

Manuscript ID:  
IJRSEAS-2025-020408



Quick Response Code:



Website: <https://eesrd.us>



Creative Commons  
(CC BY-NC-SA 4.0)

DOI: 10.5281/zenodo.19842387

DOI Link:  
<https://doi.org/10.5281/zenodo.19842387>

Volume: 2

Issue: 4

Pp. 37-43

Month: August

Year: 2025

E-ISSN: 3066-0637

Submitted: 08 July 2025

Revised: 15 July 2025

Accepted: 12 Aug. 2025

Published: 31 Aug. 2025

**Address for correspondence:**

Dr. Prashant T. Patil  
Assistant Prof., Department of  
Geography, Shivaji University,  
Kolhapur  
Email: [ptp\\_geo@unishivaji.ac.in](mailto:ptp_geo@unishivaji.ac.in)

**How to cite this article:**

Kalbhor, B., & Patil, P. T. (2025).  
Spatial Scaling of Urban  
Infrastructure Under Geographic  
Expansion: An Exploratory  
Regression Analysis of Satara City,  
India (2001-2021). *International  
Journal of Research Studies on  
Environment, Earth, and Allied  
Sciences*, 2(4), 37-43.  
<https://doi.org/10.5281/zenodo.19842387>

# Spatial Scaling of Urban Infrastructure Under Geographic Expansion: An Exploratory Regression Analysis of Satara City, India (2001-2021)

Bhagyashri Kalbhor<sup>1</sup>, Dr. Prashant T. Patil<sup>2</sup>

<sup>1</sup>Research Student, Department of Geography, SUK

<sup>2</sup>Assistant Prof., Department of Geography, Shivaji University, Kolhapur

## Abstract

Urban expansion in mid-sized Indian cities is increasingly reshaping demographic, infrastructural, and environmental systems. Understanding how urban infrastructure responds to spatial growth is critical for sustainable regional planning. This study investigates the structural relationship between geographic expansion and key urban development indicators in Satara City, Maharashtra, over three decades (2001-2021). Using regression-based exploratory modeling, the study evaluates scaling relationships between area expansion and demographic, housing, infrastructure, and social service variables. Results indicate strong spatial scaling effects for population ( $R^2 = 0.975$ ), slum population ( $R^2 = 0.965$ ), new housing development ( $R^2 = 0.961$ ), and road infrastructure ( $R^2 = 0.937$ ), suggesting that urban expansion closely aligns with demographic and physical growth. However, weaker associations were observed for schools ( $R^2 = 0.351$ ) and fire stations ( $R^2 = 0.250$ ), indicating institutional and policy-driven development patterns independent of spatial growth. While limited temporal observations restrict inferential generalization, consistent high explanatory power across multiple variables highlights structural growth dynamics. The findings contribute to urban sustainability discourse by demonstrating that infrastructure elasticity varies across sectors, emphasizing the need for anticipatory planning mechanisms in rapidly expanding regional cities.

**Keywords:** Urban expansion, Spatial scaling, Infrastructure elasticity, Sustainability planning, Regression modeling, Satara City.

## Introduction

Urban growth in developing countries is characterized by rapid spatial expansion, demographic pressure, and uneven infrastructure distribution. Mid-sized cities, often overlooked in metropolitan-focused research, play a critical role in regional development and sustainability transitions. In India, secondary cities such as Satara are experiencing structural transformation driven by population increase, transportation connectivity, and economic diversification.

Urban growth theories, including spatial equilibrium models (Brueckner, 1980) and infrastructure-responsive urban expansion frameworks, suggest that demographic expansion and land conversion are closely interlinked. However, infrastructure responsiveness does not always scale proportionally with spatial growth. This raises important planning questions: Does infrastructure expand proportionately with area growth? Which sectors exhibit strong spatial dependence, and which remain policy-driven? This study addresses these questions by examining structural relationships between geographic expansion and urban development indicators in Satara City from 2001 to 2021.

