an individual spatial unit.

$$H_n i \text{th} \Sigma p_i \log(1/p_i) \tag{17.4}$$

P_i represents the proportion of land use/cover class in ith ward.

n denotes total number of land use/cover classes.

Log n represents the upper limit of entropy, i.e., equal to log 1.3413

Relatively lower value of Shannon's entropy (1.3092) in the year 1991 indicates the compact and homogeneous distribution of the built-up area. Entropy value has increased from 1.3092 in year 1991 to 1.3276 in year 2001. Further, value of Shannon's entropy has increased from 1.3276 in year 2001 to 1.3413 in year 2011. This increase in value of entropy indicates increase in dispersion of built-up area, which indicates urban sprawl. The entropy values obtained during 3 years (1991, 2001 and 2011) are closer to the upper limit of log n, i.e., 1.3413, showing the degree of dispersion of built-up area in the region. Higher value of overall entropy for the whole urban area represents higher dispersion of built-up area, which is an indication of urban sprawl. Lower entropy values of wards (given in table), during 2011 shows an aggregated or compact growth in the whole region. However, the wards under Shimla city, grew phenomenally with dispersed growth during the study period (1991, 2001 and 2011) and reached higher value of entropy (Table 17.8) during 2011.

17.4.3.2 Urban Map Density

In present study Urban map density parameter was used to determine the compactness/dispersion of spatial occurrence of urbanization. Distribution of built-up areas, as an indicator of urban sprawl, has been studied using density metrics. Map density values were estimated by determining the number of built-up area pixels out of the total number of pixels in a 3 × 3 kernel. In this analysis, again size of kernel has been used as per the maximum number of land use/cover categories available in a specific classified image. There are five land use/cover categories available in most
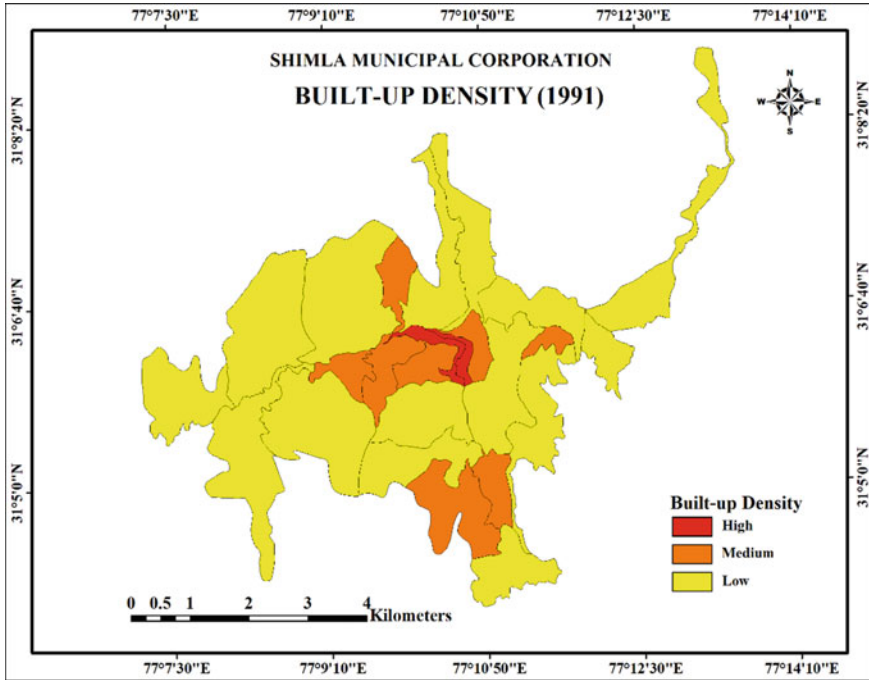
Fig. 17.9 Density of Urban Area of Shimla for 1991 (*Source* Landsat TM 1991)

