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Comparative Study for Understanding the Spatial Growth Pattern of Pune and Jaipur City from 1990 to 2020

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Abstract

Understanding the urban form, conducting spatial change analysis of an urban area using time-series data, and identifying urban growth drivers play a crucial part in framing policies for sustainable planning practices. In this research, an inverse S-curve function is employed to examine Urban Land Densities (ULD) derived from concentric divisions of urban regions in Pune and Jaipur. The inverse S-curve quantitatively describes variations in Urban Land Density (ULD) from the urban center to the outskirts. Consequently, the parameters identified during the curve-fitting process offer information about the urban form of the cities, shedding light on their rate of expansion, level of compactness, and the nature of sprawl. Built-up area is determined from the Landsat datasets for the years 1991, 1996, 2001, 2006, 2011,2016, and 2021. The analysis confirmed that Pune revealed an increase in sprawling, expansive, and low-density development. As a city that has grown linearly, Jaipur has experienced more constrained growth than Pune. Additionally, the fitted ULD equation provided an accurately fitted radius for Jaipur, but not for Pune, highlighting the equation's shortcomings. The direction analysis and understanding of the change in the slopes of the S curve further led to identifying growth drivers, broadly classified into proximity, government intervention, socioeconomic, and physical factors. The study can help achieve future research objectives in simulating and modeling urban growth and creating policies to deal with related problems.

1. Introduction

Urban sprawl can have a significant impact on the environment and quality of life in urban areas (Kumar et al., 2022). The rapid pace of urbanization has led to the loss of rural landscapes (Hakim et al., 2019), green spaces, farmland, and other natural habitats, which can result in increased pollution and greenhouse gas emissions. The depletion of resources such as water, soil, and air, can have negative impacts on the health of local communities and the environment (Yadav et al., 2015). In addition, unplanned urban development often results in a fragmented landscape, with artificial features such as roads, buildings, and other structures dominating the landscape (Ismael, 2021). This can lead to the loss of historic and cultural heritage, as well as increased energy consumption and traffic congestion (Abiden et al., 2010).

To mitigate these negative impacts, it is essential to adopt a proactive approach to urban land management. This may involve creating policies and strategies for sustainable urban development that balance the needs of residents, businesses, and the environment. Monitoring and measuring urban sprawl are an important first step in this process, as it can help identify areas of concern and provide information for informed decision-making. It is also important to engage local communities in the planning process, to ensure that their needs and concerns are taken into account. By working together, cities can create a more sustainable and liveable future for their residents.

Remote sensing and Geographic information system play a crucial role in revealing changes in the urban landscape and their effects on the environment. As a result, since its inception in 1995, research on land use dynamics has grown to be a significant area of study in urban planning, environmental change, and sustainable development (Li et al., 2015). Over the past three decades, Landsat satellite images have been crucial for analyzing urban land use and growth. The fact that the spectral and spatial characteristics of the urban landscape are more varied and complex is a further cause for concern (Dadras et al., 2015). Thus, it is crucial to produce accurate Land use land cover (LULC) maps depicting the area's land use.

Urban sprawl assessment and urban growth modeling is essential to understand how cities grow, what patterns and processes they follow, and what their future development will look like. Additionally, it aids planners in developing and putting into practice efficient plans and policies for a sustainable future. Many researchers have employed a variety of models and sprawl assessment methods to achieve this. Landscape metrics, which numerically measure the spatial growth pattern of urban areas at various patch, class, and landscape levels, are one of many techniques used to quantify urban sprawl and character. These metrics can be used to assess urban sprawl, compactness, and the intricate and dynamic patterns of spatial and temporal growth that characterize the urban form of metropolitan areas worldwide (Getu & Bhat, 2021). Total area (TA), number of patches (NP), largest patch index (LPI) (Zhang et al., 2012), edge density (ED), and area-weighted mean (Li et al., 2014) patch fractal dimension (FRAC AM) (Dietzel et al., 2005) were the landscape metrics used in many types of research.

These studies quantify urban sprawl patterns (Lv et al., 2018) and, using various methods, establish a relation between built-up areas and population density. None of the studies address how to apply sprawl metrics and urban sprawl indices to explore further potential growth drivers or the causes of urban sprawl. As a result, to fill the research gap, the main objective of the study is to define the urban extent, conduct a micro-scale analysis of urban growth by concentric and directional divisions of the built-up area of cities, identify the type of urban growth, and to find out the potential drivers of urban sprawl.

Another category of urban area is the compact cities have better public transportation and higher density with mixed land uses (Mouratidis, 2019). They offer a better quality of life and are considered based on density. Recently, researchers have begun to look beyond density as its definition (Neuman, 2005). And have considered other factors such as transit-oriented development and smart growth (Daneshpour & Shakibamanesh, 2011). Policymakers must consider the environmental and livability implications of high-density living. Compact city planning can enhance urban resilience and be measured using density, mixed-use, and intensification indicators (Mahriyar & Rho, 2014).. However, the cost of living, lack of space, transportation, noise, and pollution are obstacles to urban living (Howley, 2009).

In conclusion, urbanization is a complex phenomenon that has far-reaching impacts on the environment, natural resources, and quality of life. Rapid urbanization in developing nations has led to urban sprawl, land depletion, and increased pressure on urban sustainability. This research aims to understand the urban character of two cities in India, Pune, and Jaipur, through the assessment of urban sprawl and the factors driving urban growth. The use of LULC maps and the Urban Land Density function, along with concentric and directional analysis, provides a comprehensive understanding of the urban form of these cities. By understanding the drivers of urban growth, planners and policymakers can make informed decisions that promote sustainable urban development and address the challenges posed by rapid urbanization (Shafizadeh-Moghadam et al., 2017).

This study bridges a gap in prior research by incorporating direction-wise zoning for the identification of urban growth drivers which generally are identified without zoning only basic factors are considered and added in the growth simulation model (Altuwaijri et al., 2019) whereas, for some studies, this research is expanding direction analysis from 5-8 (Yin et al., 2018; Firozjaei et al., 2019) to 12 directions and integrating it with the identification of urban growth drivers. Unlike previous studies where the direction analysis approach is not used (la Luz Hernández-Flores et al., 2017) the present approach combines distance and direction analysis, laying the groundwork for urban growth simulation based on past and present trends. In some

research logistic regression model is also used to study the urban growth but lacks temporal dynamics and spatial autocorrection, a pattern often present in spatial data that can affect the model's accuracy. Whereas this direction-wise zoning approach of integration with GIS data can solve the problem (Hu & Lo, 2007). Another method used is the Thiessen polygons method, creating polygons with the city center as the nucleus which has limitations: sensitivity to changes in polygons, impacting outcomes with the addition or removal of points, and challenges in accurately predicting urban spatial structures due to the dynamic nature of cities with changing boundaries over time (Kazemzadeh-zow et al., 2016)

The comprehensive analysis categorizes drivers into proximity factors related to major transport networks and hubs, government interventions, socioeconomic factors, and physical factors. These specific drivers provide nuanced insights for urban growth modeling, allowing for a more tailored simulation that goes beyond general factors considered in typical urban growth simulations of cities.