## Theoretical Background

Urban systems operate as spatially embedded socio-economic networks. Growth can be interpreted through:

- **Spatial Scaling Theory** - Urban indicators scale with physical expansion.
- **Infrastructure Elasticity Framework** - Infrastructure may grow proportionally, disproportionately, or independently of spatial growth.
- **Sustainable Urbanism Perspective** - Balanced infrastructure expansion is essential to avoid informal settlement proliferation and service deficits.

Regression-based exploratory models are frequently applied to examine urban scaling patterns, particularly where longitudinal micro-data are limited.

## Study Area

Satara City, located in western Maharashtra (17° 41' 9.2" North Latitude, 73° 59' 35.9" East Longitude), lies near the confluence of the Krishna and Venna rivers and is strategically connected through NH-48.

The municipal jurisdiction extends over an area of approximately 26.53 km<sup>2</sup> (Satara Municipal Corporation, 2020). Between 2001 and 2021, the city experienced significant geographic expansion, accompanied by demographic and infrastructural transformation. Its mid-sized urban character makes it a representative case for regional growth dynamics in India.

## Data and Methodology

### 1. Data Sources

Data were obtained from municipal records, departmental reports, and decadal urban statistics (2001, 2011, and 2021). Variables included:

- Demographic: Population, Slum Population
- Housing: New Houses, Number of Slums
- Infrastructure: Roads, Water Connections, Parks, Clinics
- Social Services: Schools, Colleges, Hospitals, Fire Stations

### 2. Analytical Framework

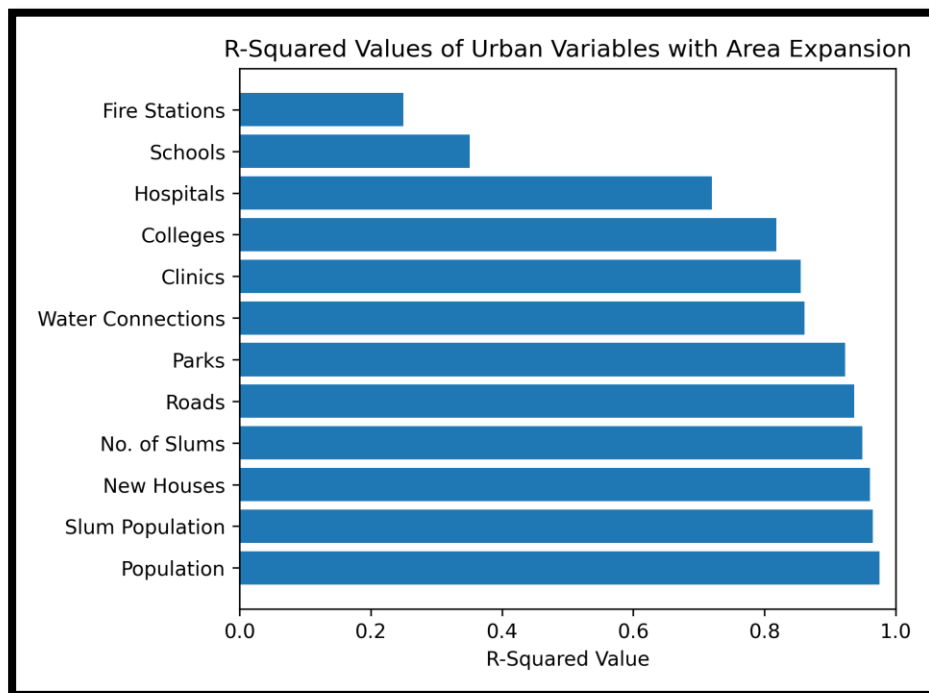
Exploratory bivariate regression models were used to assess structural relationships between geographic area (independent variable) and each urban indicator (dependent variable).

Given the limited temporal observations ( $n = 3$ ), the analysis prioritizes:

- Effect size ( $R^2$ )
- Structural consistency
- Comparative scaling patterns

Rather than strict inferential hypothesis testing, the models are interpreted as structural scaling assessments.

