



Indices based assessment of built-up density and urban expansion of fast growing Surat city using multi-temporal Landsat data sets

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Abstract The population growth in urban areas leads to the expansion of built-up area which leads to a number of serious problems like environmental pollution, destruction of urban ecology, climatic modification etc. In this study, we have tried to assess the linkages and association between population growth and built-up expansion in Surat city. Landsat satellite data (TM, ETM+ and OLI/TIRS) has been used for 1991, 2001, 2011 and 2019 to extract the built-up area while the demographic data of the city was obtained

from the Census of India and SMC. The built-up area has been extracted using index based built-up index (IBI) method. The association between urban expansion rate (RUE) and population growth rate (PGR), distribution of population and built-up area and the population and built-up density was analyzed using linear regression technique. The result shows that both the population and built-up area of Surat has increased rapidly but the rate of increase of built-up area is higher than the population. The statistical analysis

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shows that the density of population and built-up area have very strong-positive relationship while their distribution have moderate-positive relationship. On the other hand the PGR and RUE shows positive but weak relationship. The main finding of the study is that the growth rate of population and urban area are not identical to each other but their distribution and density have strong relationships with each other. The association between PGR and RUE is not always significant because of the variation in their rate.

Keywords Urban expansion · Built-up density · Population growth rate (PGR) · Index based built-up index (IBI) · Surat city

Introduction

The past few decades have witnessed highest level of growth and expansion of urban areas in the world mainly due to population growth and economic development (Chen et al. 2014). In 2018, the global urban population has reached to about 55% of the total population, and this will rise to about 68% (United Nations 2018). The rate of urbanization is highest in the developing nations, like India. According to Census of India (2011a) the total urban population in the country was about 377 million (31.16%) and the urban growth rate was about 31.8%. But this rate of urban population growth is not similar in the all parts of country (Balk et al. 2019). The urbanization leads to both expansions of existing cities as well as development of new towns. In 1991 Census, there were only 23 million plus cities in India, which rose to 53 in 2011 (Sudhira and Gururaja 2012). The main cause of growing urban population in India is livelihood opportunities in urban areas (Pradhan 2004), which pull people from rural areas. Urban growth is a consequence of population growth factors; natural increase as well as migration (Bhatta 2010). While former has a lesser impact on urban growth, the later has drastic impact on the urban expansion. There are three phases or processes of the urban growth, i.e. infilling, expansion and outlying (Wilson et al. 2003).

The increasing urban population leads to the increase in housing density as well as other infra-structural facilities to meet their needs and desires (Rahman et al. 2011a; Maiti and Agarwal 2005). Thus

the growth in urban population leads to the expansion of built-up areas and urban sprawl (Rahman et al. 2011b) which causes a number of serious problems related to environment, health and climate (Mohan et al. 2011; Zhou et al. 2004). The urban growth involves transformation of both socio-economic as well as physical component of the landscape (Dutta et al. 2015). The unprecedented and unplanned growth of urban areas is one of the major issues faced by the world especially developing countries like India (Kumari et al. 2017; Kumar et al. 2007). The built-up growth due to increasing urban population leads to outward expansion of the urban areas (Zeug and Eckert 2010). The growth of built-up land in urban areas occurs along the pattern of population growth and the economic development (Yi et al. 2016). Urban built-up area expands at the cost of natural land cover types like water bodies, vegetation, agricultural as well as wetlands, etc. (Patra et al. 2018).

Increasing population is the primary force behind the urban expansion and land use/land cover (LU/LC) changes (Vitousek et al. 1997) as land is the primary natural resource for the human. Dutta et al. (2019) noted that the LU/LC changes occur due to the pressure created by population growth. The growing population and economy creates additional demand of natural resources and land for further development and hence, causes expansion of built-up land (Mohan et al. 2011). To study the LU/LC changes due to urban expansion, multi-temporal satellite data with good spatial resolution is required (Almazroui et al. 2017). Studies have been carried out to assess the land use change and urban expansion (Dutta et al. 2015; Wentz et al. 2008) and to analyze its linkages with population growth and economic development (Sharifi and Hosseingholizadeh 2019; Mohan et al. 2011).

The urban ecosystem gets strongly affected by the anthropogenic activities especially population growth and land use change (Stow and Chen 2002), thus additional attention should be given to the study of urban land use changes and their driving forces. The information on urban land use change becomes more important to plan and execute the land use schemes (Guidigan et al. 2019). The studies on urban land use change helps to understand human induced impacts on the urban environment (Yeh and Li 1999). The advancement in geospatial technology has made it possible to map and monitor the LU/LC changes and its transformation at various spatial and temporal

scales (Shalaby and Tateishi 2007; Rogan and Chen 2003). The remote sensing technique provides a wide scope to map and monitor the urban growth and their consequences. To monitor the spatial and temporal pattern of urban expansion, multi-temporal satellite data have been used in the studies (Mohamed and Worku 2019; Li et al. 2018; Nguyen et al. 2018; Dutta et al. 2015; Rahman et al. 2012; Maktav and Erbek 2005). During recent past, indices based studies have been carried out to assess the growth of urban built-up land (Table 1).

Zha et al. (2003) introduced normalized differential built-up index (NDBI) based extraction of the built-up area, which was followed in many studies carried out during the recent-past (Bouhennache et al. 2018; Zhou et al. 2014; Kumar et al. 2012; He et al. 2010; Xu 2008). All these studies used various methods which were developed to extract the built-up area using either one or two land use indices. He et al. (2010) used an improved normalized differential built-up index (NDBI) based method for extraction of the built-up area. Kumar et al. (2012) developed a band based index to study the built-up density of an urban area from Worldview II satellite. Xu (2008) developed indices based built-up index (IBI) using three land use indices; normalized differential built-up index (NDBI), soil adjusted vegetation index (SAVI) and modified normalized differential water index (MNDWI) to extract the urban land. The IBI method uses three land use indices i.e. NDBI, SAVI and

MNDWI, thus it gives better accuracy than the other methods.