The study is divided into 5 sections. The first section is an introduction to the topic, second section explains the data and methodology used for sprawl assessment using GIS and remote sensing. The third section focuses on identifying urban growth drivers in the two cities. The fourth section presents the results and discussions on the urban form of the cities and the drivers of urban sprawl. The final section summarizes and concludes the study.

2. Data and Methods

2.1. Study Area

Two cities with different economic characteristics—the metropolis of Pune (comprised of Pune Municipal Corporation and Pimpri Chinchwad Municipal Corporation), and Jaipur Development Authority—are the study areas for the research that is being considered as shown in Figure 1.

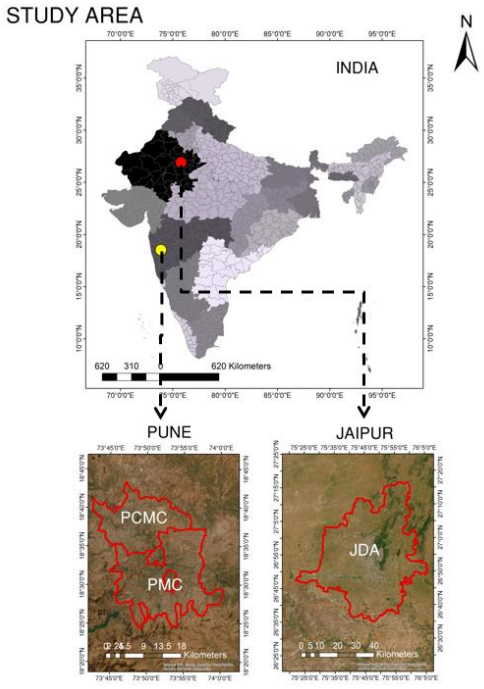

Figure 1. Study area: Pune Metropolis and Jaipur Development Authority

Pune Metropolis constitutes Pune Municipal Corporation and Pimpri Chinchwad Municipal Corporation. Pune, Maharashtra's cultural capital, is known as the "Oxford of the East" and "Queen of Deccan". It has been ranked "the most livable city in India" several times. It is the seventh most populated city in India (Development et al., 2013). It is situated 560 meters above MSL in Maharashtra's western region,

between 18°32' N and 72° 51'E, spread over an area of 497 sq. km. (PMC) and PCMC across 177 sq. km. with a population of 7.4 million in 2021. And an average population density of 148.87 PPHA. The city is located at the confluence of the Mulla and Mutha river. This region is divided by the three rivers Pavana, Mula, and Indrayani. Pune is a center for both the industry and IT sectors. Historically known for its education sector then its manufacturing sector, and now for IT sector. Its hinterland has many food processing units. Pune's industrial development ranks third after Bombay and Thane. IT industries are proliferating, and most automaker headquarters are here (Development et al., 2013).

Jaipur (Jaipur Development Authority), the administrative capital of India, is known as the "Pink City of India" and "Paris of India." It is the 10th most populated city in the country (Census 2011). It is geographically located between 26° 55' N, and 75° 49' E, spread across an area of 467 sq. km with a population of 3.73 million in 2021. The city is surrounded by Aravalli hills in the south and east of the city. And average population density of 80 PPHA. The majority of the population is involved in trade and commerce. The industry is the major employment sector, and the rest of the workforce is involved in small-scale activities in the walled city. The economy is fueled by tourism, Jewelry making, gemstone cutting, and luxury textiles. Apart from that, it is a provincial, administrative, and educational center. It is also emerging as a hub of the automobile and chemical industries. NH 48 (Delhi-Mumbai), NH 52 (Kota), and NH 21(connects Agra) all pass through Jaipur. Jaipur lies along the Delhi-Mumbai Industrial Corridor, which is a locational benefit for industries to establish here.

2.2. Methodology

The methodology for this study, as shown in Figure 2, includes the creation of LULC maps from available USGS Earth Explorer satellite images for the years 1991, 1996, 2001, 2011, 2016, and 2021, with a five-year development gap in mind.