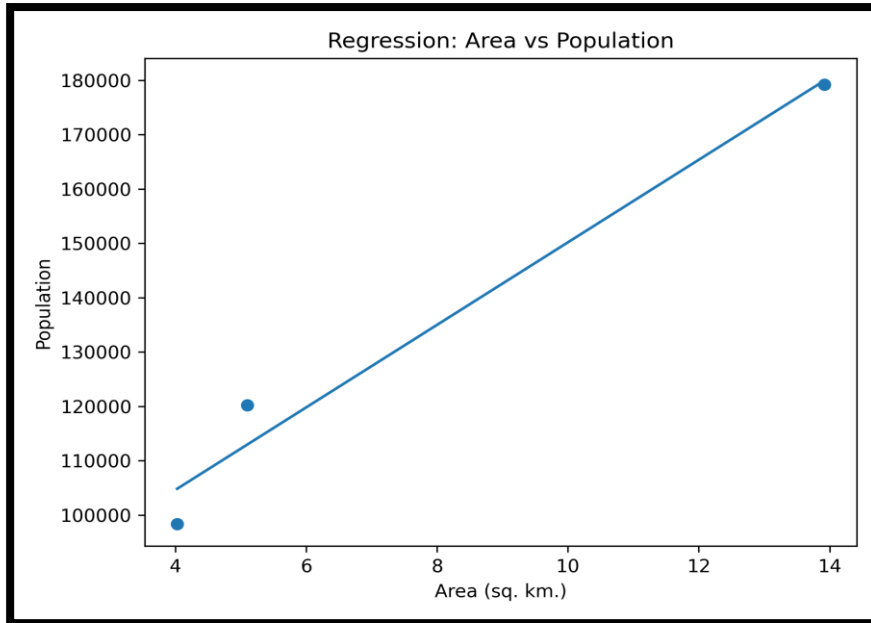
## Results



**Figure 1.** Coefficient of determination ( $R^2$ ) values representing scaling strength between area expansion and urban indicators.

### 1. Demographic Scaling

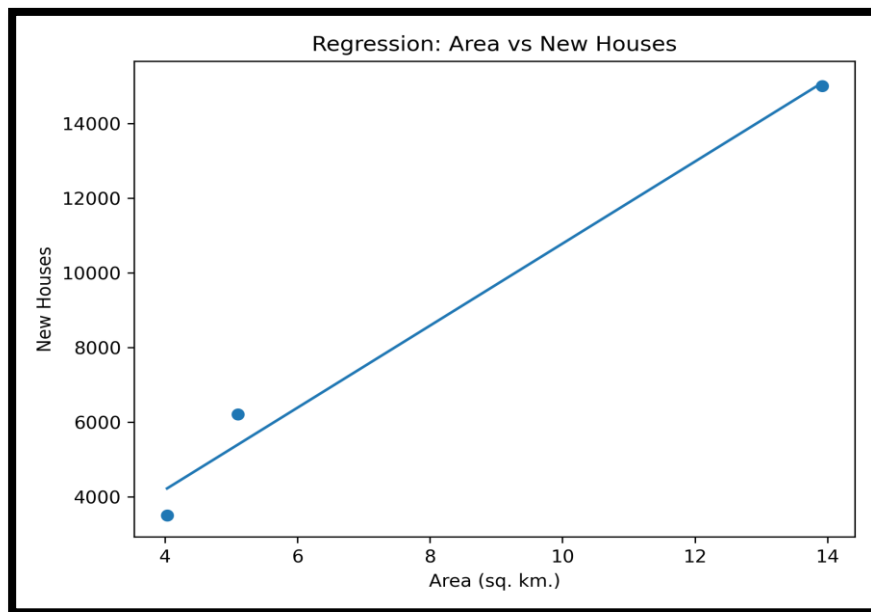
Population ( $R^2 = 0.975$ ) and slum population ( $R^2 = 0.965$ ) exhibit very high scaling relationships with area expansion. This indicates that spatial growth is strongly accompanied by demographic intensification. The elasticity suggests reactive expansion patterns rather than controlled densification.