Studies have been carried out to assess the impact of population growth on urban expansion in India (Das and Das 2019; Rahman et al. 2011b, 2012; Mohan et al. 2011; Kumar et al. 2007). But all these studies studied only urban expansion pattern in response to the population growth and the other aspects like relationships between growth rate and population and built-up density have not been studied. Studies have found that population growth rate and urban expansion rate have significant relationships (Nicolau et al. 2019; Lin et al. 2018). Thus this paper is aimed to fill this research gap and to analyze spatial relationships between (1) the distribution of population and built-up area, (2) population growth rate and urban expansion rate, and (3) the population and built-up density. The built-up area has been extracted from the Landsat TM and OLI/TIRS data using indices based built-up index (IBI) proposed by Xu (2008).

Review of literature

Numerous studies have been carried out to assess the urban expansion and LU/LC change as well as their relationships with population growth during past few decades. The LU/LC change is a massive but easily traceable transformation of the terrestrial surfaces which affects environment, society and economy and has implications for the sustainable development and

Table 1 Description of the some important indices used to extract urban areas

S. no.	Land use index	Formula	Description	Source
1	Normalized differential built-up index (NDBI)	$NDBI = \frac{(SWIR1 - NIR)}{(SWIR1 + NIR)}$	All +ve values shows built-up area	Zha et al. (2003)
2	Enhanced built-up and bareness index (EBBI)	$EBBI = \frac{(SWIR1 - NIR)}{10\sqrt{SWIR1 + TIRS1}}$	< 0.10 non-urban, 0.10–0.35 built-up and > 0.350 bare land	As-syakur (2012)
3	Urban index (UI)	$UI = \frac{SWIR2 - NIR}{SWIR2 + NIR}$	All +ve values shows built-up area	Kawamura et al. (1996)
4	Index based built-up index (IBI)	$IBI = \frac{NDBI - (SAVI + MNDWI)/2}{NDBI + (SAVI + MNDWI)/2}$	< 0.018 non urban, 0.018–0.308 built-up > 0.308 bare land	Xu (2008)
5	Dry built-up index (DBI)	$DBI = \frac{Blue - TIRS1}{Blue + TIRS1} - NDVI$	Higher values represents higher built-up area	Rasul et al. (2018)
6	Normalized difference bareness index (NDBaI)	$NDBaI = \frac{SWIR1 - TIRS1}{SWIR1 + TIRS1}$	> - 0.150 bare land	Zhao and Chen (2005)

land use planning (Alam et al. 2019). Population growth and economic development are identified as the most dominant driving force of the urban expansion and LU/LC change (Jenberu and Admasu 2019; Rahman et al. 2012; Fillion 2010). The LU/LC change is a natural process which cannot be stopped but can be regulated. The LU/LC change in urban areas occurs as a result of the utilization of natural as well as socio-economic factors by the urban dwellers in time and space (Fuller and Gaston 2009).

The mapping and monitoring of urban expansion and LU/LC change has become an important aspect of urban planning as it leads to a series of environmental consequences such as loss of biodiversity, destruction of farm and wetlands, ground water depletion, unregulated development, etc. (Mohamed and Worku 2019; Patra et al. 2018). The remote sensing technology provides a wide range of tools and techniques along with availability of satellite data at various spatial and temporal scales which have made it possible to monitor and quantify the expansion of urban areas and land use change (Nguyen et al. 2018; Dutta et al. 2015; Sharma et al. 2013). During recent years the satellite based study of urban growth has become popular among the researchers, planners and policy makers due to wide variety and easy availability of the satellite imageries and changing land use dynamics of the urban areas (Zha et al. 2003). Consequently, a number of studies have been carried out to map and monitor the land use change and urban sprawl (Rahman et al. 2011b). At the same time, the mappings of built-up areas have found to be easier and more accurate using the land use indices (NDBI, NDVI, DBI, etc.) than the traditional land use classification techniques (Rasul et al. 2018; Kumar et al. 2012; Xu 2008).

Therefore, a number of land use indices have been developed and applied to monitor the urban growth pattern in different parts of the world (Zhou et al. 2014; Kumar et al. 2012; Zha et al. 2003). The land use indices like NDBI and IBI derived from the Landsat (TM/ETM+/OLI) has been promoted for the extraction of concrete and built-up surfaces during recent years. The development of built-up land use indices has been based on the spectral response of the built-up surfaces which reflects more in the middle infrared portion of the electromagnetic spectrum than the near infrared (Aggarwal 2007). The IBI is a different land use index than the traditional indices as it uses

thematic indices derived from the original bands rather than using the thematic bands directly. Earlier produced built-up land use indices did not produced more than 85% accuracy due to spectral confusion between built-up and bare surfaces due to direct use of thematic bands (Xu 2008). To overcome these Zha et al. (2003) used vegetation index to filter the confusion and noise created due to signature variation.

Study area

Surat is a coastal city, located in the western part of state of Gujarat of India (Fig. 1). It is second largest city of Gujarat after Ahmedabad and also known as financial capital of Gujarat. It is the most dynamic city of Gujarat with fastest growth rate due to continuous immigration from its surrounding areas as well as other parts of India (SMC 2019a). Located in the centre of the Surat district, the city is famous as the diamond city of India (Sharma et al. 2013). The city is located on the Delhi–Mumbai industrial corridor and thus a number of cotton textile, automobile, hand loom, diamond processing and other industries are located in the city. Some of the major industries located in Surat are Oil and Natural Gas Corporation (ONGC) India, Reliance Petrochemicals, Shell, Larsen and Turbo, etc. (SMC 2019a). The city is facing a number of problems due to rapid urbanization like intense rainfall, urban flooding, heat waves, sea-level rise etc. (Bhat et al. 2013). River Tapi flows through the northern part of the city which joins Arabian Sea, located in west of the city. The climate of Surat is tropical Savanna type (Koppen: Aw), which is moderated by the maritime effect. The summer season starts from March and end by mid July while December and January are winter months. The summer temperature reaches up to 45 °C while winter temperature does not go below 10 °C due to maritime effect. The mean annual rainfall is about 114.3 cm.

