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Assessing Urban Morphology through Street Parameters in Patna Municipal Corporation, India, through Geoinformatics

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Abstract

The study of urban morphology plays a pivotal role in the development of sustainable and resilient cities. Street networks act as essential physical and spatial infrastructures that significantly impact mobility, accessibility, land use, and socio-economic functions. In areas experiencing swift urbanization, particularly in Bihar, the advancement of infrastructure frequently fails to keep pace with population growth. Patna, the state capital, has experienced a significant population growth of 41.18%, rising from 1.7 million in 2011 to 2.4 million in 2024. Nevertheless, the expansion of street networks has been constrained, especially in historic centers and peri-urban areas. This disparity has led to traffic congestion, reduced accessibility, and growing spatial inequalities. This study aims to evaluate changes in street infrastructure adequacy over the past decade and to detect areas of spatial stress and anomalies across 75 wards of the Patna Municipal Corporation (PMC) from 2014 to 2024. High-resolution street data from sources such as Google Earth and OpenStreetMap, along with population data from the 2011 Census and the Master Plan 2031, were employed to calculate seven meaningful indicators of street morphology. The street parameters' data were first standardized through Z-score normalization, followed by the implementation of Anselin's Local Moran's I to identify spatial clusters and outliers. The results indicate a significant increase in the percentage of High-High stress clusters, from 18.6% of wards in 2014 to 28% in 2024, with a notable concentration in Bakarganj, Gandhi Maidan, and Kankarbagh. On the other hand, Low-Low clusters witnessed a decline from 34.6% to 25.3%, suggesting an increase in stress levels in areas that were once stable, such as Rajiv Nagar and Danapur. High-Low outliers (6.6%) and Low-High outliers (5.3%) reveal specific vulnerabilities and areas of resilience, respectively. The implementation of geostatistical techniques in the analysis of street parameters provided a realistic depiction of the street-induced spatial stress variation in the study area, facilitating data-driven, holistic planning and development.

Keywords: Urban Morphology Mapping, Street-Related Indicators; Geoinformatics; Local Moran's I; Patna Municipal Corporation

Introduction

The study of urban morphology, which examines the spatial layout and structure of cities, is intricately linked to the planning and development of street networks. Streets serve as both the physical backbone for transportation and essential spatial elements that affect accessibility, mobility, land use, and socio-economic activities in urban settings. Well-designed street networks promote social interaction, enhance pedestrian comfort, improve environmental quality, and ensure the efficient delivery of public facilities. Conversely, insufficient street infrastructure often leads to traffic congestion, uneven development, and reduced urban resilience. Rapid global urbanization has highlighted the importance of understanding street dimensions in urban planning. United Nations data indicate that by 2020, over 56% of the world's population resided in urban areas, with projections suggesting that this figure will rise to 68% by 2050, equating to an additional 2.5 billion individuals moving to urban settings. This rapid urbanization creates significant strain on urban infrastructure, particularly transport networks, which are also indicators of economic strength. In many developing regions, infrastructure development has lagged, resulting in the emergence of informal settlements and congested streets. Common everyday issues such as increased travel times, reduced access to medical services, heightened air and noise pollution, and compromised pedestrian safety can arise from this situation. The groups most adversely affected include marginalized populations, as insufficient infrastructure amplifies socio-economic disparities and limits mobility options, especially for vulnerable demographics such as the elderly, women, and the urban poor. To effectively tackle these challenges, a thorough understanding of urban street patterns and the adoption of sustainable development strategies are essential.

The sustainability of expanding urban areas depends significantly on the configuration and purpose of the street, as demonstrated by studies [4], [5]. Approximately 35% of Indians now reside in urban regions, contributing more than 65% of the country's GDP. There has been urban growth in the country, characterized by informal expansions, densification imbalances, and inadequate street planning, particularly in peri-urban areas and so-called secondary cities. It has been researched [7], [8] that street network indicators, people per street, street length densification, as well as street coverage per unit area, relate significantly to understanding urban mobility dynamics as well as urban compactness. Kumar and Mishra [9] demonstrate how the Indian cities of Varanasi and Patna exhibit an observable mismatch between the population and the streets, characterized by inadequate street development amidst accelerated population growth. It has an urbanisation level of 11.3%, according to the 2011 Census for the state of Bihar, the most populated among the Indian states, significantly less compared to the country as well as the country's average. Nevertheless, the cities of the province of Bihar have been experiencing accelerated urbanisation within the recent past, driven primarily by regional migration as well as demographic change. Its capital city, Patna, demonstrates a case where its population has surged from approximately 1.7 million people in 2011 to 2.4 million in 2024, representing a 41.18% growth. Despite this demographic growth, the street infrastructure, evaluated by road length, coverage, and distribution, has not developed proportionately, especially in historical hubs like Patna City and developing peripheries such as Danapur, Phulwarisharif, and Digha.