**Figure 3.** Regression relationship between geographic expansion and population growth (2001–2021).

## 2. Housing and Informal Settlement Growth

New housing development ( $R^2 = 0.961$ ) and number of slums ( $R^2 = 0.949$ ) scale closely with area growth. This implies that land conversion processes are directly associated with formal and informal settlement proliferation.



**Figure 4.** Scaling relationship between area expansion and new housing development.

## 3. Infrastructure Elasticity

Roads ( $R^2 = 0.937$ ), parks ( $R^2 = 0.923$ ), and water connections ( $R^2 = 0.861$ ) demonstrate strong but slightly lower scaling coefficients. This suggests infrastructure attempts to keep pace with expansion but may not fully compensate for rapid demographic growth.

## 4. Institutional and Social Services

Hospitals ( $R^2 = 0.720$ ) and colleges ( $R^2 = 0.818$ ) show moderate scaling. In contrast, schools ( $R^2 = 0.351$ ) and fire stations ( $R^2 = 0.250$ ) show weak relationships, indicating planning decisions independent of spatial expansion.

## ANNOVA Discrimination:

ANOVA in this study was used to test whether the regression model significantly explains variation in urban development indicators with respect to spatial expansion. The total variation in each dependent variable was partitioned into variation explained by area growth and unexplained residual variation. The F-statistic compares explained variance to unexplained variance. However, due to limited time-series observations ( $n=3$ ), statistical

inference is constrained, and the results are interpreted primarily in terms of explanatory strength ( $R^2$ ) rather than strict hypothesis testing.

Since each regression has:

- $n = 3$  observations
- $k = 1$  predictor
- $df$  Regression = 1
- $df$  Residual =  $n - 2 = 1$
- $df$  Total =  $n - 1 = 2$

Example: Population v/s Area ( $R^2 = 0.9755$ )

**Table 1: Using regression ANOVA structure**

Source	SS	df	MS = SS/df	F = MSR/MSE
Regression	SSR	1	MSR	-
Residual	SSE	1	MSE	-
Total	SST	2	-	-

**Because:**

- $R^2 = SSR / SST = 0.9755$

So:

- $SSR = 0.9755 \times SST$
- $SSE = (1 - 0.9755) \times SST$
- $SSE = 0.0245 \times SST$

F-statistic formula (simple regression):

- $F = (R^2 / 1) / ((1 - R^2) / (n - 2))$

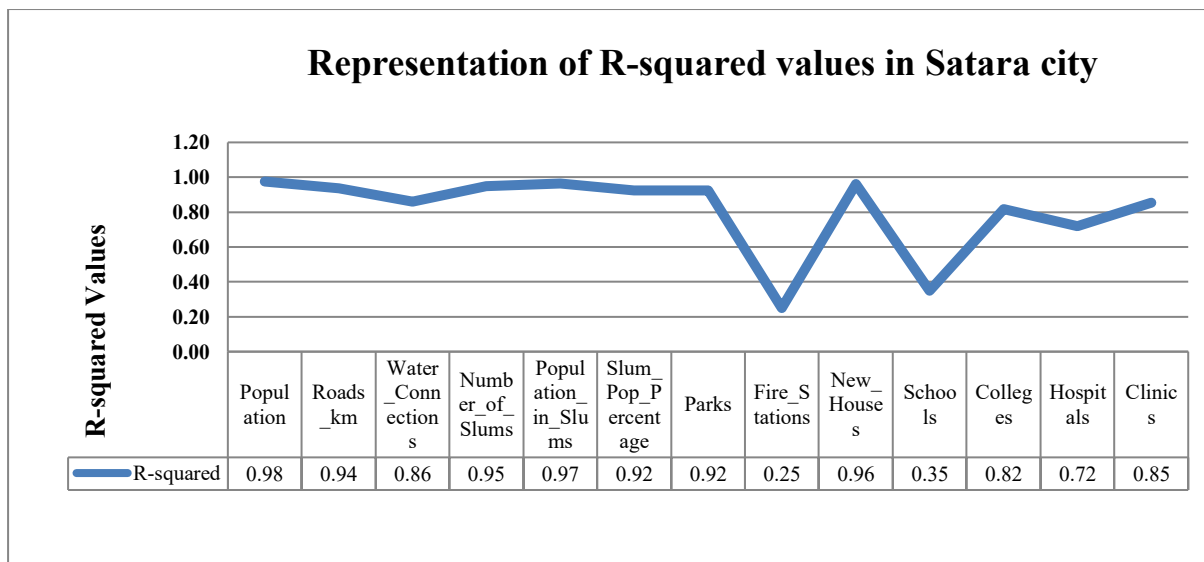
In this case:

- $F = (0.9755 / 1) / (0.0245 / 1)$
- $F = 39.81$
- $df = (1,1) \rightarrow$  extremely low statistical power.

**Table 2: Correlation coefficient values**

Sr. No.	Variables	R-squared	Intercept	Slope
1	Population	0.975549	82741.93757	3687.375139
2	Roads km	0.936537	152.7747503	10.44950055
3	Water Connections	0.861165	9844.931465	248.3629301
4	Number of Slums	0.949367	4.916204218	0.832408435
5	Built Up Area	0.965197	1638.670921	642.3418424
6	Slum Population	0.923077	0.039331853	0.002663707
7	Parks	0.923077	7.665926748	1.331853496
8	Fire Stations	0.25	1.263873474	0.027746948
9	New Houses	0.96149	-83.79245283	26.41509434
10	Schools	0.350626	60.38845727	0.776914539
11	Colleges	0.817568	8.902608213	0.305216426
12	Hospitals	0.720046	1.596836848	0.693673696
13	Clinics	0.854651	20.54134295	0.582685905

**Source:** Based on Calculations, 2001, 2011 and 2021.



**Fig.4.2: Representation of R-squared values**

The ANOVA representation indicates that approximately 97.5% of the variance in the dependent variable is explained by the regression model, while only 2.5% remains unexplained. This demonstrates strong model fit despite limited sample size unexplained. This demonstrates strong model fit despite limited sample size