The history of Surat city dates back to the ancient periods (mentioned in one of the oldest epic text *Maharabharata*, written around 400 BCE by Vyasa). During thirteenth century the city was referred as ‘Suryapur’ by the locals (GOJ 2019). The city has a varied heritage since medieval periods as several colonial empires including British and Dutch established their business in India from here during sixteenth century (SMC 2019a). The city becomes

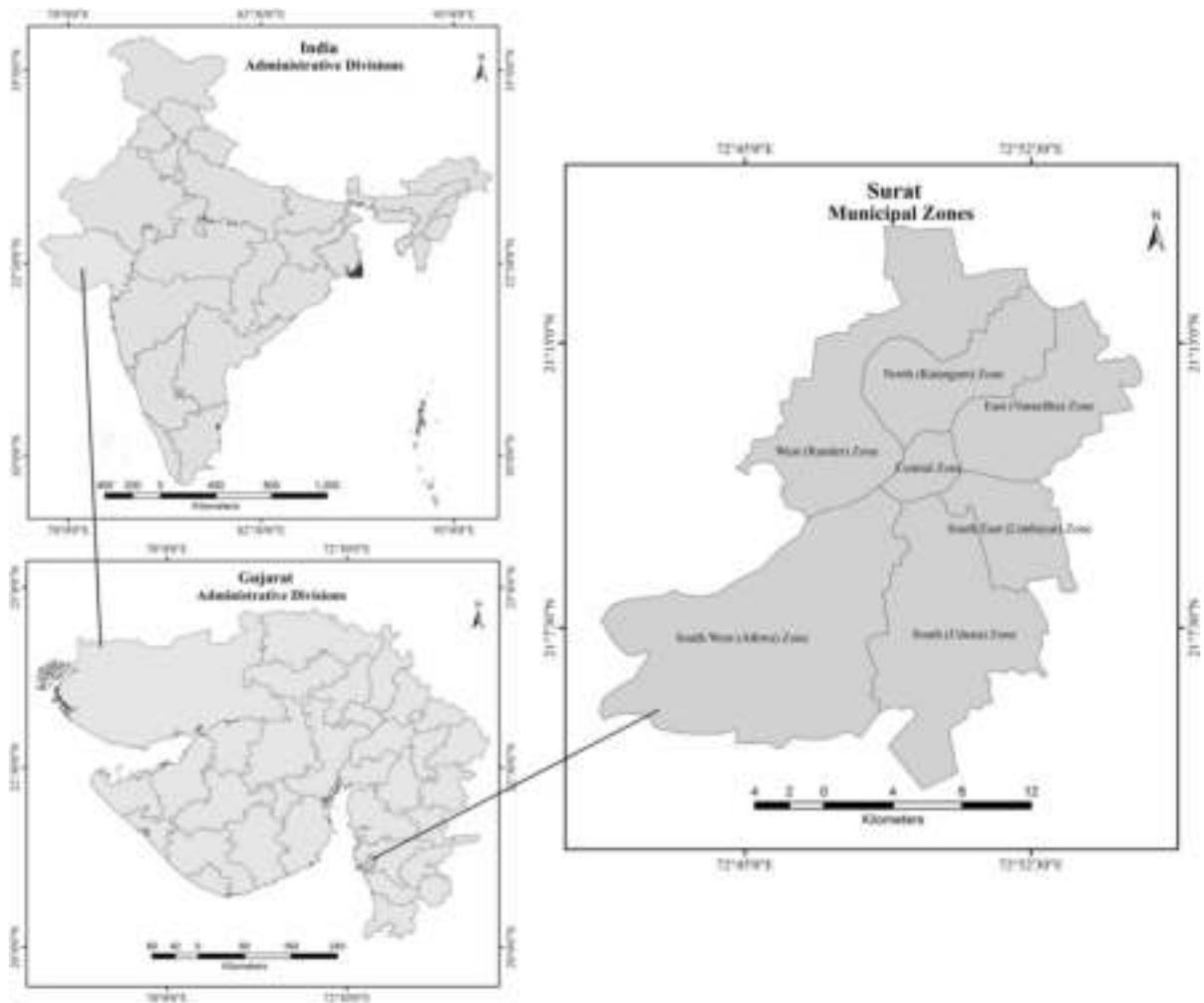


Fig. 1 Location of the study area

an important trade route for the traders during this period and thus British and Portuguese fought several times to establish their control over the city. The warrior king of Maratha Empire, Shivaji Maharaj attacked several times to remove the European powers from the city during second half of the seventeenth century. The city has experienced significant increase in population during the post independence era (from 2,23,182 in 1951 to 6,673,957 in 2019), more than any other city in India in terms of per cent change (Census of India 2011b). According to City Mayor Statistics (2016), Surat is the second fastest growing city of India and fourth fastest growing city of the world. In 2011, the total population of Surat was 4.47 million and the population density was about 14,000 persons per sq. km (Census of India 2011b). The estimated

population by Surat Municipal Corporation (SMC) for 2019 (SMC 2019b) is 6.60 million. The city has experienced continuous rapid growth in population in all zones except central zone (Table 2). The city has enormous employment and business opportunities due to its economic and commercial importance that attract the population from all parts of India. The diamond cutting is the main economic activity of the city while various automobiles and other industries also offers job opportunities which have resulted in rapid population growth.

Table 2 Zone wise distribution of population and built-up area (in hectares) in SMC

Zones	Urban area	1991		2001		2011		2019	
		Population	Built-up area						
Central	818	436,776	671.13	413,641	746.82	408,760	747.81	405,163	780.93
South west	11,191.2	137,359	221.4	242,466	1374.21	347,447	2062.62	467,803	2091.69
South east	6176.4	191,119	614.97	407,980	1465.29	695,028	1491.53	1,085,912	1589.13
East	1949.2	194,909	229.68	397,257	1116	748,304	1290.24	1,276,906	1662.39
North	3752.5	326,805	398.97	711,516	1175.94	1,137,138	2312.55	1,682,964	2601.27
West	3636.3	206,202	303.39	416,370	969.21	705,163	1393.78	1,096,105	1923.21
Total	5127.9	141,435	228.51	287,144	1071.99	424,986	1259.28	588,181	1812.33
Total	32,651.5	1,634,605	2668.05	2,876,374	7919.46	4,466,826	10,557.81	6,603,034	12,460.95

Data sources and methods

Data sources

The Landsat satellite data has been used to assess the built-up expansion of Surat city which has ability to view and assess the spatio-temporal LU/LC changes, but the estimation of changes in LU/LC at micro level also depends on the degree of accuracy (Roy and Inamdar 2019). For this study, the Landsat data, having 30 m spatial resolution of 1991, 2001, 2011 and 2019 have been used for built-up area extraction (Table 3). For a better spatio-temporal comparison, it is essential to use the satellite data of the same month/season for the different years (Phiri and Morgenroth 2017). Further, it is suggested that to avoid the cloud and haze, it is better to use the data of either spring or autumn seasons, but the cloud free data for Surat was

not available for these seasons for all the study years. Therefore, in this study, the data used were from the winter season (January) for the each study year (Table 3). The data used were downloaded from United States Geological Survey earth explorer (<https://earthexplorer.usgs.gov/>). The demographic data of the city were obtained from the Census of India. The expected demographic data of the year 2019 has been obtained from the Surat Municipal Corporation (SMC 2019b).