of the classified images, which is less than the number of pixels in a 3 × 3 size kernel. Therefore, kernel of 3 × 3 size has been use in the present analysis. This when applied to a classified satellite image of 1991, 2001, and 2011, converts land cover classes to density classes. Depending on the map density levels, it was categorized as Low, Medium and High density (Figs. 17.9, 17.10 and 17.11). Further, the relative share of each category was computed (area in percentage). This helps in identifying the different urban growth centres which then subsequently assist in correlating the results with Shannon's Entropy. The calculation of built-up density gave the distribution of the High, Medium and Low-density built-up clusters as categorized in the study area. High density of built-up refers to compact nature of the built-up theme, while medium density denotes relatively lesser compact built-up; whereas, low density referred to sparsely spread built-up areas. This revealed that the study area comprised of a smaller area (of more compact or highly dense in nature); and more dispersed or least dense built-up area. Results showed that the high and medium map density was found all along the highways and in the city centres. High map density was found within and closer to the cities; whereas, medium density was found mostly around the city periphery and along the highways. Further, the distribution of low density was observed in the study area due to the higher dispersion of the built-up in the study area. This further confirms the results of Shannon's Entropy, which denotes a high dispersion of the built-up feature in the study area.
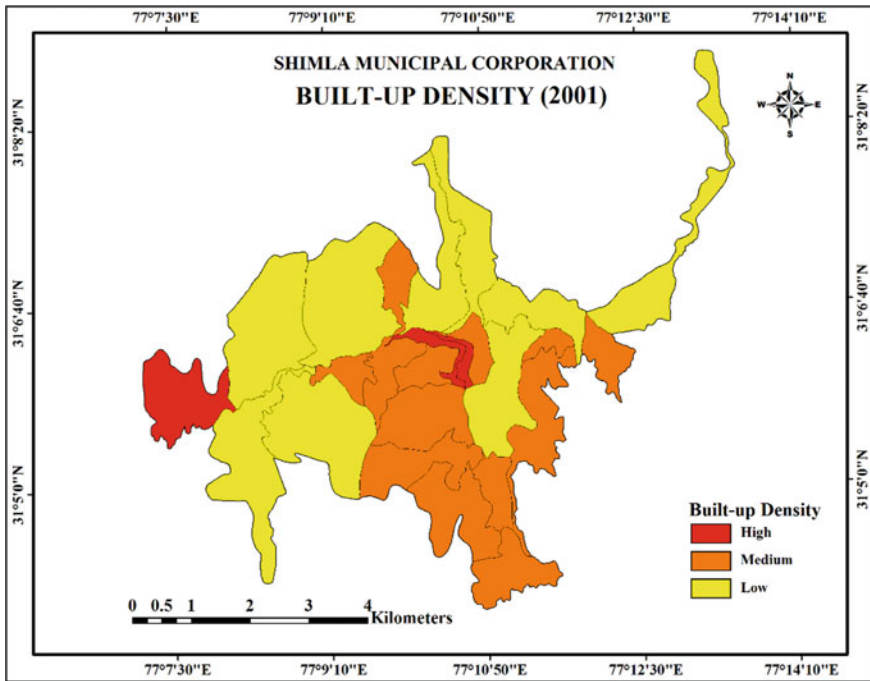
Fig. 17.10   Density of Urban Area of Shimla for 2001 (*Source* Landsat ETM+ 2001)
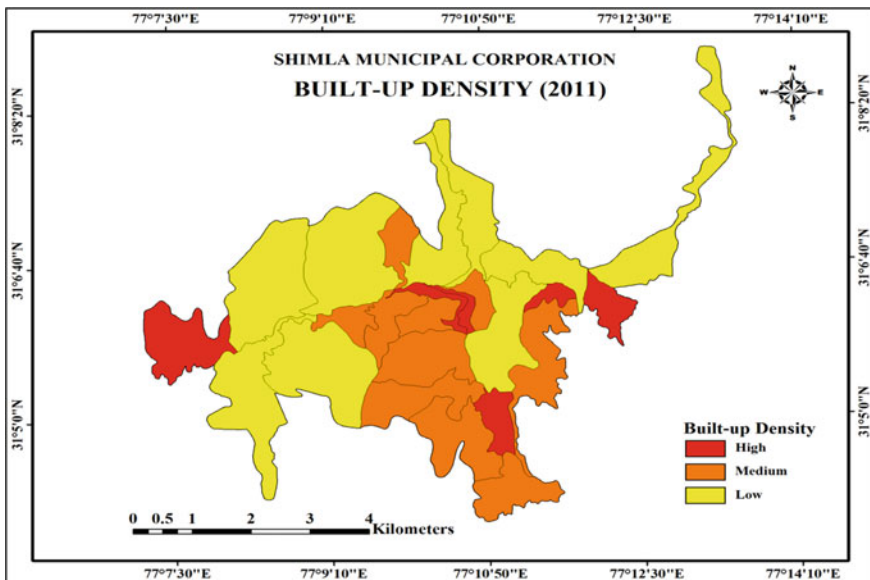