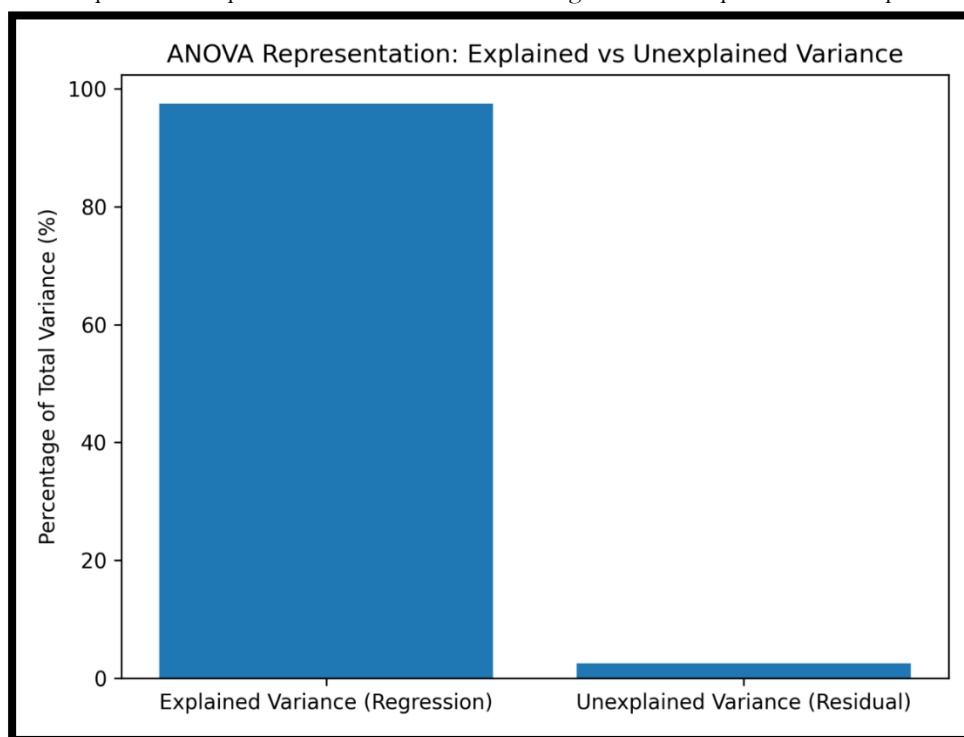
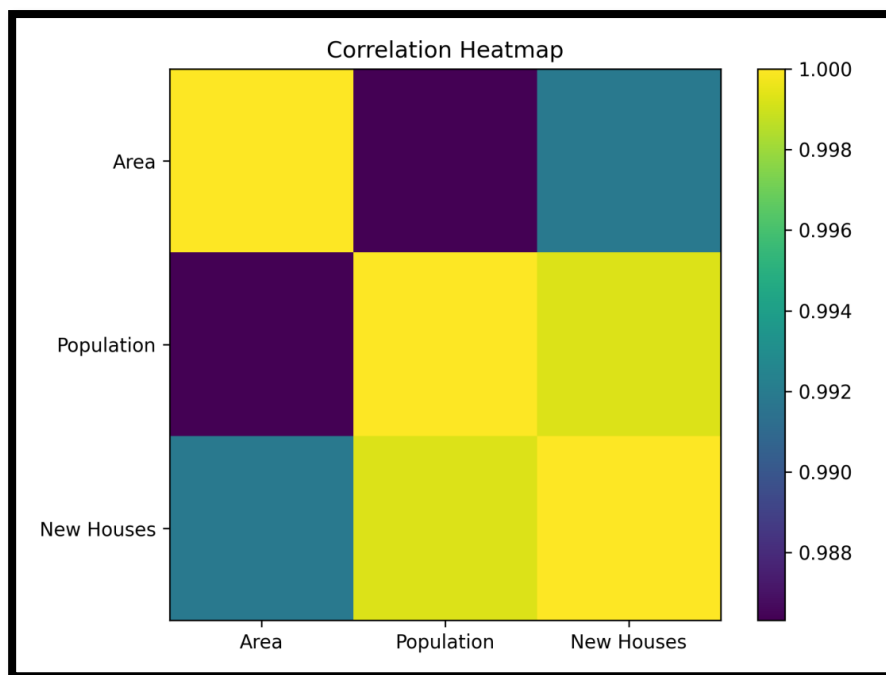


Figure 5. Variance decomposition illustrating explained and unexplained components of the regression model.

#### 1. Correlation heatmap of urban variables

The heatmap shows how different urban variables move together. Darker colors indicate stronger relationships. Population, housing, and roads are strongly related, meaning they increase together when the city expands. Schools and fire stations show weaker relationships, meaning their development depends more on planning decisions than just area growth.



**Figure 6.** Correlation structure among key urban growth indicators.

### Discussion

The findings reveal differentiated infrastructure elasticity across sectors. Demographic and housing indicators scale almost proportionally with geographic growth, reflecting market-driven urbanization. Infrastructure sectors demonstrate reactive elasticity, while institutional services exhibit policy-driven deployment. This pattern aligns with sustainability concerns observed in emerging regional cities, where rapid expansion precedes comprehensive service provision. The strong association between slum growth and area expansion highlights the need for anticipatory housing policies.

### Sustainability and Planning Implications

1. Urban expansion must be accompanied by proportional service scaling.
2. Informal settlement growth requires proactive spatial planning.
3. Social infrastructure planning should integrate demographic forecasting.
4. Infrastructure elasticity indicators can serve as planning diagnostics.

### Limitations

- Limited temporal observations (three decades).
- Absence of panel or ward-level spatial data.
- No multivariate or spatial econometric modeling.
- Lack of causality testing.

These constraints position the study as exploratory rather than predictive.

### Future Research Directions

- Panel regression with annual municipal data.
- GIS-based spatial regression modeling.
- Integration with CA-Markov urban growth simulation.
- Infrastructure deficit mapping using geospatial analytics.