Methods

In this study, Landsat thematic mapper (TM) data of 1991 and 2011, and enhanced thematic mapper (ETM+) data of 2001 and operational land imager/thermal infrared sensor (OLI/TIRS) data of 2019 have been used to extract the urban area. Although the cloud

Table 3 Sources of the data used in study

S. no.	Data source	Data type	Path/row	Date of acquisition
1	United States Geological Survey	Landsat 4–5 (TM)	148/45	07 January, 1991
		Landsat 7 (ETM+)	148/45	10 January, 2001
		Landsat 4–5 (TM)	148/45	14 January, 2011
		Landsat 8 (OLI/TIRS)	148/45	20 January, 2019
2	Surat Municipal Corporation	Demographic data	–	2019
		City map	–	–
3	Census of India	Demographic data	–	1991, 2001 and 2011

free data were used in the study, it often required pre-processing prior to the analysis due to solar, atmospheric, topographic and sensor effects (Young et al. 2017). The atmospheric and radiometric corrections is recommended for the all Landsat data series because the Landsat data always posses some atmospheric errors in the form of either noise or haze (Song et al. 2001). The problem of haze and noise is more common in the case of Coastal areas like Surat. Further, the Landsat level I data products are available without any type of pre-processing. Thus, firstly, the pre-processing (atmospheric and radiometric corrections) were applied on all images to minimize any kind of errors. To extract (map) the built-up area, indices based built-up index (IBI) given by Xu (2008), has been used to extract the built-up area. The extracted built-up area was then used to calculate the built-up density/urban compactness ratio. The Kappa statistics was used for the accuracy assessment, the linear regression technique was applied to assess the spatio-temporal relationships between the population and built-up area. The whole methodology has been explained in the flowchart (Fig. 2).

Indices based built-up index (IBI)

Several techniques were used for the mapping of the built-up area during past decades such as normalized

differential built-up index (NDBI) by Zha et al. (2003), indices based built-up index (IBI) by Xu (2008), machine learning technique by Goldblatt et al. (2018) and supervised classification technique (Rahman et al. 2012). In this study, the IBI proposed by Xu (2008) has been applied for the mapping/extraction of built-up land of Surat city. The IBI is based on three land use indices; NDBI, soil adjusted vegetation index (SAVI) proposed by Huete (1988) and modified normalized differential water index (MNDWI) proposed by Xu (2006). The SAVI is suitable index for the urban areas because the vegetation cover is low while for rural areas where the vegetation cover is high, NDVI is suitable index (Xu 2008). In the first step, NDBI is calculated using Eq. (1).

$$NDBI = \frac{(MIR - NIR)}{(MIR + NIR)} \quad (1)$$

In the next step, SAVI was calculated using Eq. (2).

$$SAVI = \frac{(NIR - R)}{(NIR + R + l)} (1 + l) \quad (2)$$

where l is the correction factor which ranges between 0 (for extremely dense vegetation) and 1 (for sparse vegetation or bare soil). Ren et al. (2018) suggested a correction factor (l) between 0.2 and 0.5 for the areas having sparse to moderate vegetation cover. In this study, a correction factor of 0.5 has been used for all

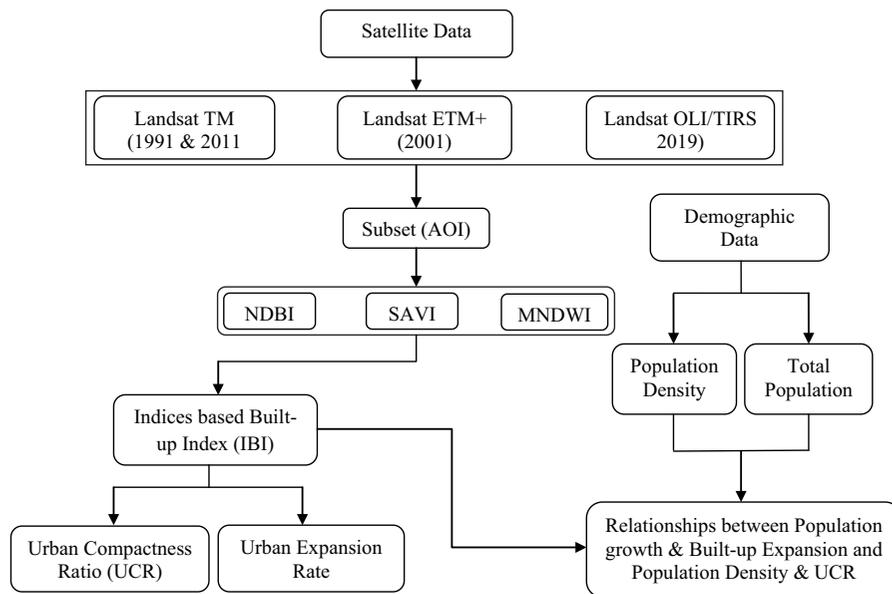


Fig. 2 Flow chart of the methodology

the years, to generate the vegetation index as the study area has mixed land use type with intermediate vegetation cover.

In the third step, the MNDWI was calculated using Eq. (3).

$$MNDWI = \frac{Green - MIR}{Green + MIR} \quad (3)$$

In the last step, the IBI was calculated using Eq. (4).

$$IBI = \frac{[NDBI - (SAVI + MNDWI)/2]}{[NDBI + (SAVI + MNDWI)/2]} \quad (4)$$

Accuracy assessment

The accuracy assessment is an important aspect of the LULC classification as it describes the degree of accuracy of the image classified. In this study, the Kappa Coefficient technique has been used to assess the accuracy using 250 randomly selected points (training sets). The points selected were similar for the all years and for the same location in both satellite

image and classified map. In Fig. 3, it can be clearly seen that grey and dark grey pixels have been classified into built-up area (in red) while all the rest pixels have been classified into other land use class. Further, cross validation of the points was also done, using Google Earth Pro domain. Anderson et al. (1976) pointed that the level of accuracy for a classified map should not be less than 85% for a better interpretation of the image. The overall classification accuracy for 1991, 2001, 2011 and 2019 was 89.74%, 88.41%, 89.53% and 91.01%, respectively and the kappa statistics was 0.8601, 0.8511, 0.8703 and 0.9006, respectively.