Urban sprawl lacking simultaneous infrastructure development leads to problems such as insufficient last-mile connectivity, persistent traffic congestion, reduced walkability, and inefficient land use [12], [13]. Street features are crucial physical indicators that help uncover inefficiencies within the urban landscape. Metrics such as Population per Number of Streets, Population per Length of Streets, and Area per Unit Street Length quantitatively demonstrate the correlation between urban expansion and infrastructure provision [14]. Contemporary urban research increasingly depends on Geographic Information Systems (GIS) to tackle these challenges. GIS-based solutions enable the integration of spatial and non-spatial datasets to calculate and depict critical street-related indicators. Urban planners can identify areas of inadequate infrastructure in connection to population or spatial metrics by employing GIS forward- and circle-specific analyses [15]. Studies by Singh and Ghosh [16] and Rana et al. [17] demonstrate the efficacy of GIS in conducting spatial analyses of street morphology, especially in intermediate cities in India, where data-driven design is constrained.

Additionally, urban morphology studies are augmented by GIS applications in analyzing street connectivity, direction, intersection density, and accessibility to essential services. Bhattacharya and Mukherjee [18] applied GIS-based network analysis to identify mobility challenges in Kolkata, whereas Pandey et al. [19] developed spatial congestion models for tier-2 cities. These solutions are particularly relevant to Patna, where planning interventions are essential to align infrastructure development with demographic realities. This initiative aims to rectify the lack of decadal morphological studies by conducting a comparative analysis of roadway metrics in the Patna Municipal Corporation from 2014 to 2024. The study will employ GIS and statistical models to compute standardized urban indicators across more than 75 wards and evaluate the sufficiency of street infrastructure in relation to population and spatial expansion. The results will elucidate spatial disparities, identify areas of infrastructural strain, and offer actionable strategies for sustainable and equitable urban growth.

Study Area

The Patna Municipal Corporation (PMC) is the designated urban municipal government administering Patna, the capital city of Bihar, India. PMC is situated between 25°30' and 25°40' N latitude and 85°00' and 85°20' E longitude, on the southern bank of the River Ganga. It spans over 108.87 square kilometers of a developed and growing urban region and runs longitudinally from east to west. The region is physiographically classed as part of the Middle Ganga Plain, distinguished by its level topography, fertile alluvial soils, and vulnerability to seasonal inundation from the Ganga and its tributaries. The city's low height and closeness to the river render urban drainage and transportation infrastructure essential for its resilience and habitability.

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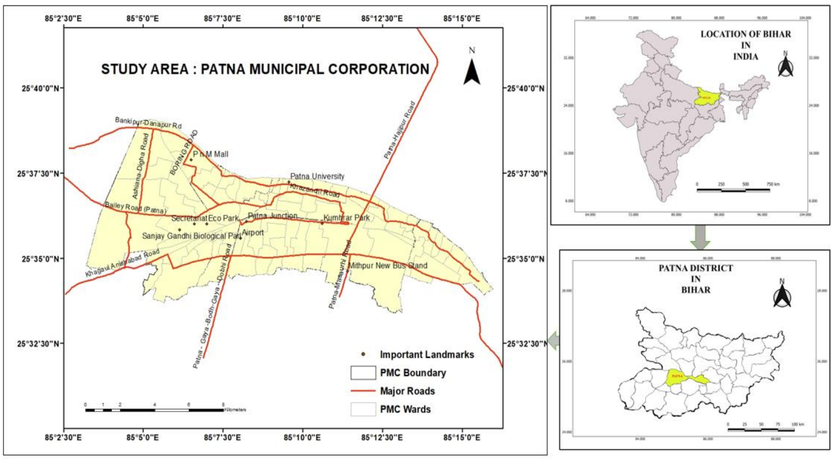
Map-1: Study Area



Administratively, the Patna Municipal Corporation is organized into six circles: New Capital, Kankarbagh, Bankipur, Patna City, Azimabad, and Patliputra, comprising a total of 75 wards. The transportation network of PMC comprises a hierarchy of arterial highways, collector roads, and smaller streets, many of which are strained by heightened vehicular volume and population pressure. Prominent routes, such as Bailey Road, Ashok Rajpath, Boring Road, and Exhibition Road, function as essential intra-city arteries but often suffer from congestion and encroachments. Patna is comprehensively linked both locally and nationally by significant highways. The city is traversed by National Highway 30 (NH-30), NH-31, and NH-83, along with the newly finished AIIMS-Digha Elevated Corridor, which serves as a crucial bypass to mitigate urban congestion. Notwithstanding these infrastructural advantages, the expansion of the road network has failed to keep pace with population growth, especially in informal settlements and developing peripheral areas [14], [17].