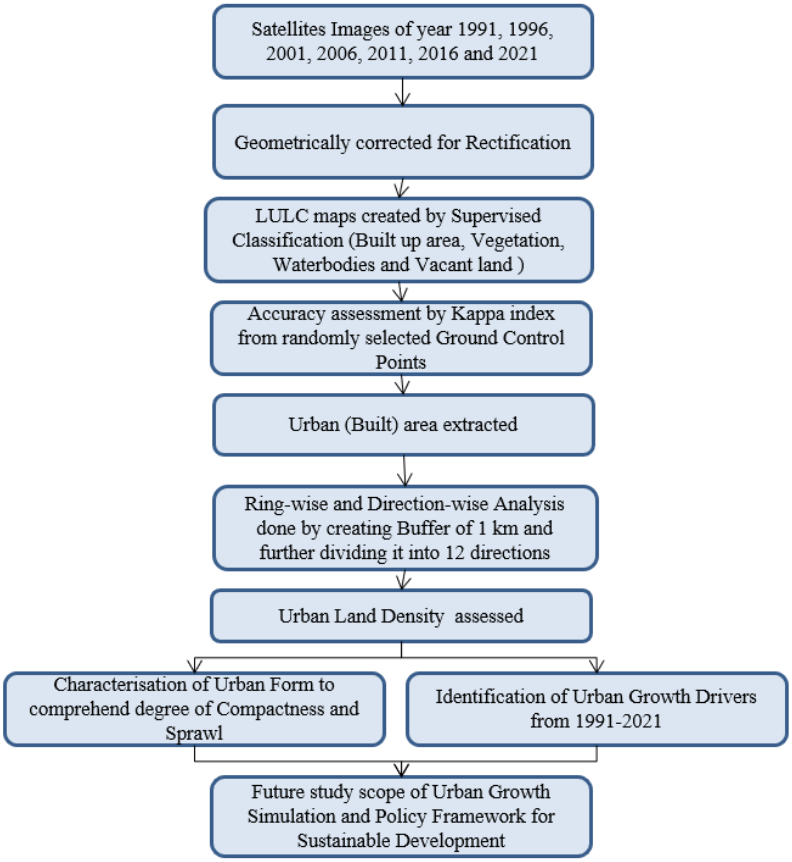

Figure 2. Methodology Flow Chart

Details of the satellite images are mentioned in Tables 1 and 2. The supervised classification method in ArcMap 10.4 was used to create LULC maps whose classes were categorized into four: built-up area vegetation, water bodies, and vacant land. Later, the urban area is extracted. To better understand the urban morphology of the research area, the extracted urban area is divided into one-kilometer concentric rings to obtain Urban Land Densities and fitted in a function such that its shape describes the study area's compactness expansion rate and sprawl extent. The area's urban morphology changes are examined by certain parameters obtained from the fitted curve year by year. To determine the factors driving urban growth, additional analysis is conducted both distance-wise and direction-wise. The concentrically partitioned sections were further split into 12 directions at an angle of 30° in Pune and Jaipur. Examination of how the urban area changes in each direction and determining any plausible causes, which will reveal the driving force for expansion, is also carried out. Future urban studies of urban growth simulation and policy framework for repercussions of urban expansion and urban sprawl could employ an understanding of the urban form and the potential factors that are producing the growth of the urban area.

2.2.1. Image Classification and Urban Area Extraction

To map the sprawl dynamics, satellite images from USGS Earth Explore were used to make land use and land cover maps (https://earthexplorer.usgs.gov/). filtered for zero percent cloud cover and dated between January to May to reduce the processing discrepancy and image correction. The radiometric and geometric corrections were performed on the satellite images to rectify the images and were set to the Projected Coordinate System Universal Transverse Mercator WGS 1984 43N (all two cities lay in 43N). False Color Composite (FCC) bands were used to distinguish cells belonging to one feature class in the image bands. The FCC of built-up appears light blue, and the vegetation in red (dense vegetation in dark red and sparse vegetation in light red). The LULC map was prepared in ArcMap 10.4 from the Landsat images using a Supervised Classification technique. The Classification techniques classified the satellite image into four features of land use, namely Built-up area, vegetation cover (Sparse and Dense Vegetation), Vacant lands, and Water bodies. The urban area was extracted from the LULC maps. For the accuracy assessment of the LULC maps prepared, 150 randomly selected ground control points covering all land use types as samples were chosen from Google Earth. These ground control points were visually compared, and the LULC maps were validated by computing the kappa coefficient and ground truthing. Accuracies greater than 80% are considered suitable for further analysis of land use land cover studies. The accuracies obtained in this study ranged from 80% to 85%. Hence, the accuracy level obtained is satisfactory for carrying out the study.

The study aims to identify changes in built-up areas to analyze urban growth patterns, growth direction, and characterize urban form. The accuracy assessment ensures the reliability of Land Use/Land Cover (LULC) maps, allowing for additional spatial analysis. In this context, "built-up area" encompasses land use designated for residential, commercial, institutional, and industrial purposes, and includes roads and other constructed forms.

Table 1. Details of Satellite Images used for Pune City

Pune City				
Year	**Dataset**	**Resolution**	**Sensor**	**Path/Row**
1st Feb 1991	Landsat 5	30 m × 30 m	TM	147/047
3rd April,1996	Landsat 5		TM	
12th Feb,2001	Landsat 5		TM	
14th Nov, 2006	Landsat 5		TM	
23rd Jan, 2011	Landsat 5		TM	
26th April,2016	Landsat 8		OLI/TIRS	
7th March, 2021	Landsat 8		OLI/TIRS	

Table 2. Details of Satellite Images used for Jaipur City

Jaipur City				
Year	**Dataset**	**Resolution**	**Sensor**	**Path/Row**
5th March ,1991	Landsat 5	30 m × 30 m	TM	147/041
15th Feb,1996	Landsat 5		TM	
24th Mar, 2001	Landsat 5		TM	
13th Oct,2006	Landsat 7		ETM	
8th Feb,2011	Landsat 7		ETM	
28th May, 2016	Landsat 8		OLI/TIRS	
24th April, 2021	Landsat 8		OLI/TIRS	

2.2.2. Concentric Ring partitioning

The urban area is analyzed using Concentric Ring partitioning for extracting urban land density ring-wise as per Eq. 1. This helps match the values to the fitted function and understand urban expansion trajectories. Research has proved that spatial-temporal analysis across the buffer zoning method is more useful in understanding the city's urban form than the traditional aggregate urban growth rate. The rings are portioned 1 km from the urban center to the administrative boundary and the railway station is considered the urban center. The expansion rate varies across different time periods and parts of the city; thus the portioned rings of 1 km are used instead of administrative wards. The cantonments are excluded from the administrative boundary in Pune to avoid hindrance in urban expansion.

$$Urban\ Land\ Denisty\ (ULD) = \frac{Built-up\ area\ in\ the\ ring}{Total\ area\ of\ the\ ring} \ldots\ldots\ldots\ldots\ldots (Eq.1)$$

For Polycentric cities, the urban center is considered a different nucleus from which the growth has been induced. Hence, the urban centers for PMC and PCMC are considered separately. The urban center is regarded as the railway station for PMC and MIDC area (Maharashtra Industrial Development Corporation) for PCMC, from which growth and development began in Pimpri Chinchwad Municipal Corporation (Plan, 2008).

2.2.3. Urban Land Density Function

The function proposed (Jiao, 2015) is a sigmoid function of an inverse S shape which intends to state the variation of urban land density (Lv et al., 2018) as per Eq. 2. The function described below

$$f(r) = \frac{1-C}{1+e^{\left(A\left(\frac{2r}{D}\right)-1\right)}} + C \ldots\ldots\ldots\ldots\ldots (Eq.\ 2)$$

Where f(r) is the urban area density function, r is the radius from the center, and A, C, and D are the parameters indicating the character of the urban form. The proposed function is a continuous decreasing function. At r = 0, the f(r) value tends to become 1, and at r = infinity, f(r) tends to become c. The function exhibits an inverse S curve indicating the ULD decreases gradually from the urban center and decreases quickly in the area between the urban and suburban areas, then decreases gradually again in the periphery of the urban area. The function quantitatively describes the trend of ULD from the core to the outskirts, and parameters also mean some fundamental characteristics about the urban form of the city for monocentric cities, whereas, for linear or polycentric cities, these will represent the character of CBD or central part of the city.