Calculation of built-up density (BD) and urban expansion rate (RUE)

To analyze the urban expansion rate, Eq. (5), modified technique from Xiao et al. (2006), was applied using Eq. (5). The built-up area extracted using IBI was used to assess the of urban expansion rate.

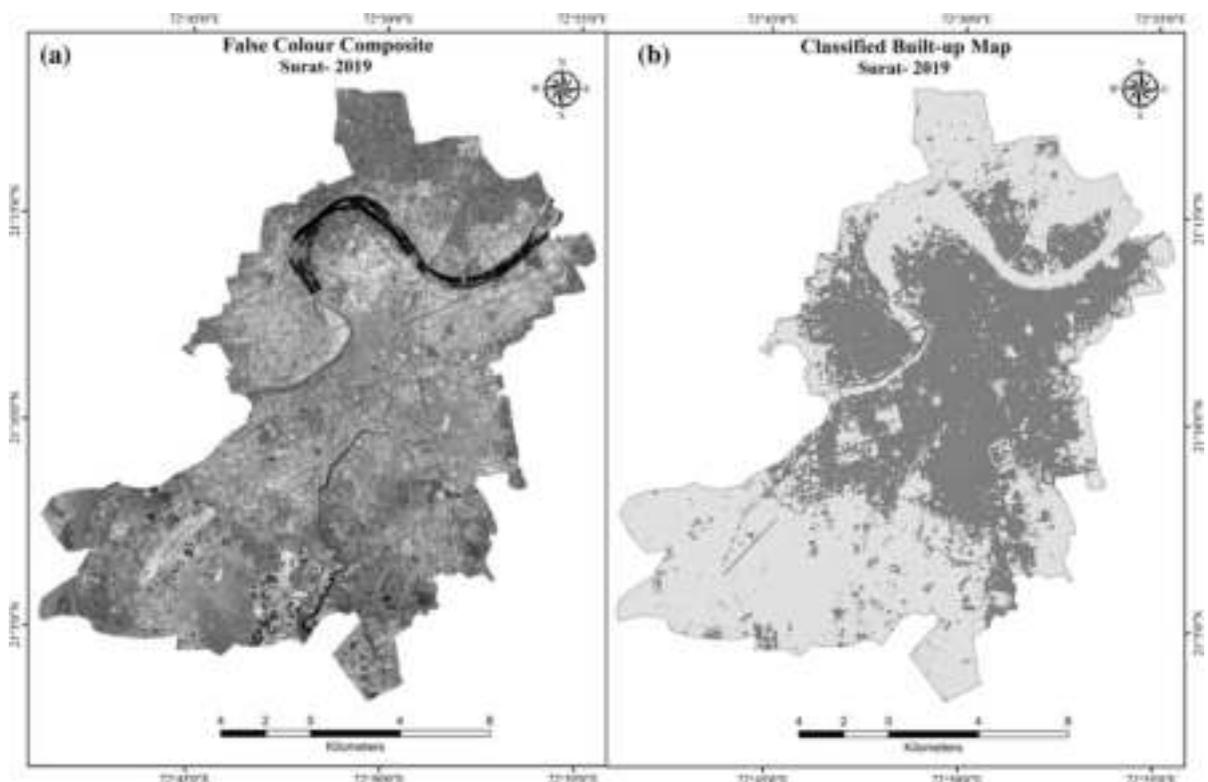


Fig. 3 a FCC image of 2019, b built-up area extracted for 2019

$$RUE = \frac{(BUA)_{i+n} - (BUA)_i}{n \times (BUA)_i} \times 100 \quad (5)$$

where $(BUA)_{i+n}$ and $(BUA)_i$ are the built-up area at $i+n$ th and i th times, respectively, and n is the time break in years.

The urban built-up density (BD) reflects the compactness of an urban area. It can be expressed as built-up area per square meter of urban area and in urban studies, it is also called urban compactness ratio (UCR). The UCR directly affects the pattern of urban heat island, building energy balance, as well as sustainable urban development (Kotharkar et al. 2014). Built-up density is directly proportional to the population density. The UCR or BD was calculated using Eq. (6).

$$BD = \frac{BA}{UA} \quad (6)$$

where BD is the built-up density, UA is the urban area (i.e. area under SMC) and BA is the built-up area (extracted from the satellite data) within that urban area.

Calculation of spatial relationships between population and built-up area

To study the linkages between population and built-up area, the simple linear regression has been applied using scatter plot method. Thus the regression analysis of zone wise distribution of population and built-up area, population growth rate (PGR) and built-up/urban expansion rate (RUE) and population and built-up density were calculated. The uplifting trend line in scatter plots show a positive relationship while down lifting trend line shows a negative relationship between the variables. The R^2 value shows the coefficient of determination of one variable to the other, i.e. how much a variable explains the other variable.

Results

Zone wise expansion of built-up area during 1991–2019

The analysis of Spatio-temporal pattern of built-up area in Surat shows a continuous expansion of built-up

area in all directions and in all zones except in the central zone (Fig. 3). In central zone the built-up area has increased at a lower rate, because the built-up density was already high in 1991 (Fig. 4). The highest increase in built-up area during 1991–2019 has been observed in south-west zone (844.76%) followed by western zone (693.11%) and south-eastern zone (623.79%), while lowest increase has been observed in the central zone. Zone wise there is a fluctuation in the increase in built-up area for each decade as some wards experienced highest increase during 1991–2001 but lowest increase during 2011–2019 and some wards experienced low increase during 2001–2011 and high increase during 2011–2019 (Table 4).

During 1991–2001, the south-western zone experienced highest increase in built up area (1152.81 ha) followed by south-east (886.32 ha) and southern zone (850.32 ha) while central zone experienced lowest increase in built-up area (75.69 ha). On the other hand, during 2001–2011, the eastern zone experienced highest increase in built-up area (1136.61 ha) but central zone again experienced lowest increase (0.99 ha). During 2011–2019, the built-up expansion rate declined in some zones but western (553.05 ha) and northern zone (529.43 ha) observed highest increase in built-up area and south-western (29.07 ha) and central zone (33.12 ha) observed lowest increase.