Fig. 17.11   Density of Urban Area of Shimla for 2011 (*Source* Landsat TM 2011)

17.4.3.3 Spatial Dynamics of Urban Sprawl

The modeling of dynamic urban sprawl and its future prediction is a greater challenge rather than its quantification; which gives ways to policy planning for city development. Although, different sprawl types were identified here, still there is inadequacy in developing mathematical relationships to define them. This necessitates the characterization of urban sprawl. This exercise helps in city planning and development of water resources projects and/or designing of urban drainage infrastructure along with other facility within and around the city area. In the present study, population and related densities were used as independent variables for simulation modelling of the urban sprawl. The Shimla Municipal Corporation is known to have undergone extremely fast area expansion in recent years due to an unprecedented population growth over a period of 20 years. Shimla is heavily built up across the hill slopes and characterized by mixed commercial and transports related activities. The public, semi-public, residential and other land use activities in the city have been mostly concentrated in the South. On comparing the satellite data sets of 1991–2011, it was found that the built up area in and around the Shimla Municipal Corporation has increased by 529.65 hectares (26.48%) over the period of 20 years (1991–2011). Urban expansion processes in the Shimla Municipal Corporation during the period of 20 years (1991–2011) were further evaluated by analyzing a distance decay concept from major roads (Table 17.9 and Fig. 17.12). For this purpose National Highway No.—NH 22, National Highway No.—NH 88, Summer hill road, Bharari road, Mall road, Ridge road, etc., have been taken for analysis. Urban expansion and four buffer zones were created along these roads with 0–50 m each. The result of the present analysis indicated that the area and density under urban land was decreasing while going the away from major roads.

Table 17.9 Urban Expansion along a major road of Shimla city in 1991–2011

Proximity to road (mts)	1991		2011		Change During 1991–2011	
	Urban area (km^2)	Urban density (urban area km^2)	Urban area (km^2)	Urban density (urban area km^2)	Urban area (km^2)	Rate of expansion of urban area (km^2/Year)
0–50	1.25	0.21	2.74	0.46	1.49	0.07
50–100	0.79	0.18	1.80	0.41	1.01	0.05
100–150	0.44	0.14	1.09	0.34	0.65	0.03
150–200	0.30	0.12	0.70	0.28	0.40	0.02