2.2.4. Fitting of the function with ring-wise ULD

The values of ring-wise urban land density are fit to the curve to obtain the parameters indicating the character of the urban form of the study area. The function is fitted with the ring-wise urban land density for all seven years and two cities. The solver in Excel is used to get the parameters in successive iterations. The iterations are stopped as the function curve, and the ULD values match nearly. The function in the solver is set

to optimization of function to value 1. Many algorithms are also used to refine the constants A, C, and D. The iterative parameters for the curve fitted are shown below in Table 3. for PMC, PCMC, and Jaipur.

Table 3. Parameters Obtained After Urban Land Density Curve Fitting

CITY	PMC			PCMC			JAIPUR		
Year	A	C	D	A	C	D	A	C	D
1991	0.551	0.010	3.644	0.236	0.026	0.833	0.321	0.007	1.881
1996	0.959	0.029	6.721	0.634	0.040	2.960	0.612	0.008	3.630
2001	0.999	0.010	7.116	1.047	0.024	4.071	1.290	0.001	7.530
2006	0.725	0.093	7.150	0.964	0.045	6.650	2.350	0.022	13.000
2011	2.170	0.062	13.256	2.425	0.080	9.349	2.356	0.002	13.250
2016	3.603	0.098	19.925	3.034	0.020	15.500	2.294	0.035	13.795
2021	3.631	0.119	21.810	3.281	0.061	17.782	2.009	0.025	14.383

2.2.5. Characterizing Urban Form

Urban form is mainly categorized into two categories, i.e., compact and sprawl development. This section explains how the city's core areas, inner fringe areas, and sub-urban areas transformed from dispersed to compact urban forms. The parameters obtained from curve fitting through optimization are used to comprehend the urban morphology of the study area (Eq. 3). The constant C indicates the ULD of the hinterlands. This shows that built-up is increasing in the rural areas around the cities as the entire region develops. The D denotes the approximate boundary the city poses between the urban fringe and the periphery. Outliers will exist because the assumptions made for the equation are for the monocentric form.

From the curve, we can identify that the portion of the curve with high ULD and slow decrease will represent the Core area dynamics of the study area, whereas the inner and suburban areas will tend to have a rapid decrease in ULD. The curve also highlights the compact character of the city. Steep curves indicate compact cities and gradual curves for sprawling cities. In a compact city, the ULD is high in the city center and drops steeply to a very low value around the city center. Then constants like C which are generally less than 0.1 but can also be more than 0.1 in the case of metropolises that are surrounded by cities with almost continuous areas. Ks is a parameter to test

$$ks = \frac{0.57735(1-C)A}{1.316957D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{(Eq. 3)}$$

Lower Ks means a lower overall ULD, and possibly experienced more expansive urban growth. However, Ks can be called biased as it is derived from 3 parameters in which D is changeable. The Ks value generally decreases for most of the cities with an increase in growth. Large cities tend to have lower Ks values. Furthermore, it can be used for cities with the same urban scale.

To avoid biases, the part of the curve that shows the proportion of the quickly decreasing part, i.e., the part that shows the inner cities and suburbs, Kp index, and A, is the parameter that controls it and is considered a measure to compare the cities' urban form (Eq. 4).

$$kp = \frac{1.316957}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{(Eq. 4)}$$

A small Kp value means a city has a narrow area that includes both the city centre and the suburbs. On the other hand, a city with a high Kp value has a low population density and is spread out. The Kp is only related to constant A and can be used to measure how dispersive different cities are getting over time. Where constant A controls the slope of the curve. Hence making the Kp index a more robust measure. The Kp and Ks indices of the respective cities are as shown below in Table 4.

Table 4. Parameters for Characterisation of Urban form

	Kp			Ks		
Year	**PMC**	**PCMC**	**Jaipur**	**PMC**	**PCMC**	**Jaipur**
1991	2.391	5.588	4.103	0.072	0.121	0.074
1996	1.373	2.079	2.152	0.067	0.110	0.073
2001	1.318	1.258	1.021	0.066	0.105	0.075
2006	1.817	1.366	0.560	0.064	0.090	0.078
2011	0.607	0.543	0.559	0.061	0.084	0.078
2016	0.366	0.434	0.574	0.061	0.076	0.070
2021	0.363	0.401	0.656	0.040	0.061	0.060

2.2.6. Distance and Direction Analysis and Identification of Urban Growth Drivers

Urban growth drivers are analyzed by performing distance and direction analysis of urban land density for each period (1991-2021) using ArcMap 10.4. The urban area is clipped into 1 km rings and ULD is calculated in 12 directions for both Pune and Jaipur respectively. Identification of urban growth drivers is done through a combination of primary surveys (site visits and discussions with locals and officials) and secondary surveys (using Google Earth, development plan reports, and comprehensive mobility plan reports).

3. Results and Discussion

3.1. Urban Area Extracted

The graph shown below in Figure 3 shows the urbanization trend of Pune and Jaipur. Urbanization was seen maximum in 2006 for Pune and Jaipur (Figure 4). Pune has shown no growth rate from 2016-2021 due to the alarming risk of saturation. Jaipur has also not shown significant urban growth from 2016 to 2021 because of negligible population growth. Jaipur's population growth has been less compared to urban growth, as urban growth is only because of an increase in the urban area of industries and tourism activities and accommodation where tourists are a floating population.