Analysis of spatio-temporal pattern of built-up density (BD)

The built-up density of Surat city has increased from 0.08 to 0.38 ha built-up area per hectare of the city's area during 1991–2019 (Table 5). The maximum increase has been experienced from south-east zone (from 0.12 in 1991 to 0.85 ha in 2019) while central zone experienced least increase (from 0.82 in 1991 to 0.95 ha in 2019). During 1991–2001, the south-eastern zone experienced highest increase in built-up density followed by eastern and northern zones, while central and south-western zones experienced lowest increase. On the other hand during 2001–2011, the eastern zone experienced highest increase in built-up density followed by south-eastern and northern zones, while central and southern zones experienced lowest increase. During 2011–2019, only northern, western and south-eastern zones experienced significant

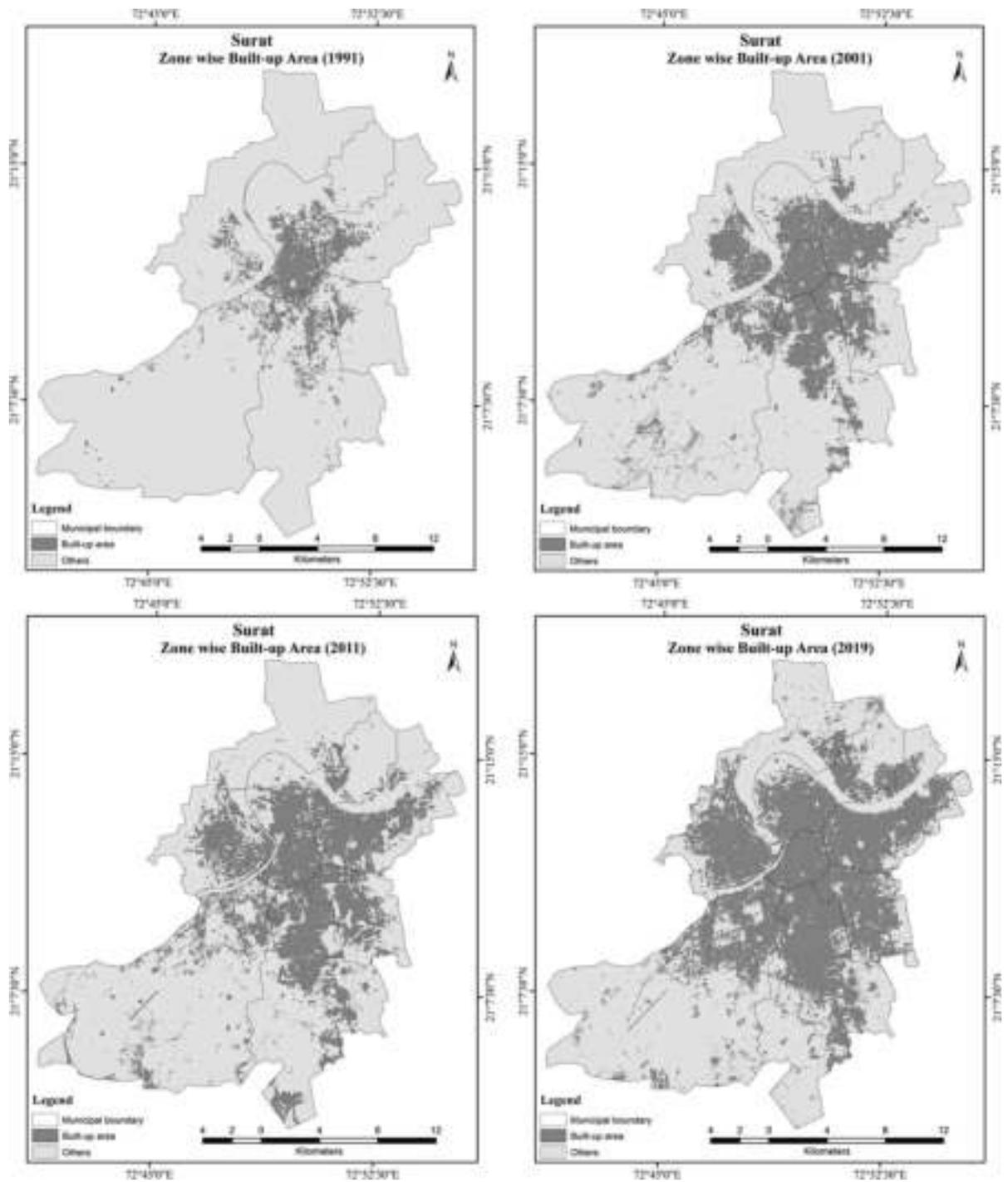


Fig. 4 Spatial pattern of built-up area in Surat during 1991–2019

Table 4 Zone wise decadal growth in built-up area during 1991–2019 (in hectares)

Zone	1991–2001		2001–2011		2011–2019		1991–2019	
	Built-up growth	% growth						
Central	75.69	11.28	0.99	0.13	33.12	4.43	109.80	16.36
South west	1152.81	520.69	688.41	50.09	29.07	1.41	1870.29	844.76
South	850.32	138.27	26.24	1.79	97.60	6.54	974.16	158.41
South east	886.32	385.89	174.24	15.61	372.15	28.84	1432.71	623.79
East	776.97	194.74	1136.61	96.66	288.72	12.48	2202.30	552.00
North	665.82	219.46	424.57	43.81	529.43	37.99	1619.82	533.91
West	843.48	369.12	187.29	17.47	553.05	43.92	1583.82	693.11

Table 5 Zone wise population density (persons per hectares) and built-up density (in hectares)

Zones	1991		2001		2011		2019	
	Population density	Built-up density						
Central	533.96	0.82	505.67	0.91	499.71	0.92	495.31	0.95
South west	12.27	0.02	21.67	0.12	31.05	0.18	41.80	0.19
South	30.94	0.10	66.05	0.23	112.53	0.24	175.82	0.26
South east	99.99	0.12	203.81	0.57	383.90	0.66	655.09	0.85
East	87.09	0.11	189.61	0.31	303.03	0.62	448.49	0.69
North	56.71	0.08	114.50	0.27	193.92	0.38	301.43	0.53
West	27.58	0.04	56.00	0.21	82.88	0.25	114.70	0.35
Surat	50.06	0.08	88.09	0.21	136.80	0.32	202.23	0.38

increase in built-up density while all other zones experienced very low increase (Table 5).