Data and Methodology

Data pertaining to Streets from 2014 were digitized using Google Earth Pro and Topographical sheets from the Survey of India, thereby ensuring spatial precision. In 2024, revised street data were obtained from OpenStreetMap (OSM) and processed in ArcMap 10.8.2 to align with ward boundaries. Population data were obtained from the Census of India (2011) and extrapolated for 2024 utilizing decadal growth rates (Patna Master Plan, 2031). With the help of these data sets, a range of statistical indicators mentioned in table.1 were calculated in a GIS environment and validated using MS Excel.

S.No.	Indicator Name	Formula	Inference	Reference
1	Population per No. of Streets	Population / No. of Streets	Congestion per street	[9]
2	Area per No. of Streets	Area / No. of Streets	Spatial coverage of road network	[13]
3	Population per Street Length	Population / Street Length	Traffic load indicator	[7]
4	Area per Street Length	Area / Street Length	Compactness and connectivity	[16]
5	Population Density	Population / Area	Urban density level	[3]
6	(Pop/Area) per Street Count	(Pop/Area) / No. of Streets	Infrastructure pressure	[14]
7	(Pop/Area) per Street Length	(Pop/Area) / Street Length	Network efficiency	[15]

Table: 1 Statistical Parameters related to Street Morphology

The study identified seven critical indicators used to assess the sufficiency of the street network at the ward level. The calculation of Population per Street Length indicated wards experiencing disproportionate population demand in relation to the existing street infrastructure, commonly the primary cause of congestion and service inefficiency, as highlighted by Porta et al. [20]. Area per street length is used to evaluate spatial adequacy, highlighting wards where spatial areas are insufficiently serviced by street networks, in line with Marshall's studies on spatial morphology [21]. The population density per area provided a comprehensive perspective on the stress of the built environment, highlighting the effects of residential density on urban morphology (Bhatta, 2010) [22]. Notably, composite indicators that synthesize multidimensional urban stress, such as Population/Area/Street Length, offer an integrative diagnostic tool that aligns with Singh et al.'s recommendations [23].

Anselin [24] has emphasized the importance of maintaining a similar level of methodological rigor in urban stress studies, particularly when employing spatial autocorrelation techniques, such as Local Moran's I.

Z-Score Standardization

Due to the incompatible ranges of raw values across parameters and decades, Z-score normalization was conducted separately for 2014 and 2024 to standardize the

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data.
The formula employed for calculating the Z-score is:
$z = (X - \mu) / \sigma$
where,
z = Standardized value
X = Raw parameter value
μ = Mean of the dataset
σ = Standard deviation of the dataset
This standardization enabled a comparative analysis of wards, regardless of the initial magnitude of parameters. The implementation of Z-score normalization was essential due to the heterogeneous scales and variability among parameters. Standardization facilitated the conversion of raw data into a uniform format, ensuring reliable statistical comparisons both within and across decades.

Anselin Local Moran's I Cluster-Outlier Analysis

Anselin Local Moran's I was employed to identify spatial clusters and outliers following Z-Score normalization. The equation for Local Moran's I is:
$I_i = (x_i - \bar{x}) \Sigma_j w_{ij} (x_j - \bar{x}) / S^2$

Where-

Symbol	Meaning	Explanation
I_i	Local Moran's I value for feature i	Measures the degree of spatial clustering around feature i.
x_i	Attribute value for feature i	The Z-score value (e.g., population per street) of the ward you are analyzing.
$\bar{x}$	Mean of all attribute values	The average Z-score value across all wards.
w_{ij}	Spatial weight between feature i and j	Defines whether ward i and ward j are neighbors (typically 1 if neighbors, 0 otherwise).
x_j	Attribute value for neighboring feature j	The Z-score value of the neighboring ward.
S^2	Variance of attribute values	Represents the overall spread (dispersion) of Z-scores across all wards.

In this study, x_i represents the Z-score standardized value of a particular street parameter for each ward. w_{ij} defines the spatial relationship based on shared ward boundaries (Contiguity Edges Only). The computation of I_i enables the identification of wards participating in significant high-stress or low-stress clusters, as well as the detection of localized anomalies.