Sources Landsat TM and ETM+ satellite data (1991, 2011) and Google Earth Engine for roads (2011)
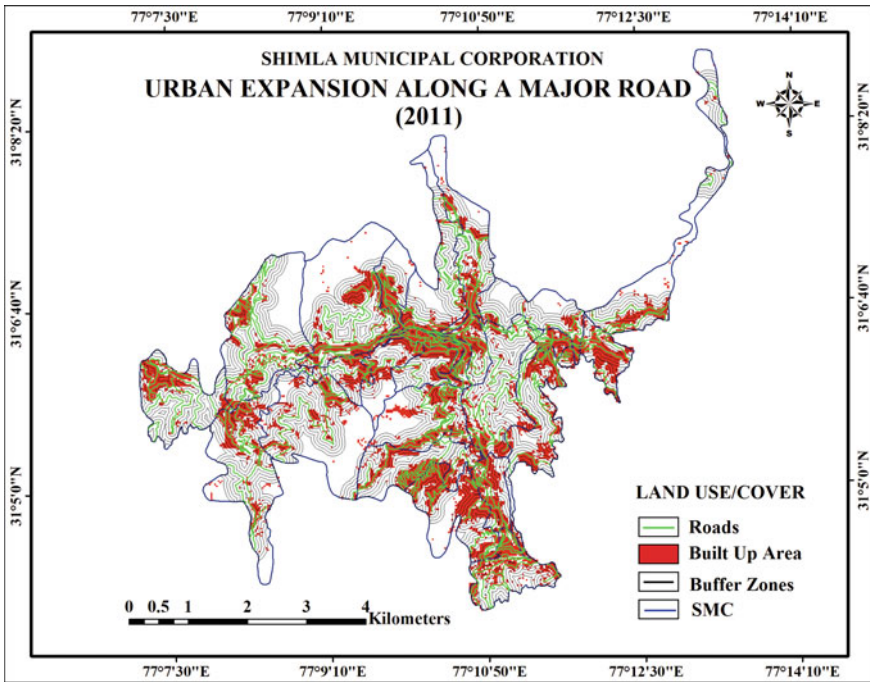
Fig. 17.12 Buffering along Major Roads of Shimla City (*Source* Landsat TM and Google Earth Engine of 2011)

17.4.4   Analysis of Landscape Metrics

Landscape metrics were used to quantify and measure the spatial patterns and structures of urban sprawl. Eight landscapes indices were used to quantify urban structure and form (Table 17.10). Class Area (CA) measures the total built-up growth of an area. It basically measures the amount of built-up pixels per time step. It is also possible to measure the percentage of the total area covered by the built-up class, by dividing the class area by the total area (Alexakis et al. 2011; Araya 2009; Herold et al. 2002; Xi et al. 2009). Spatial metrics and their variation were calculated for the built-up area (urban impervious area), which increased by 79.16% between 1991 and 2001. Similarly, Built-up growth was also increased by 37.68% from 2001 to 2011; however, the rate of growth was slower compared to previous decade. The Number of Patches (NP) is a simple quantification of the amount of individual built-up patches. It does not contain any information about the area, or the disparity of patches, or the density. However, it does provide information on the amount of new created patches in time (Alexakis et al. 2011; Araya 2009; Herold et al. 2002; Xi et al. 2009; Yu and Ng 2007). The NP in a landscape analysis indicates the aggregation or disaggregation in the landscape, while Large Patch Index (LPI) measures the proportion of total landscape area comprised by the largest urban patch. The NP (*i.e.*, built-up

Table 17.10 Landscape indices and their percentages of changes of Shimla city from 1991–2011

Metrics	1991	2001	2011	Δ%1991–2001	Δ%2001–2011	Δ%1991–2011
Class Area (CA)	361.080	646.920	890.730	79.162	37.687	146.684
Number of patches (NP)	696.000	932.000	784.000	33.908	−15.879	12.643
Largest patch index (LPI)	38.2263	38.227	38.226	0.002	−0.002	0
Edge density (ED)	34.1856	42.449	42.153	24.174	−0.698	23.307
Euclidian mean nearest Neighbour distance (EMN_MN)	117.791	104.045	108.588	−11.669	4.366	−7.813
Area weighted mean patch fractal dimension (FRAC_AM)	1.135	1.138	1.141	0.246	0.2811	0.528
Contagion	69.863	68.044	68.155	−2.604	0.1638	−2.445

blocks) increased (33.90%) between 1991 and 2001, which depicts the dispersed pattern of urban growth. The development of a number of isolated, fragmented, or discontinuous built-up areas occurred in the first period while in the second (i.e., 2001–2011) it was decreased by −15.87%. This suggests that small patches were transformed into larger patches and urbanization is made in agglomerated form.