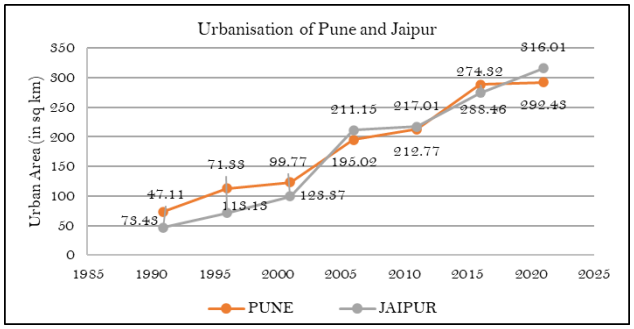

Figure 3. Urbanization of Pune and Jaipur

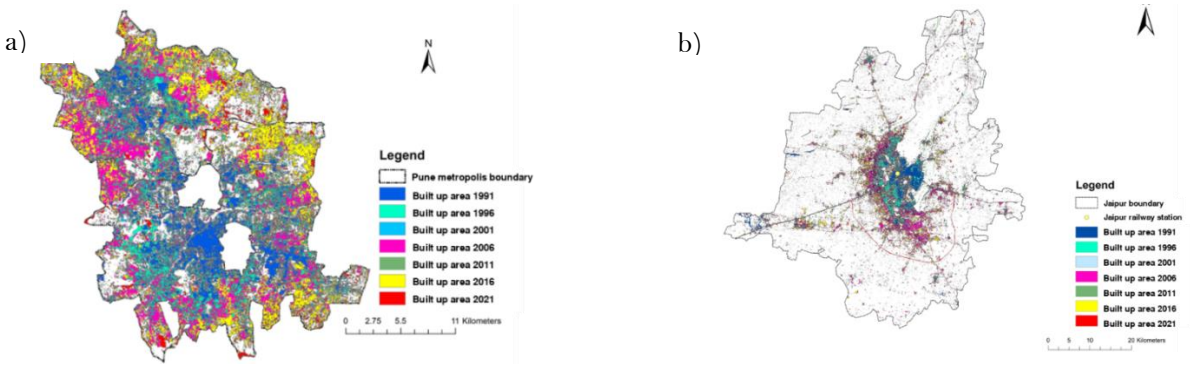

Figure 4. Change in Urban Area Over the Years for a) Pune, and b) Jaipur

3.2. Identification of Urban Growth Drivers by Distance and Direction Analysis

As per Distance and Direction analysis of Pune Metropolis as shown in Figure 5. In 1991 highest ULD was seen in the SW1, SW2, and SW3 direction, which is the core area of Pune. The core area further divides into business centers known as Peth of Pune, which today forms the heart of the city with all types of markets situated in it. Currently, the old city of Pune possesses the characteristics of a potential Central Business District, which needs to be notified. In NW2 from 13 – 19kms, the moderate ULD is because of the establishment of Maharashtra Industrial Development Corporation, which brought many large automobile companies and the coming up of Drugs and pharmaceutical companies like Hindustan Antibiotics Pvt Ltd. in the 1960s.

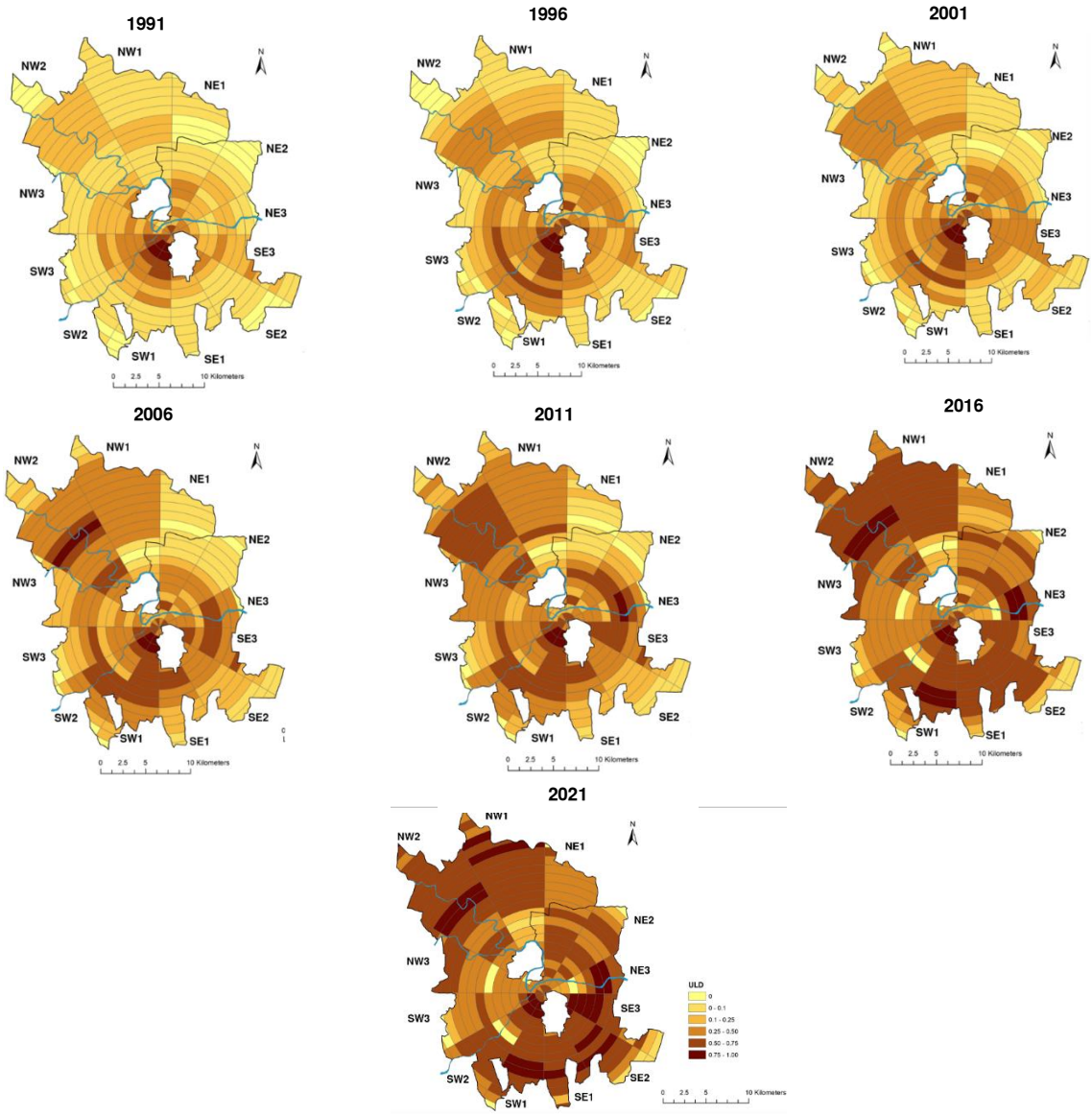

Figure 5. Distance and Direction Analysis for Pune a) 1991 b) 1996 c) 2001 d) 2006 e) 2011 f) 2016 g) 2021

In 1996, The significant growth during this period was due to industrialization in Pimpri Chinchwad. Since the airport was certified as a customs airport for goods attracted many industries to settle around Pune, i.e., in Pimpri Chinchwad especially. Residential development also flourished after the Development Plan in 1987. Direction SW1, Residential and commercial activities up to 7 km along the NH 60 (old NH4 road). By

2001, the IT industry had emerged in Talawade, Kharadi, and Hadapsar, Hinjewadi. The development in direction SE3 was seen due to the IT park establishment. Whereas in NW1, NW2 showed growth in industries. Moreover, SW1 continued showing growth in residential and commercial activities.