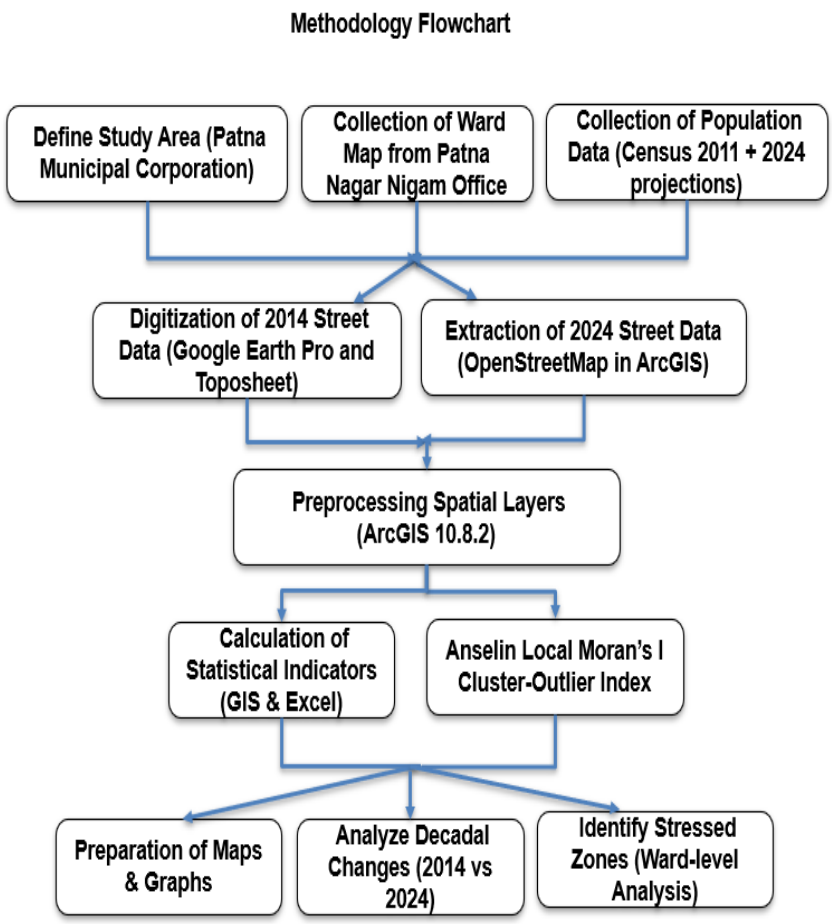

Figure 1: Data and Methodology

Anselin Local Moran's I analysis identifies four distinct types of spatial patterns:

- *High-High Clusters* (deep red) indicate areas with consistently high stress levels that require urgent infrastructural intervention.
- *Low-Low Clusters* (deep blue) indicate areas of diminished stress, offering opportunities for strategic advancement.
- *The High-Low Outliers* (pink) are wards undergoing concentrated street stress inside predominantly low-stress environments, requiring targeted micro-level management techniques.

· *Low-High Outliers* (light blue) denote wards characterized by comparatively lenient conditions amidst stressed areas, essential for functioning as urban buffers.
· *The grey areas* denote wards lacking statistically significant spatial clustering. Maps and statistical graphs were created to illustrate regional disparities and morp hological alterations.

Results and Discussion

The selection and calculation of street-related statistical parameters are essential for determining the severity of urban infrastructure stress. The spatial analysis of street-related indicators across the 75 wards of Patna Municipal Corporation (PMC), employing Anselin Local Moran's I offers an extensive overview of urban street stress and its development from 2014 to 2024. The application of Z-score normalization eliminated the variability of the raw data, allowing for significant inter-ward comparisons. Each metric was methodically assessed for spatial clustering and outlier patterns, providing valuable insights into systemic urban issues and localized anomalies.

Population per street Length is a vital indicator of infrastructure stress, quantifying the number of residents dependent on each unit length of street within each ward. High values indicate systemic congestion and insufficient mobility infrastructure, aligning with the findings of Porta et al. [20] about vulnerabilities in the street network. The utilization of Anselin Local Moran's I indicated significant High-High clusters in central historic wards, specifically Ward 23, 24, and 25, in both the 2014 and 2024 datasets. These regions, influenced by organic and unregulated urban expansion (Marshall, 2005) [21], are characterized by narrow, fragmented street grids that lack hierarchical order, resulting in persistent congestion for both pedestrians and vehicles. Stress intensification in neighbouring wards suggests the existence of a contiguous zone of infrastructural collapse, rather than isolated incidents. In contrast, peripheral wards such as 67, 68, and 71 exhibited Low-Low clustering, indicative of reduced urban concentrations and favourable spatial conditions for sustainable growth. The identification of High-Low outliers in wards 45 and 52 indicates localized failures, which may be attributable to vertical densification and isolated urban mismanagement (Bhatta, 2010) [22]. Low-High outliers, shown by Ward 70, highlight the necessity of proactive planning in rising residential areas that demonstrate resilient street designs in high-density stress scenarios.