Largest Patch Index is the ratio of the area of the largest patch in the landscape and the total landscape area. When the largest patch in the landscape is increasingly small, LPI approaches 0%. It reaches 100% when the complete landscape consists of a single patch. LPI increased by 0.002% between 1991 and 2001, thus indicating significant growth within the historical city core. Edge Density (ED) does in contrast to number of patches and patch density take into account the shapes of patches, the complexity of the shape of a patch. When new built-up areas emerge the edge density of the urban land use class should increase, a decrease is possible when areas agglomerate (Araya 2009; Alexakis et al. 2011; Eiden et al. 2012; Herold et al. 2002). ED increased by 24.174% and −0.698% between 1991–2001 and 2001–2011 period respectively, thus indicating an increase in the total length of the edge of the urban patches, as due to disintegration of land use pattern. The increasing trend in first two periods demonstrated the strong urban sprawl phenomena.

A decreasing trend in Euclidian Mean Nearest Neighbour Distance (ENN_MN) was −11.669% seen from 1991, which shows a reduction in the distance between the built-up patches, thus suggesting coalescence. The Area Weighted Mean Patch Fractal Dimension (AWMPFD) measures the shape of urban patches. Whereas, the edge density takes the complexity of the shapes of the patches into account. Relatively

higher values were estimated during first phase of urban development (i.e., 2001–2011). Contagion index measures the extent to which a landscape is aggregated or clumped (dispersed or interspersed). The value of the contagion index ranges between 0 and 100. A value of 0 is obtained when patch types are well interspersed, scattered and not aggregated, referring to many small and dispersed patches. A value of 100 is obtained when maximum aggregation of patch types is witnessed, i.e., only a few large contiguous patch types do exist (Weijers 2012). Relatively high Contagion index values during first decadal period were obtained which depicts the landscape with few large, and contiguous patches (contagion is high because many cells are adjacent to each other in large and contiguous patches (many internal cells)) while lower values was obtained during the second decadal period. During this period the development was taken place in scattered and not aggregated form, referring to many small and dispersed patches. But during second period again relatively high contagion index values was seen because of conversion of small patches into large and contiguous patches.

17.4.5 Modelling of Urban Sprawl

Urban sprawl dynamics was modelled using the causal factors (Independent variables) such as Population Density (PD), α-Population Density (α-PD), β-Population Density (β-PD), Total workers (TW), Road density (RD), Female literacy rate (FLR), Sex ratio, (SR) and No of Household's (HH). The percentage built-up is the proportion of the built-up area to the total area of the ward. The α-population density denotes the proportion of the population in each ward to the built-up area of the respective ward. The β-population density (often referred as population density) is the proportion of population in each ward to the total area the respective ward. Since the present study mainly concentrated on built-up area, the percentage built-up, α and β population densities were computed and analyzed ward-wise. Ward-wise population data includes the information of some of the key factors of urban sprawl like total workers in secondary and tertiary sectors, and female literacy rate. The physical growth of city is mostly driven by its secondary and tertiary sectors. Hence, ward wise total worker in secondary and tertiary sectors were calculated. When the population of any region grows and become urbanized. Urban growth follows the major transportation nodes. So as to calculate the road density, ward wise road network has been digitized in GIS platform. With the help of these underlying factors, modelling of urban sprawl was carried out. To explore the possible relationship of percentage built-up (dependent variable) with causal factors of sprawl, regression analysis was carried out. Various regression analyses (Linear, Polynomial, Exponential and Logarithmic) were undertaken to determine the nature of significance of the causal factors (independent variables) on the sprawl, and quantified in terms of percentage built-up. The Regression analyses disclose the individual contribution of

causal factors on the nature of urban sprawl. A variety of relationships and corresponding statistical parameters have been presented in Appendices 1–5. Some of the significant relationships are,

Population

$$y = -(0.098)\,x^2 + (1.436)\,x + 0.100 \qquad (17.5)$$

y = percentage built-up, x = Population
Road Density

$$y = -(0.207)\,x + 4.826 \qquad (17.6)$$

y = percentage built-up, x = RD
α-population density

$$y = (0.123)\,x^2 - (1.686)\,x + 8.408 \qquad (17.7)$$

y = percentage built-up, x = α − opulation density
β – population density

$$y = (0.029)\,x^2 - (0.551)\,x + 5.473 \qquad (17.8)$$

y = percentage built-up, x = β − P
Female Literacy

$$y = -(0.125)\,x^2 + (1.742)\,x - (0.601) \qquad (17.9)$$

y = percentage built-up, x = Female Literacy
Total Workers

$$y = -(0.037)\,x^2 + (0.819)\,x + 1.407 \qquad (17.10)$$

y = percentage built-up, x = Total Workers
Sex Ratio

$$y = -(0.086)x^2 + (1.546)x - 0.775 \qquad (17.11)$$

y = percentage built-up, x = Sex Ratio
No of household's (HH)