In 2006, the completion of the 6-lane Mumbai Pune expressway created good connectivity to PMC and PCMC. Also, a population shift was seen to PCMC after this due to lower land prices. In 2011 various government interventions like the airport being certified as an international airport, MSMEs Act,2006. Special Economic Zone Policy,2006 which had drawn many IT industries, numerous road upgradation and BRTS projects implemented in 2007 by JNNURM, were the reason for the development in directions NE1, NE2, NE3, SE3, SW2, NW2, and NW3. IT Parks flourished from 2016 to 2021, with 35 registered IT Parks (2010) and 16 recognized Special Economic Zones. Pune became the state's second-most popular investment location after Mumbai (SEZ), Maharashtra Township Policy, 2005, 25 registered townships again government interventions played a significant role in the growth in all the directions of Pune Metropolis. The Regional Plan revision effect was seen in these years' population shift to cheaper lands in the outskirts with amenities and good connectivity to worKplaces was the reason for the sprawl outwards. The growth nodes identified are Chakan, Alandi, Wagholi, Loni, Kalbhor, Khadakwasla, Pirangaut, Hinjewadi, Talegaon, Malavali, Rajgurunagar, Shikrapur, Urali-Kanchan, Shivapur, Nasarapur, Ranjangaon, Kedgaon, Yawat.

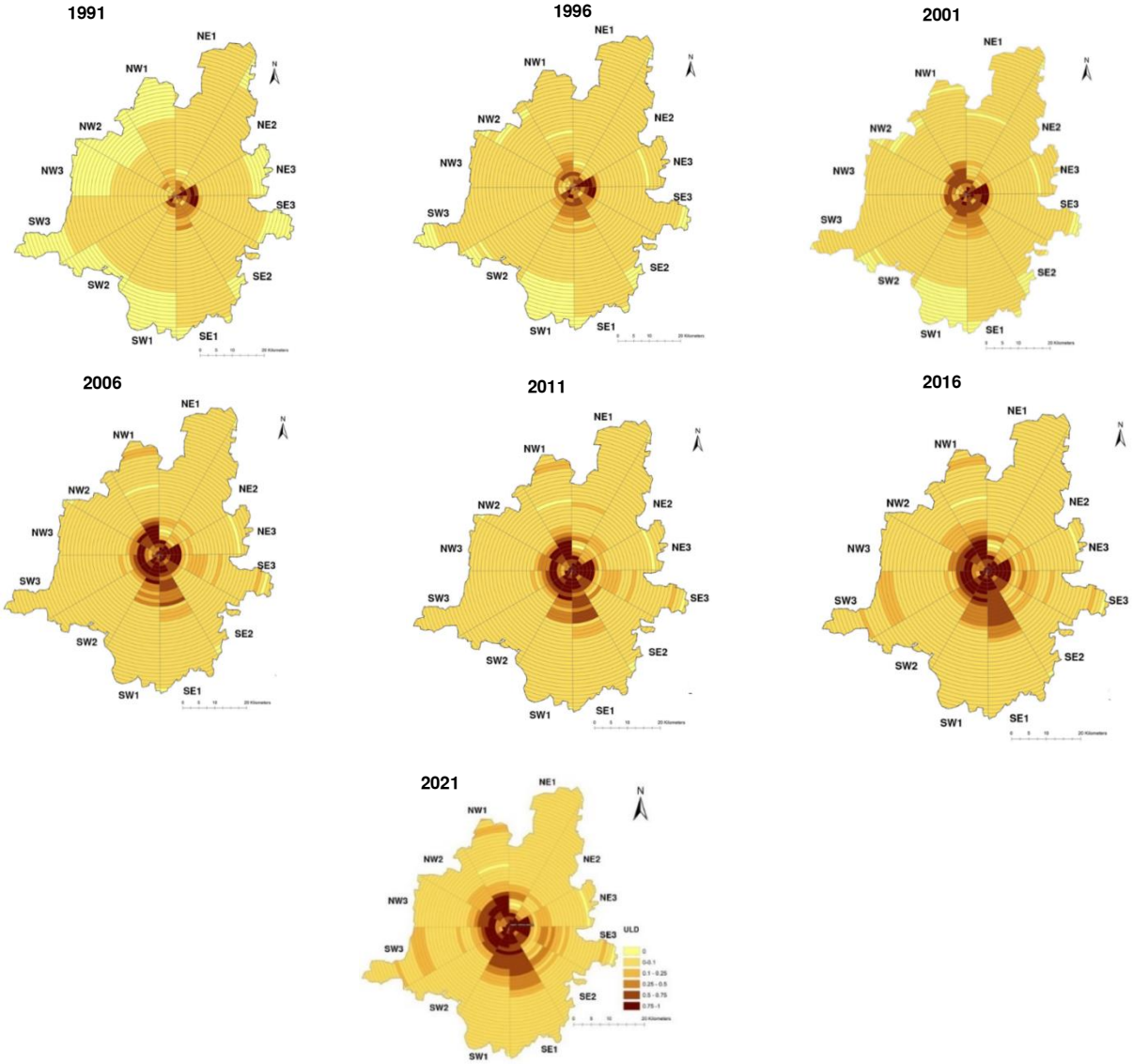

Figure 6. Distance and Direction Analysis for Jaipur a) 1991 b) 1996 c) 2001 d) 2006 e) 2011 f) 2016 g) 2021

As per the Distance and Direction analysis of Jaipur as shown in Figure 6. From the beginning, Jaipur's economy was based on tourism and related markets. Hence in 1991, directions NE2, NE3, and SE3 maximum ULD is seen as predominating with tourism activities-based land use and market. National highway development projects in 1998 caused development along these highways, and linear development started in directions NW1, SE3, and SW1 during 2001. In 2006 growth was seen in all directions. Jaipur airport was declared an international airport, and National Highways brought manufacturing industries of marble and stones after 2006. Northeast Valley is primarily developed for tourist facilities of hotels and markets. An increase in compactness is seen only in 1-2 km, with a substantial increase in ULD. In 2011 Jaipur metro Phase-1A, the third Master Plan approved and enforced for 2025, Provision of a ring road circumventing the U1 area, induced growth in directions SE1, SW1, NW1, and NW3. SE1 predominantly saw an increase in industries. And SW1 educational setups for coaching classes. The effect of the DMIC Corridor (Delhi Mumbai Industrial Corridor, by 2014) and the Golden Quadrilateral (by 2012) was seen in the growth of industrialization in Jaipur from 2016 to 2021. Jaipur is the administrative capital of Rajasthan; hence many government offices, bureaucrats' residences, government areas, and colonies came up. The city is restricted from the east and northwest due to hills and military-restricted areas, respectively. 2011 -2021 saw significant developments of SEZ located close to the proposed Ring Road, near Bhankrota on Jaipur-Ajmer Road, Phulera logistic park, Dhund River for riverfront development, which in due course of time made the city compact after the linear development of the city. The growth nodes identified are Kotputli, Shahpura, Achrol, Bassi, ChaKsu, Phagi, Narayana, Phulera, Kishangarh, and Chomu.