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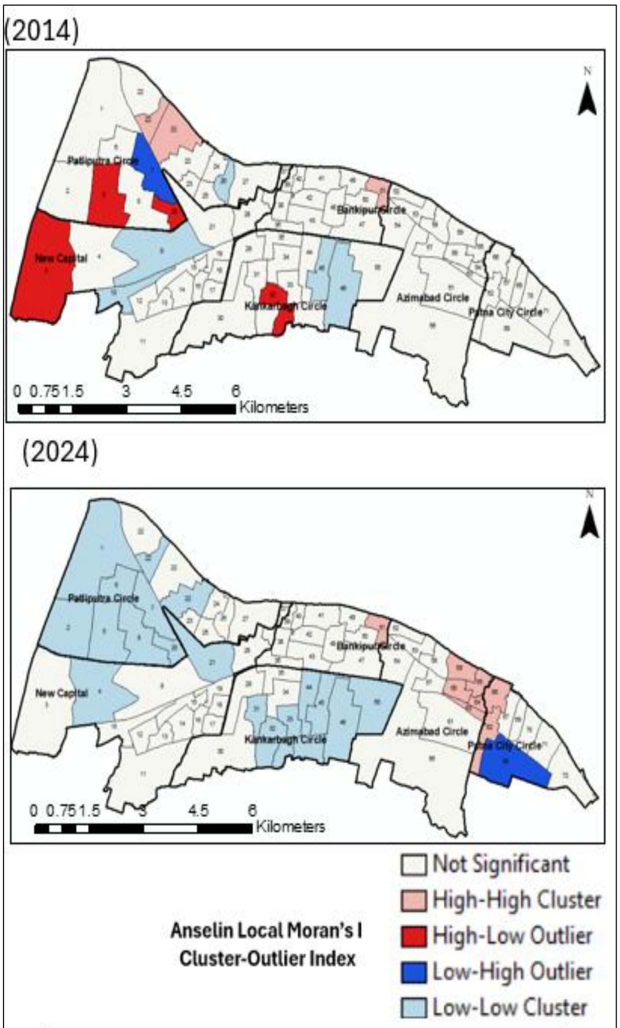

Map 2: *Ward map of PMC showing Population per street Length*

Area per street Length parameter effectively quantifies the spatial coverage provided by each unit length of street infrastructure within a ward. The results of the analysis show that wards with exceptionally low Area per Street values suffer from more severe infrastructure bottlenecks, because the streets are not large enough to disperse and accommodate urban activity. Employing Anselin Local Moran's I, significant High-High clusters were identified in the central wards of Patna Municipal Corporation, notably surrounding Gandhi Maidan, Fraser Road, and Ashok Rajpath. These regions, limited by past urban development patterns

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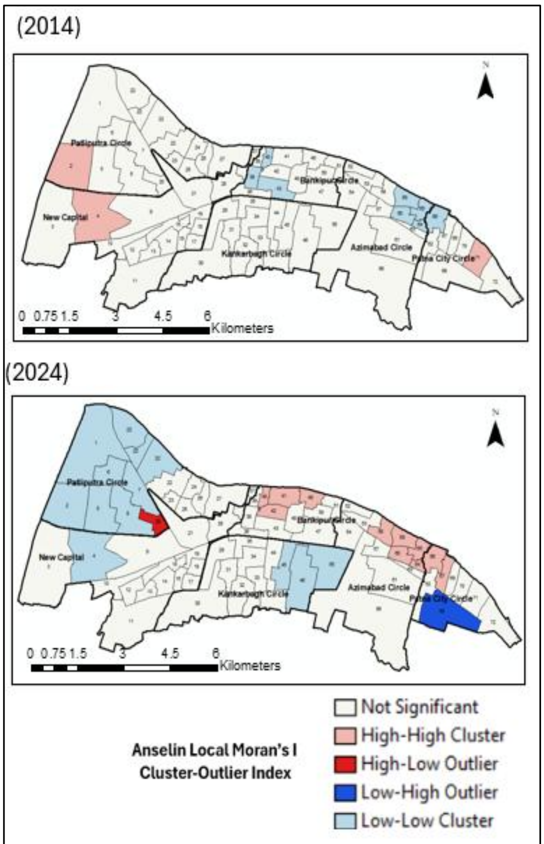
(Marshall, 2005) [21], exhibit significantly fragmented roadway configurations that cannot accommodate the increasing volume of automobiles, resulting in persistent congestion, diminished emergency response efficiency, and heightened pedestrian hazards.