$$y = -(0.072)\,x^2 + (1.127)\,x + 0.909 \qquad (17.12)$$

y = percentage built-up, x = No of household's (*HH*)
Linear regression model evaluated here has been found to be the lower correlation coefficient Eq. (17.6) ($R^2 = 0.101$) to show the relationship between % built-up and

road density as compared to linear, polynomial, logarithmic, exponential, distributions. Relationships between % built-up and β-population density have been found to be polynomial. Polynomial regression results show higher correlation coefficient ($R^2 = 0.178$). Relationships between percentage built-up and α-population density have been found to be linear with higher correlation coefficient ($R^2 = 0.349$). Polynomial regression model has higher correlation coefficient ($R^2 = 0.325$) to explain the relationship between percentage built-up and female literacy rate. Relationships between percentage built-up area and total works have been found to be polynomial regression with higher correlation coefficient ($R^2 = 0.191$). Relationships between percentage built-up area and population have been found to be linear with highest correlation coefficient ($r^2 = 0.059$). The linear and polynomial regression analyses reveal that the road density and population density have considerate influence on percentage built-up. To estimate the collective effects of causal factors, stepwise multivariate regression analysis was also carried out (Table 17.11). In the stepwise multivariate regression, it is assumed that the relationships between variables are linear. Considering all the causal factors in the stepwise regression, Appendix 5 indicates the highest correlation coefficient ($R^2 = 0.928$) which collectively explains the 92.08% variation in the urban growth. The α-population density of 90.04% represents the distinctive characteristic of Shimla city development.

Table 17.11 Model summary of stepwise regression

Model	R	R square	Increase in R square	Adjusted R square	Increase in adjusted R square	Std. error of the estimate
1	0.540	0.291	–	0.260	–	1.497
2	0.953	0.908	0.617	0.900	0.640	0.551
3	0.957	0.915	0.007	0.903	0.003	0.542
4	0.960	0.921	0.006	0.905	0.002	0.535
5	0.963	0.928	0.007	0.908	0.003	0.527
6	0.963	0.928	0	0.904	−0.004	0.540
7	0.963	0.928	0	0.899	−0.005	0.554
8	0.964	0.928	0	0.893	0.006	0.571

a. Predictors: (Constant), α-PD
b. Predictors: (Constant), α-PD, P
c. Predictors: (Constant), α-PD, P, No HH
d. Predictors: (Constant), α-PD, P, No HH, SR
e. Predictors: (Constant), α-PD, P, No HH, SR, FLR
f. Predictors: (Constant), α-PD, P, No HH, SR, FLR, β-PD
g. Predictors: (Constant), α-PD, P, No HH, SR, FLR, β-PD, RD
h. Predictors: (Constant), α-PD, P, No HH, SR, FLR, β-PD, RD, TW