3.3. Fitted ULD Function

The graphs below in Figure 7. show the comparison of Pune and Jaipur's Kp and Ks Index values. As seen in the graph of the ULD fitted curve for Pune Metropolis (PMC and PCMC) in Figure 8. For Pune Metropolis, the slopes are not steep. They are gradual, indicating that it has not sprawled from the urban core to urban to peri-urban and is not distinctive in these three forms. The C is less than 0.1 for all the years. The curve is not steep and hence not a compact and sprawling city. Ks values are less than 0.1; hence the city has experienced more expansive urban growth. Large cities have lower Ks values. With time higher Kp value is seen decreasing, indicating the dispersive nature of the city and since the city is getting saturated and dense. PMC had C >0.1 in 2021 as PCMC (another city) was growing in continuation with PMC and together working as twin cities.

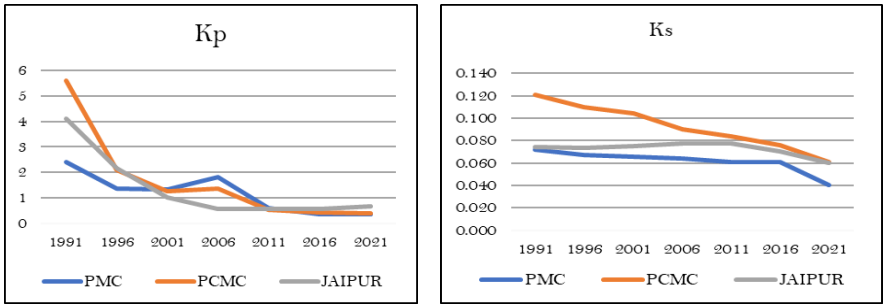

Figure 7. Graphs Showing a Comparison of Characterization of Urban Form Parameters

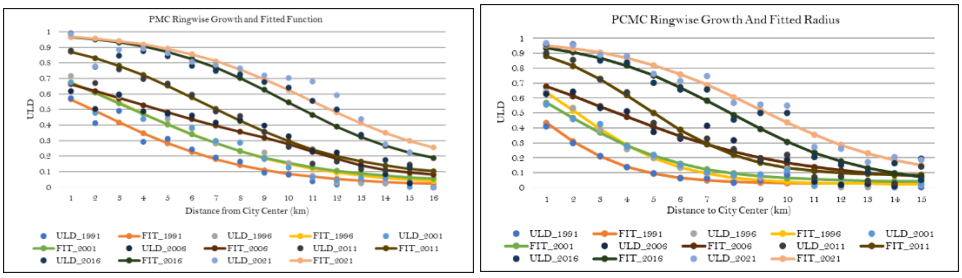

Figure 8. ULD v/s Distance from City Center and Fitted Curve Graph for Pune Metropolis

As seen in the graph of the ULD fitted curve for Jaipur in Figure 9. Jaipur has a S curve with high density at the start, which decreases gradually and then follows a rapid decrease. Hence it is not sprawled in nature and can be said to be compact in nature. The C is less than 0.1 for all the years. Hence is not continuous with an urban area like Delhi, surrounded by satellite towns. The Ks values are less than 0.1 but more than the values of Pune; hence not more expansive than Pune. The mean Kp value of both PMC and PCMC is greater than Jaipur; hence the city has experienced less dispersive growth than Pune. The conclusion is that Jaipur is compact and expansive but does not have low urban land density and is dispersive like Pune Metropolis. Jaipur is a linear city, and its growth started along the DMIC corridor along the NH 48 connecting Delhi and Mumbai.

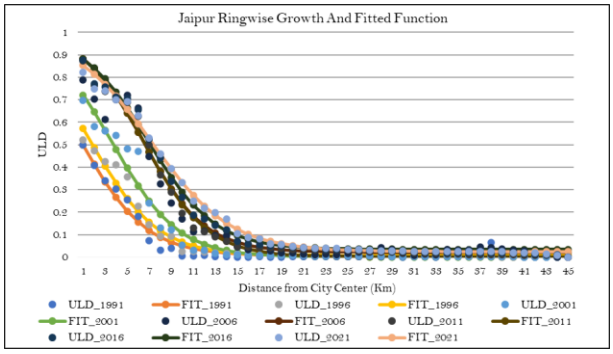

Figure 9. ULD v/s Distance from City Center and Fitted Curve Graph for Jaipur

3.4. Discussion

3.4.1. Distance and Direction Analysis

From the beginning, growth was induced by the strategic locations of industries, Hindustan Laboratory Pvt Ltd, or educational hubs, which were all scattered, and development happened around them (Catalán et al., 2008; Shukla & Jain, 2020) . The declaration of the airport as an international airport (Okwuashi & Ndehedehe, 2021) brought IT Parks and small-scale industries, all spread out in the city. We can see that the S curve is disappearing in the case of Pune. In 1997 first Regional Plan was made for the PMR region to reduce the influence of Pune City on the haphazard development of nearby areas. The effect of the Regional Plan is seen from 2001 when the city began to sprawl. People started shifting outwards for better amenities and lower land prices. Pune had a hike in Land prices from a very early period because of the Urban Land Ceiling Act, which was formulated for the urban poor, and it mentioned not to touch encroached or illegal settlement of the urban poor in the core area. The Maharashtra government purchased large tracts of land under this act to provide low-cost housing. However, this land remained vacant; hence the prices hiked, and people had to shift outwards. The curve in 2016 and 2021 shows that it is multinucleated after the coming of IT Parks. People migrated for employment and started settling near their workplaces (Cho, 2005). IT Parks coming to Pune was a government initiative in the Regional Plan 1997, which gave incentives to establish IT Parks in peri-urban areas to decentralize the population and amenities. In 2009, another initiative was the Integrated Township Policy 2005, in which townships came in the outskirts of the city and in the peri-urban areas, which led to the shift of the population to the outer areas and made the density unevenly distributed in the city and outskirts. Since the city is saturated now, it is getting denser and is witnessing low Kp over the years.