In contrast, Low-Low clusters were observed in growing neighborhoods such as Rajiv Nagar, Boring Road Extension, and Punai Chak, where pre-designed layouts facilitated enhanced spatial adequacy (Bhatta, 2010) [22]. Localized High-Low outlier pockets, particularly in the Kurji and Patliputra Industrial Area, reveal stress resulting from unregulated commercial encroachments and informal settlements. These micro-level abnormalities highlight the potential for emerging congestion, even in situations that are generally low-stress. Mitigating these vulnerabilities through targeted urban design strategies is crucial for maintaining sustainable spatial equilibrium within Patna's evolving urban environment.



Map 3: *Ward map of PMC showing Area per street Length*

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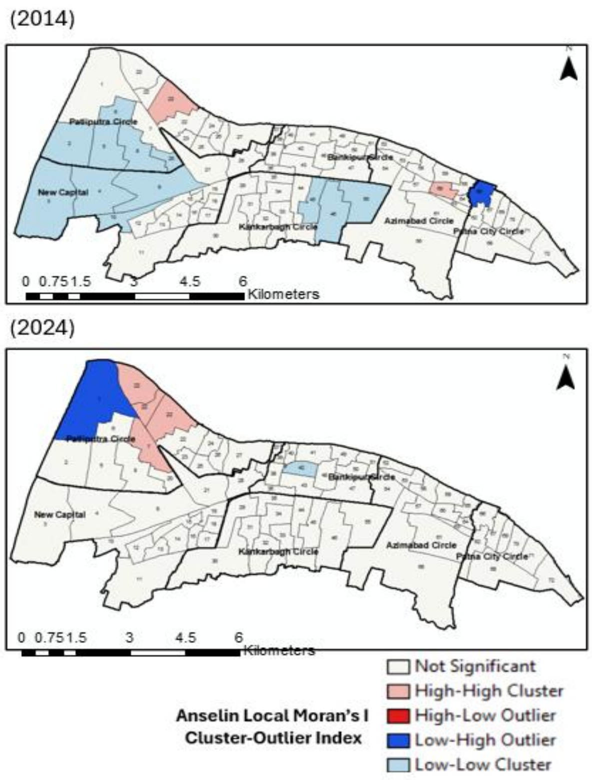
Population per Area metric was essential for objectively assessing demographic pressures within Patna's urban environment, independent of street infrastructure density. High-High clusters identified through Anselin Local Moran's I analysis correspond closely with the densely populated inner core, especially in the area between Bakarganj and Kankarbagh Circle. The wards, shaped by historical densification and constrained spatial expansion (Marshall, 2005) [21], exhibit significant residential overcrowding, increased challenges in service delivery, housing shortages, and an intensified urban heat island effect. Areas with high population density geographically align with clusters of elevated street stress, confirming the interconnected influence of demographic concentration and limited development on infrastructure deterioration. Peripheral wards, such as the newly merged areas of Digha and Danapur, displayed Low-Low clusters, indicating relatively low population densities and presenting significant prospects for sustainable urban development (Bhatta, 2010) [22]. Localized high-low outliers were observed in the peri-urban peripheries, particularly within the Phulwari and Sampatchak circles.



Map 4: *Ward map of PMC showing Population per Area*

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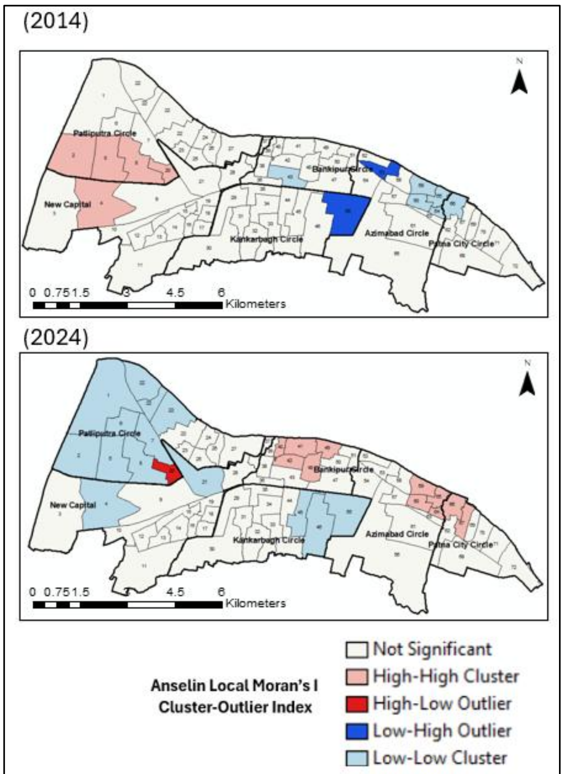
The wards exhibit significant demographic growth that is not matched by corresponding infrastructural development, often driven by unregulated real estate expansion, illegal housing projects, and inadequate zoning enforcement. Strict peri-urban management policies are essential to prevent urban stress and ensure that population growth aligns with planned infrastructure development.