17.5   Summery and Conclusion

Shimla city had experienced a tremendous rate of growth over the period of two decade. Satellite Remote Sensing is crucial in dealing the dynamic event, like urban sprawl phenomena. Without past remote sensing data, one may not be able to monitor past urban growth events and compare with the recent trend and predict the future growth pattern effectively over a time period at less time, in low cost and with better accuracy which is otherwise not possible to attempt through conventional mapping techniques. The application of Remote Sensing, GIS, spatial metrics and urban growth models provides novel approach for the study of spatio-temporal dynamics of urban sprawl. Considering the availability of past data sources from Landsat archive at medium resolution, demonstrated the capabilities for improving the knowledge, understanding and modelling of urban sprawl dynamics of Shimla city. This paper has presented a detailed analysis of 20 years of spatial urban growth pattern of Shimla city. The result shows that built-up area has increased from 361.05 ha in year 1991 to 890.7 ha in year 2011. This continuous increase in built-up area in Shimla city has outstripped the rate of population growth. The Shannon's entropy index and landscape metrics have quantified the urban sprawl. The entropy values obtained during the study period are closer to the upper limit of log n, i.e. 1.3413, showing the degree of dispersion of built-up area in the region, which is an indication of urban sprawl. All the parameter of spatial metrics has shown their inclination towards overall urban growth pattern in the study area. Multivariate regression analysis was performed in order to establish a relationship between urban sprawl and some of its contributory factors. Analysis of the contributory factors of urban growth collectively explains the 92.08% variation in the urban growth. Regression model developed here reveals that the most reasonable variable for the variation in built up area is α population density. These measures of spatial sprawl may even help in refining our understanding of this phenomenon. In addition, future development of Shimla city would also influenced by other contributory factors such as tourism initiatives, physical constrains, socio-economic change, population migration, future government investments corridors, smart city plan, development of small and medium towns around vicinity, scope of industrialization, and distances from major locations. These factors can be considered for urban growth modeling in future research work.

Appendix 1: Coefficients of Causal Factors and Percentage Built-Up by Linear Regression Analyses

Dependent variable (y)	Independent variable (x)	Equation ($y = ax + b$)	R	R^2	Adjusted R^2	Std. error of the estimate
Percentage Built-up	Population	$y = 0.460x + 2.161$	0.46	0.21	0.17	1.58
Percentage Built-up	α-population density	$y = -0.530x + 6.118$	0.54	0.29	0.26	1.50
Percentage Built-up	β-population density	$y = -0.228x + 4.910$	0.40	0.16	0.12	1.63
Percentage Built-up	Road Density	$y = -0.207x + 4.826$	0.32	0.10	0.06	1.69
Percentage Built-up	Total Workers	$y = 0.452x + 2.193$	0.43	0.19	0.15	1.60
Percentage Built-up	No. of Household's	$y = 0.398x + 2.408$	0.45	0.20	0.17	1.59
Percentage Built-up	Sex Ratio	$y = 0.834x + 0.662$	0.23	0.08	0.04	1.71
Percentage Built-up	Female Literacy	$y = 0.834x + 0.662$	0.49	0.24	0.21	1.55

Sources Landsat TM and ETM+ satellite data and Census of India (1991, 2001 and 2011)

Appendix 2: Coefficients of Causal Factors and Percentage Built-Up by Polynomial (Order = 2) Regression Analyses

Dependent variable (y)	Independent variable (x)	Equation ($y = ax^2 + bx + c$)	R	R^2	Adjusted R^2	Std. error of the estimate
Percentage Built-up	Population	$y = -0.098x^2 + 1.436x + 0.100$	0.51	0.26	0.19	1.57
Percentage Built-up	α-population density	$y = 0.123x^2 - 1.686x + 8.408$	0.59	0.35	0.29	1.45
Percentage Built-up	β-population density	$y = 0.029x^2 - 0.551x + 5.473$	0.42	0.18	0.10	1.65
Percentage Built-up	Road density	$y = -0.018x^2 + 0.016x + 4.351$	0.33	0.11	0.02	1.72
Percentage Built-up	Total workers	$y = -0.037x^2 + 0.819x + 1.407$	0.44	0.19	0.12	1.64
Percentage Built-up	No. of household's	$y = -0.072x^2 + 1.127x + 0.909$	0.49	0.24	0.17	1.59
Percentage Built-up	Sex ratio	$y = -0.086x^2 + 1.546x - 0.775$	0.28	0.08	-0.01	1.75

(continued)

Dependent variable (y)	Independent variable (x)	Equation ($y = ax^2 + bx + c$)	R	R^2	Adjusted R^2	Std. error of the estimate
Percentage Built-up	Female literacy	$y = -0.125x^2 + 1.742x - 0.601$	0.57	0.31	−0.26	1.49

Sources Landsat TM and ETM+ satellite data and Census of India (1991, 2001 and 2011)

Appendix 3: Coefficients of Causal Factors and Percentage Built-Up by Logarithmic Regression Analyses