In PCMC, the growth began with MIDC and Hindustan Antibiotics in the 1960s, which brought employment opportunities (Cho, 2005) to people in Pune and Pimpri Chinchwad, and many other companies to set up here as the airport was declared a customs airport. Along with it, the connectivity with Pune and Pimpri Chinchwad was made strong, which led to population migration. The development was seen around MIDC and along the highways connecting PMC and PCMC. So, it was a dispersed growth from the beginning. The PCNTDA was established to make residential pockets in sectors in the other surrounding areas. PCMC was developing extremely fast because of its large revenues from industries, infrastructure is developed the best

there, and the land prices are also lower. RP 1997 was also responsible for the scattered development of PCMC. Then came the IT park in Hinjewadi, which caused development there, resulting in multi nuclei nature of the city from the beginning, like previous studies considering multiple city centers for zoning of urban land. (Hu & Lo, 2007). Since the city is saturated, it is getting denser and has witnessed low Kp over the years.

Jaipur was concentrated as only core city because of the tourism industry and employment activities related (Lv et al., 2018) to tourism, craft, and jewelry. Then the Jaipur airport was declared an international airport, and national highway (Okwuashi & Ndehedehe, 2021) development projects in 1998 brought industries, and development mainly happened along the highways and getting compacted in between the areas of the road (Altuwaijri et al., 2019). Jaipur has witnessed three master plans (Bharath et al., 2018) in 1976, 1998, and 2011 and their effects are witnessed in the city's growth, making it compact after its development along the roads (Subrahmanya & Hillemane, 2009). So, from linear development, it became compact.

The results of the urban land density function were compared with results in (Jiao, 2015) for different cities of China where Wuhan showed higher Kp values of 0.47,0.40,0.41 from 1990 to 2010, whereas Jinan, Zhengzhou, and Xi'an values ranged from 0.31-0.30, 025-0.32, 0.29-0.24 indicating smaller Kp values and proving that higher values of Kp of Wuhan indicate less compactness than compared to the other three cities. Wuhan's inverse S curve was more like Jaipur without a distinctive core, whereas Jinan, Zhengzhou, and Xi'an showed distinctive urban core, inner and suburban areas.

3.4.2. Categorization of Urban Growth Drivers

The growth drivers identified can be categorized into four categories of Proximity factors (Milad et al., 2017) include proximity from major roads, highways, industrial corridors/industries, basic infrastructure facilities, transportation centers (BRTS, Metro stations), workplaces (IT Parks), commercial centers, Central business district or core area, recreational places all of these which may affect the residential neighborhood preferences. The second category includes government interventions like the construction of bridges that overcome physical barriers of the waterbody and cause development, TP schemes or Integrated Township policies, Development Plans, and Regional Plans (land management and land use planning techniques) that have a significant impact on how a city's land use pattern develops over time and how it changes. Pradhan Mantri Aawas Yojna (PMAY) or any other affordable housing scheme that attracts the population for cheaper residential living in a city. The third category is the socio-economic (Kim & Newman, 2020) which includes the population density, land prices, employment opportunities, community community-specific choice of residential area. Last are the physical factors of slope, elevation, and restrictions like mountains, military-restricted areas, water bodies, and reserved forests.

In the study, from the distance and direction analysis of Pune, it is seen that there are physical impediments to growth. Barriers such as waterways, hills, and military cantonments limit development in that direction, like physical constraints considered in the previous study (Zhou et al., 2020). However, once this barrier is removed, it is evident that growth has occurred in that direction. Removing the river as a barrier through the construction of bridges has led to the development in the adjacent direction. Here the government intervention of creating a bridge was the potential reason for urban growth.

Likewise, the growth drivers identified were categorized into proximity, government interventions, socioeconomic, and physical factors. The findings and debate demonstrated that Pune has been significantly impacted by government initiatives like incentives to IT sector establishment boomed the IT sector and employment opportunities; MIDC in Pimpri Chinchwad that has increased industrial activity in the city; Integrated Township policy,2005, implementation of Regional Plans prepared are one of the significant reasons. However, these two cities show a difference in their urban structure. The government intervention of the TP scheme has made the city more compact through judicious utilization of land and consolidated land use planning. Whereas the government initiatives in Pune have made the population move outwards in search of better amenities at lower prices. It demonstrates that socioeconomic factors also contributed to the city's urban sprawl.

On the other hand, Jaipur has experienced considerable growth along its main roads and highways. It exhibits linear development (Subrahmanya & Hillemane, 2009). Proximity to roads DMIC corridor passing through Jaipur brought industrial development to the city. However, some interventions, like the master plan for the city, envisioned consolidated land use planning, which was achieved. As a result, even though the city has grown linearly, there has been compact development between the linear growth. Hence proximity factors and planning strategies largely streamlined its urban form today.

This study addresses a gap in previous research by introducing direction-wise zoning to identify urban growth drivers, a departure from conventional approaches that consider basic factors without zoning (Altuwaijri et al., 2019). While some studies extend direction analysis from 5-8 directions, this research expands it to 12 directions, integrating it with the identification of urban growth drivers (Yin et al., 2018; Karimi et al., 2019). In contrast to studies that omit direction analysis, the present approach combines distance and direction analysis, forming a foundation for urban growth simulation based on historical trends.

4. Conclusion

The hypothesis used to propose a modified sigmoid function for urban land density with distance is tested for the Indian city scenario where the two cities are different in function, and characters are chosen. The ULD function, optimized to 1 for both cities, revealed distinct urban forms. Jaipur displayed an inner urban area and suburbs, while Pune exhibited multinucleated development and sprawl with high ULD at various points. The parameters of the ULD function provide insights into compactness, expansion rate, and sprawl, enabling city comparisons over different time periods.

The study finds that physical barriers like waterways in Pune were overcome by government interventions, such as bridge construction, promoting urban growth. Pune's urban form reflects the impact of government initiatives like IT sector incentives and the TP scheme, balancing compactness and sprawl driven by socioeconomic factors. Jaipur experienced linear growth along roads and highways, influenced by the DMIC corridor, with master planning ensuring a compact urban form. The research highlights the pivotal role of government interventions and socioeconomic factors in shaping the distinct urban structures of Pune and Jaipur.

To conclude, the study focused first on understanding the urban pattern and defining the shape of the cities, which can be a valuable tool for several researchers who wish to examine urban growth and evaluate the sustainability of a city. Second, distance and direction analysis can help policymakers and decision-makers discover potential urban growth drivers and forecast where growth is most likely. A clear understanding of whether to encourage or restrict growth in a particular direction would allow for the development of policies to effectively address the issues of sprawl. Its application has a futuristic reach in urban growth simulation studies as well. Hence, it is important to fully comprehend the factors driving it for proactive planning and management.

The only limitation in this study could be the use of higher resolution satellite imagery, further research can be carried out with better resolution images like Sentinel imagery of 10-20 m resolution and Bhuvan Imagery of 24 m. This study ultimately identifies stress points where urban transformations significantly affect the environment and ecology.

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