Map 5: *Ward map of PMC showing Area by number of Streets*

Area by Number of Street metric evaluates the spatial coverage provided per unit length of the street network in urban wards. Lower values indicate spatial insufficiency, characterized by a limited amount of street infrastructure required to serve disproportionately large areas, often resulting in infrastructure bottlenecks and inadequate accessibility. Anselin Local Moran's I analysis identified considerable High-High clusters in central Patna, notably at Gandhi Maidan, Fraser Road, and Rajendra Nagar. These regions, historically defined by organic urban development lacking formal planning frameworks (Marshall, 2005) [21], feature short internal streets, inadequate connectivity, and encroachments, which hinder the efficient spatial distribution of urban activities. Issues include traffic congestion,

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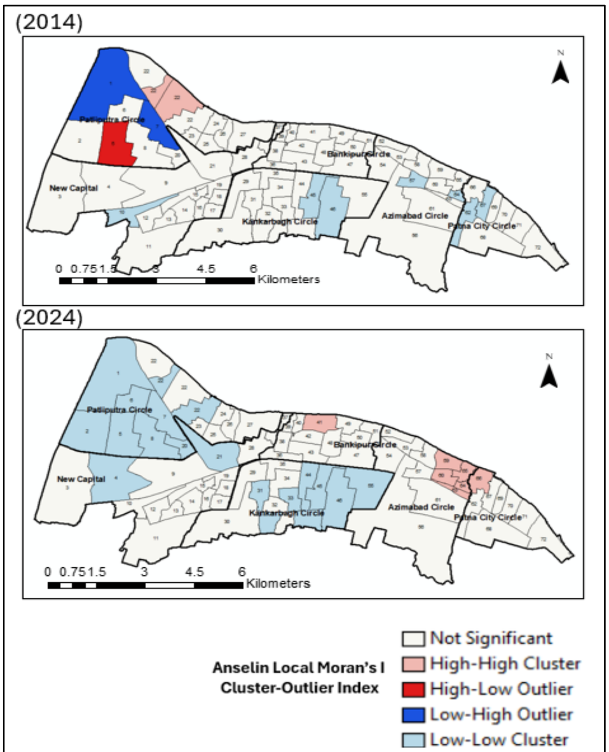
restricted access for emergency services, and a decrease in public spaces. Conversely, Low-Low clusters were identified in peripheral regions such as Rajiv Nagar and Punai Chak, where systematic urban planning has enabled a more favorable area-to-street ratio. The identification of High-Low outlier pockets in semi-developed areas such as Kurji reveals growing micro-level stress associated with unregulated business development and informal settlements. This underscores the necessity for localized remedial planning. The Area per Street study provides a strategic framework for identifying areas where enhancing street infrastructure could substantially reduce spatial and mobility strain.



Map 6: *Ward map of PMC showing Population by Count of Streets*

Population expressed as a count of the street parameter is a direct indicator of the pressure that residential density places on the street network. High values indicate wards where inadequate street infrastructure is burdened by substantial resident populations, often resulting in congested streets, mobility difficulties, and reduced service delivery. Spatial clustering analysis using Anselin Local Moran's I identified High-High stress zones predominantly in central wards, such as Bakarganj, Kankarbagh, and Fraser Road. The historic centers, characterized by limited street grid expansion, exhibit the cumulative effects of unregulated

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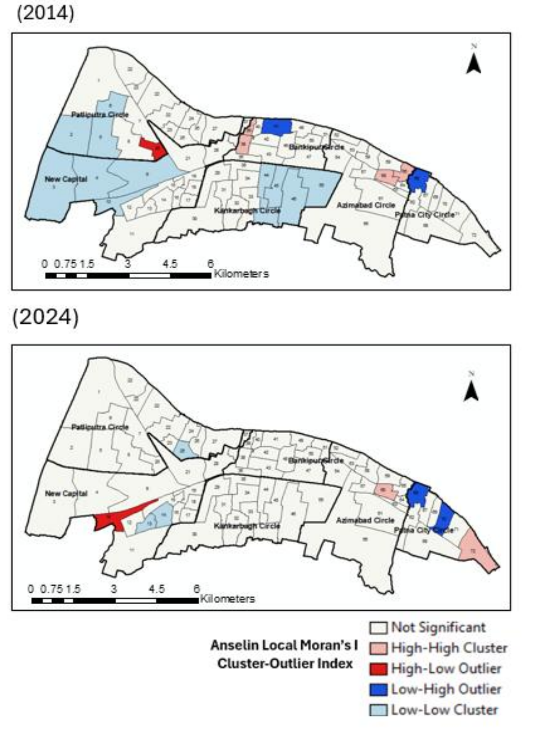
urbanization, vehicular congestion, and considerable pedestrian congestion (Porta et al., 2006) [20]. Low-Low clusters were identified in outlying wards such as Digha and Danapur, where population densities are comparatively low in relation to the existing roadway network.