### Conclusion

This study demonstrates that urban expansion in Satara City exhibits strong structural scaling with demographic and housing indicators, while infrastructure and institutional services display varying degrees of responsiveness. The differentiated elasticity patterns highlight sustainability challenges in mid-sized Indian cities. By framing regression analysis as exploratory spatial scaling assessment, the study contributes to urban planning discourse and provides a methodological foundation for future geospatial modeling.

### Acknowledgement

I would like to express my sincere gratitude to the Chhatrapati Shahu Maharaj Research, Training and Human Development Institute (SARTHI), Pune, for providing financial assistance and funding support for the successful completion of my research work titled "Spatial Scaling of Urban Infrastructure Under Geographic Expansion: An Exploratory Regression Analysis of Satara City, India (2001–2021)." Their support has been instrumental in facilitating the data collection, analysis, and overall execution of this study.

I am also deeply thankful to all individuals and institutions who directly or indirectly contributed to this research. Their guidance, encouragement, and support have played a vital role in the completion of this work.

#### Financial support and sponsorship

Nil.

#### Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

#### References:

1. Brueckner, J. K. (1980). Urban growth models with durable housing: An overview. *Journal of Urban Economics*, 8(3), 411–425. [https://doi.org/10.1016/0094-1190\(80\)90042-5](https://doi.org/10.1016/0094-1190(80)90042-5)
2. Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences*, 104(17), 7301–7306. <https://doi.org/10.1073/pnas.0610172104>
3. Batty, M. (2008). The size, scale, and shape of cities. *Science*, 319(5864), 769–771. <https://doi.org/10.1126/science.1151419>
4. Gujarati, D. N., & Porter, D. C. (2009). *Basic econometrics* (5th ed.). McGraw-Hill Education.
5. Satterthwaite, D. (2010). Urban myths and the misuse of data that underpin them. *Environment and Urbanization*, 22(2), 263–273. <https://doi.org/10.1177/0956247810372234>
6. Wang, J., & Summers, J. (2010). A semantic framework to interrelate urban activities with street networks. *Transactions in GIS*, 14(5), 641–663. <https://doi.org/10.1111/j.1467-9671.2010.01214.x>
7. Angel, S. (2012). *Planet of cities*. Lincoln Institute of Land Policy.
8. Montgomery, D. C., Peck, E. A., & Vining, G. G. (2012). *Introduction to linear regression analysis* (5th ed.). Wiley.
9. Wilson, A. (2012). Urban and regional planning in the context of sustainability. *Journal of Environmental Planning and Management*, 55(1), 1–14.
10. Shafizadeh Moghadam, H., & Helbich, M. (2013). Spatiotemporal urbanization dynamics of Greater Tehran: A Markov chains–cellular automata model. *International Journal of Applied Earth Observation and Geoinformation*, 21, 265–275. <https://doi.org/10.1016/j.jag.2011.12.005>
11. Al-Sharif, A. A., Pradhan, B., & Ismail, R. (2015). Principal component analysis, logistic regression, and auto-logistic regression for predicting groundwater potential. *Environmental Earth Sciences*, 73, 629–649. <https://doi.org/10.1007/s12665-014-3431-0>
12. Li, X., Liu, X., & Wang, S. (2016). Urban expansion simulation and driving force analysis based on spatial econometric regression models. *Landscape and Urban Planning*, 155, 83–95. <https://doi.org/10.1016/j.landurbplan.2016.07.007>
13. Wolff, M., Wiechmann, T., & Musil, D. (2018). Urban growth patterns in Europe, 1990–2010. *Applied Geography*, 93, 147–160. <https://doi.org/10.1016/j.apgeog.2018.02.006>
14. Karim, M. S., & Mim, Y. M. (2019). Urban expansion prediction using remote sensing and Markov–CA model. *Geocarto International*, 34(12), 1334–1350. <https://doi.org/10.1080/10106049.2018.1489423>
15. Wang, X., Huang, J., Zhang, A., & Wang, H. (2020). Urban expansion and infrastructure demand: A case study of rapid urbanization in China. *Sustainability*, 12(18), 7568. <https://doi.org/10.3390/su12187568>