Dependent variable (y)	Independent variable (x)	Equation ($\log y = \log(a) + b \log x$)	R	R^2	Adjusted R^2	Std. error of the estimate
Percentage Built-up	Population	$y = 2.105 \ln(x) + 1.250$	0.48	0.23	0.20	1.56
Percentage Built-up	α-population density	$y = -2.265 \ln(x) + 6.934$	0.57	0.32	0.29	1.47
Percentage Built-up	β-population density	$y = -0.935 \ln(x) + 5.032$	0.42	0.18	0.14	1.61
Percentage Built-up	Road density	$y = -0.805 \ln(x) + 4.984$	0.26	0.07	0.03	1.72
Percentage Built-up	Total workers	$y = 1.915 \ln(x) + 1.483$	0.45	0.17	0.14	1.62
Percentage Built-up	No. of household's	$y = 1.777 \ln(x) + 1.723$	0.47	0.22	0.19	1.57
Percentage Built-up	Sex ratio	$y = 3.322 \ln(x) - 0.571$	0.28	0.08	0.09	1.71
Percentage Built-up	Female literacy	$y = 2.268 \ln(x) + 1.043$	0.53	0.28	0.25	1.51

Sources Landsat TM and ETM+ satellite data and Census of India (1991, 2001 and 2011)

Appendix 4: Coefficients of Causal Factors and Percentage Built-Up by Exponential Regression Analyses

Dependent variable (y)	Independent variable (x)	Equation ($y = be^{ax}$)	R	R^2	Adjusted R^2	Std. error of the estimate
Percentage Built-up	Population	$y = 2.276e^{0.118x}$	0.45	0.20	0.17	0.41

(continued)

Dependent variable (y)	Independent variable (x)	Equation ($y = be^{ax}$)	R	R^2	Adjusted R^2	Std. error of the estimate
Percentage Built-up	α-population density	$y = 6.455e^{-0.143x}$	0.56	0.32	0.29	0.38
Percentage Built-up	β-population density	$y = 4.722e^{-0.065x}$	0.44	0.19	0.16	0.41
Percentage Built-up	Road density	$y = 4.644e^{-0.061x}$	0.36	0.13	0.09	0.43
Percentage Built-up	Total workers	$y = 2.328e^{0.112x}$	0.41	0.17	0.13	0.42
Percentage Built-up	No. of Household's	$y = 2.421e^{0.102x}$	0.45	0.20	0.17	0.43
Percentage Built-up	Sex ratio	$y = 1.465e^{0.228x}$	0.29	0.09	0.05	0.44
Percentage Built-up	Female literacy	$y = 2.209e^{0.125x}$	0.45	0.24	0.21	0.40

Sources Landsat TM and ETM+ satellite data and Census of India (1991, 2001 and 2011)

Appendix 5: Stepwise Regression Equations

S.N.	Stepwise Regression Equations	R^2
1	pc built-up = 6.118 − 0.530 α-PD	0.29
2	pc built-up = 4.131 − 0.921 α-PD + 0.888 P	0.91
3	pc built-up = 3.835 − 0.929 α-PD + 1.553 P − 0.583 HH	0.92
4	pc built-up = 2.790 − 0.907 α-PD + 1.563 P − 0.599 HH + 0.245 SR	0.92
5	pc built-up = 0.819 − 0.905 α-PD + 2.320 P − 0.375 HH + 0.766 SR − 1.010 FLR	0.93
6	pc built-up = 1.010 − 0.892 α-PD + 2.231 P − 0.360 HH + 0.717 SR-0.937 FLR − 0.012 β-PD	0.93
7	pc built-up = 0.783 − 0.869 α-PD + 2.256 P − 0.342 HH + 0.740 SR-0.968 FLR-0.040 β-PD + 0.028 RD	0.93
8	pc built-up = 0.867 − 0.874 α-PD + 2.395 P − 0.352 HH + 0.724 SR-1.024 FLR-0.041 β-PD + 0.030 RD-0.075 TW	0.93

Sources Landsat TM and ETM + satellite data and Census of India (1991, 2001 and 2011)

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