Analysis of population growth rate (PGR) and urban expansion rate (RUE)

During 1991–2019, the highest PGR has been noted from south-western zone (84.48%) while the highest RUE has been noted from south-eastern zone i.e. 19.83 ha per year (Table 6). During 1991–2001, the PGR was highest in south-west zone (52.07%) while RUE was highest in eastern zone (11.77 ha per year). On the other hand the both PGR and RUE was lowest in the central zone. During 2001–2011, the PGR was highest in eastern zone (9.67%) while RUE was highest in south-eastern zone (8.84 ha per year) and

during 2011–2019, the PGR was highest in western zone (4.39%) while RUE was again highest in south-eastern zone (8.83 ha per year). The RUE is negative for central zone during all three decades of the study period (Table 6).

Linkages between growth and distribution of population and built-up area

The coefficient of determination between zone wise distribution of population and built-up area for 1991, 2011 and 2019 shows moderate-positive relationship, but for 2001 the relationship is positive but weak (Fig. 5). At the same time the coefficient of determination between population growth and built-up expansion shows positive but weak relationship as the value

Table 6 Zone wise population growth rate (in per cent per year) and urban expansion rate (in hectares per year)

Zones	1991–2001		2001–2011		2011–2019		1991–2019	
	PGR	RUE	PGR	RUE	PGR	RUE	PGR	RUE
Central	1.13	− 0.53	0.01	− 0.12	0.44	− 0.11	1.64	− 0.26
South west	52.07	7.65	5.01	4.33	0.14	4.33	84.48	8.59
South	13.83	11.35	0.18	7.04	0.65	7.03	15.84	16.72
South east	38.59	10.38	1.56	8.84	2.88	8.83	62.38	19.83
East	19.47	11.77	9.67	5.98	1.25	6.00	55.2	14.82
North	21.95	10.19	4.38	6.94	3.8	6.93	53.39	15.41
West	36.91	10.30	1.75	4.80	4.39	4.80	69.31	11.28
Total	15.66	7.60	5.42	5.53	1.8	5.98	36.7	10.86

PGR population growth rate, RUE urban expansion rate

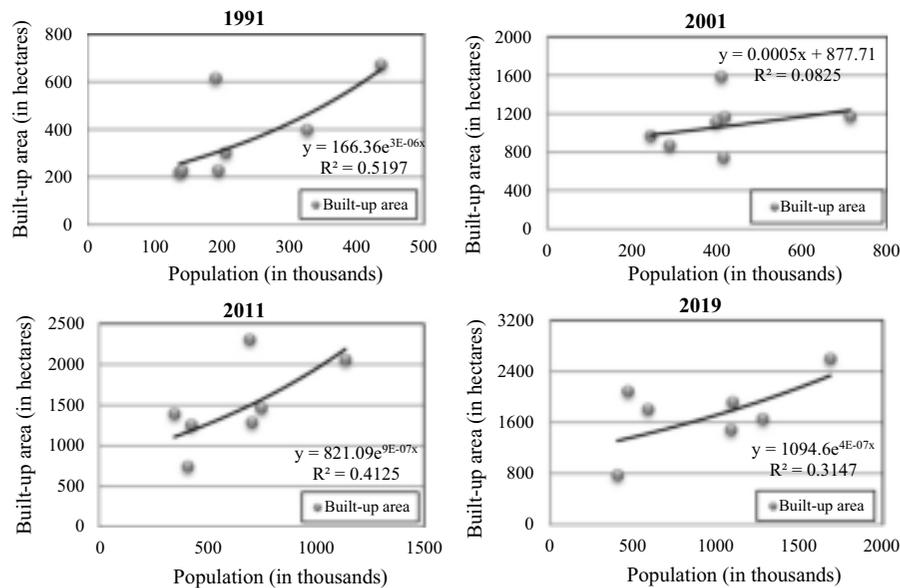


Fig. 5 Association between distribution of population and built-up area for 1991, 2001, 2011 and 2019

of R^2 is below 0.30 for all years (Fig. 6). This shows that the population growth rate (PGR) and the urban expansion rate (RUE) are not identical to each other. In central zone, the population has decreased during 1991–2019 but at the same time the built-up area continues to expand, while in other zones like south-west zone, the built-up area has increased about twice or thrice while the population has increased only a certain per cent during 1991–2001 (Table 2).

On the other hand the relationship between zone wise population and built-up density shows very high to nearly perfect relationship as the R^2 value is 0.79, 0.85, 0.97 and 0.86 for 1991, 2001, 2011 and 2019, respectively (Fig. 7). This shows that the zone-wise distribution of population and built-up area are related

to each other and the population density has influence over the built-up density. Thus the relationship between the distribution of population and built-up area is significant but the relationship between PGR and RUE is not significant.

Discussion

This study has been carried out to analyze the linkages and association between distribution and growth of population and built-up area in a fast growing city because the built-up/urban expansion is directly related to the population growth (Nicolau et al. 2019; Luo et al. 2018; Almazroui et al. 2017). The

Fig. 6 Association between population growth rate (PGR) and built-up expansion rate (RUE)

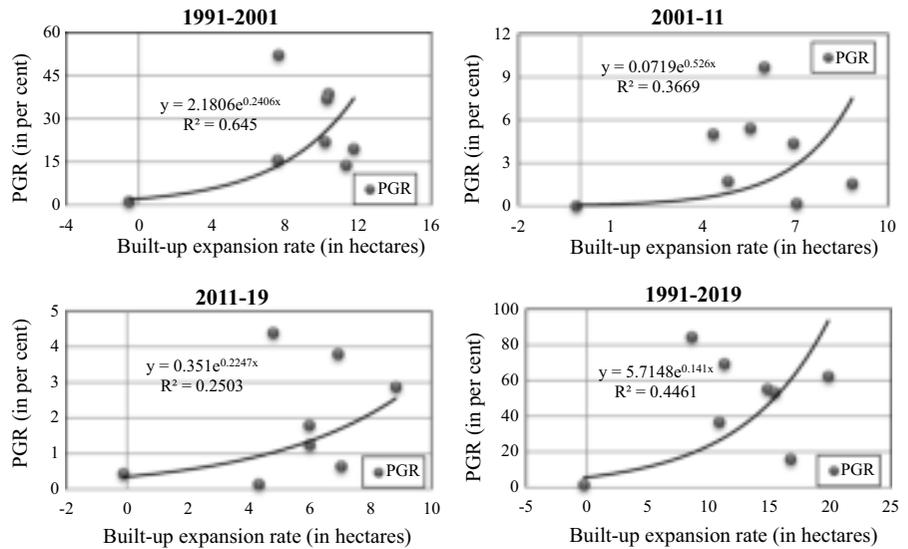
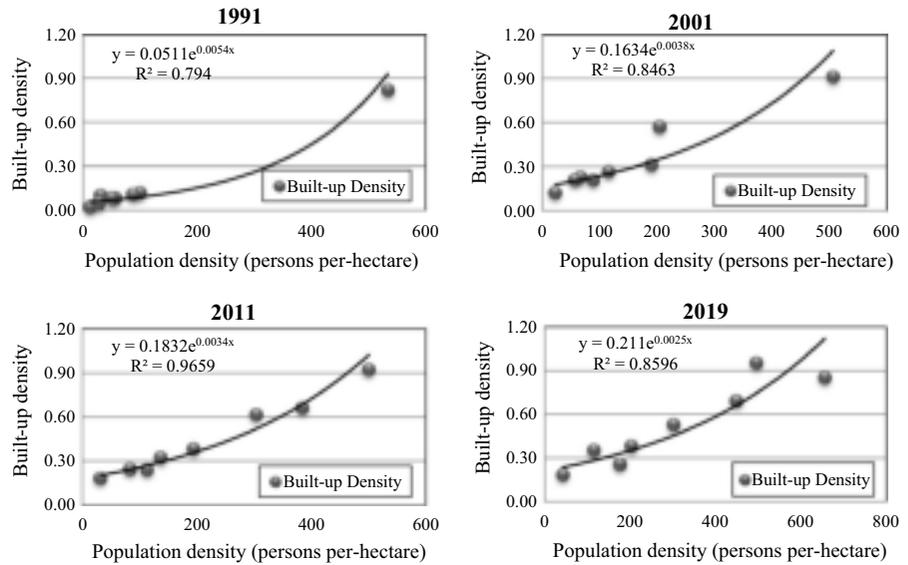


Fig. 7 Association between built-up and population density for 1991, 2001, 2011 and 2019



result shows that both the population and built-up area has increased at a rapid rate in the Surat city but the growth rate of population and urban area did not match each other. The maximum urban expansion has occurred in the south-western and western zones of the city while the central zone noted negative growth in the built-up cover. Sharma et al. (2013) noted that urban expansion has occurred in all directions in Surat city but maximum expansion occurred in the south due to better connectivity.

Population growth is the principal driving force of the built-up area expansion (Vitousek et al. 1997).

Thus an increase in population density leads to expansion of built up area which affects the built-up density (Guest 1973). The result also shows that the population density has increased about four times during the study period and during the same time period the built-up density has increased nearly five times (Table 6). During 1991–2019, the highest increase in both population and built-up density occurred in the south-eastern zone; i.e. from 99.99 to 655.09 persons per hectares and 0.12 to 0.85 ha built-up area per hectare of the total area of zone, respectively. The maximum increase in both

population density and built-up expansion occurred in the first decade of the study period.

Population density has strong positive correlation with the built-up density (Guastella et al. 2019; Bagan and Yamagata 2015) as an increase in population of an area demands more land for residential and other uses. The result shows that the population has almost perfect positive relationship with the built-up density but the relationship between PGR and RUE is positive but not significant. This reflects that the population growth has positive but weak relationship with the built-up expansion. The relationship between population growth and urban expansion are not always significant because the urban growth also causes resettlement from city's core to the peripheral areas (Guastella et al. 2019). In Surat, new residential and industrial areas have been developed in the outer fringes of the city (Sharma et al. 2013) thus the built-up area have increased at a faster rate in the outer zones than the central zone.

Further, the role of slums in relationship between population and built-up growth cannot be ignored, as the slums are informal housing units having tin or non-concrete material housing systems with deprived sanitation and living conditions (Mahabir et al. 2016). The Surat city has about 7% slum population in 2014, although during last decade, the slum population in the city has declined during last few years (Desh Gujarat 2014), and as the slum areas cannot be classified due to non-concrete housing systems, they are not included in the possible extracted built-up area. Hence the slum areas are not accounted in the built-up area which also has some effect on the correlation between the rate of population and increase in the built-up land.

Conclusion

The study shows that during last three decades, the built-up area has increased rapidly in the Surat city mainly due to increasing population and economic growth. The pattern of built-up expansion varies in different zones and the outer zones having low density of built-up area in beginning shows more increase in built-up area than the central zone. Surat has experienced very high economic growth and thus a number of industrial and commercial firms have been established during the time, which have given rise to growth

of the built environment in the city. The result shows that the distribution of built-up area has moderate correlation with the population distribution while built-up density shows almost perfect positive relationship with the population density.

The most interesting finding of the study is that the population growth rate (PGR) and urban expansion rate (RUE) are not identical to each other as the correlation between them is weak. The RUE was 7.60, 5.53, and 5.98 ha per year during 1991–2001, 2001–2011 and 2011–2019, respectively. While the annual PGR was 15.66, 5.42, and 1.8 persons per hectare for 1991–2011, 2011–2011 and 2011–2019 respectively. This shows that both PGR and RUE has declined with time but the PGR has declined at a faster rate than RUE. On the other hand, the population density was 50.06, 88.09, 136.80, and 202.23 persons per hectares during 1991, 2001, 2011 and 2019. While the built-up density was 0.08, 0.21, 0.32 and 0.38 hectare built-up area per hectare of the city area during 1991, 2001, 2011 and 2019. Thus the population and built-up density shows a similar pattern of increase. This shows that the growth rate of population and built-up area has some difference but their distribution and density are very much inter-related. The analysis of built-up expansion is important for the sustainable urban planning. It is suggested that for the future research may be taken up to assess the inter-relationships and inter-linkages between urban expansion and population growth at more precise and micro level i.e. ward level or colony level. Further it will be good to examine the role of other factors like economic growth, per capita income and purchasing power etc. in cities expansion in long run.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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