The presence of High-Low outlier wards, including Ward 45 and Ward 52, raises concerns regarding localized densification without necessary infrastructural improvements. Accelerated infill growth, vertical residential constructions lacking proportional street expansion, and unregulated commercial proliferation contribute to these stress zones.

Thus, it is imperative to monitor population trends per street in order to anticipate future congestion sites and facilitate sustainable urban transport and mobility planning, particularly in rapidly developing peripheral regions.

The Population/Area/Number of Streets composite index combines population density, spatial extent, and street network density into a single, standardized metric of multifaceted urban strain. Elevated index values indicate wards experiencing concurrent constraints from substantial population density, limited spatial availability, and insufficient street infrastructure, hence exacerbating urban stress levels. Anselin Local Moran’s I analysis indicated that High-High clusters for the composite index were concentrated in the core areas of Patna, particularly in the Bakarganj, Gandhi Maidan, and Kankarbagh zones. These areas face intricate, multifaceted challenges, including overpopulation, limited growth capacity, and traditionally narrow, fragmented street configurations (Singh et al., 2022) [23].

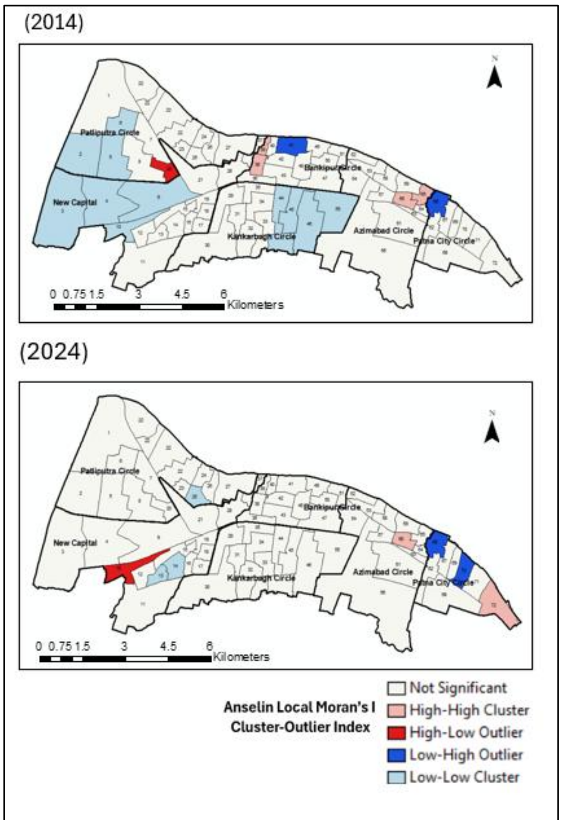
Peripheral areas, such as Boring Road Extension and Sampatchak, exhibited Low-Low clustering, indicating diminished cumulative stress and offering opportunities for organized urban development. High-Low outlier wards, particularly in expanding peri-urban regions like Phulwari and Anisabad, exhibit rapid demographic and spatial changes that are not matched by improvements to the street network. These regions are particularly susceptible to future congestion, infrastructure failure, and a decline in urban livability. The composite score serves as a planning tool, highlighting areas that require immediate coordinated reforms in land use, transportation infrastructure, and density control to improve sustainable urban resilience.



Map 7: *Ward map of PMC showing (Population/Area)/by Count of Streets*

The ***Population/Area/Street Length*** composite index serves as a multifaceted indicator, combining demographic density, spatial extent, and street infrastructure capacity into a single, normalized statistic. Elevated values of this index indicate wards undergoing concurrent stress related to population density, restricted spatial distribution, and inadequate street provision, rendering it a crucial metric of compounded urban vulnerability. Anselin Local Moran's I analysis identified High-High clusters primarily situated around the conventional urban center of Patna, encompassing Bakarganj, Gandhi Maidan, and Kankarbagh, thus creating a continuous area of significant infrastructural pressure (Singh et al., 2022) [23].
These wards have consistently encountered difficulties due to organic, uncontrolled expansion, where increasing population concentrations have not been accompanied by deliberate infrastructural enhancements.
y 2024, numerous semi-urban areas, including Kurji and Jagdeo Path, had evolved into High-High clusters, highlighting that rapid peri-urban expansion without sufficient street network enhancement exacerbates stress accumulation. Conversely, Low-Low clusters continued to exist in the southern urban peripheries between AIIMS Patna and New Gola Road, indicating regions where development is

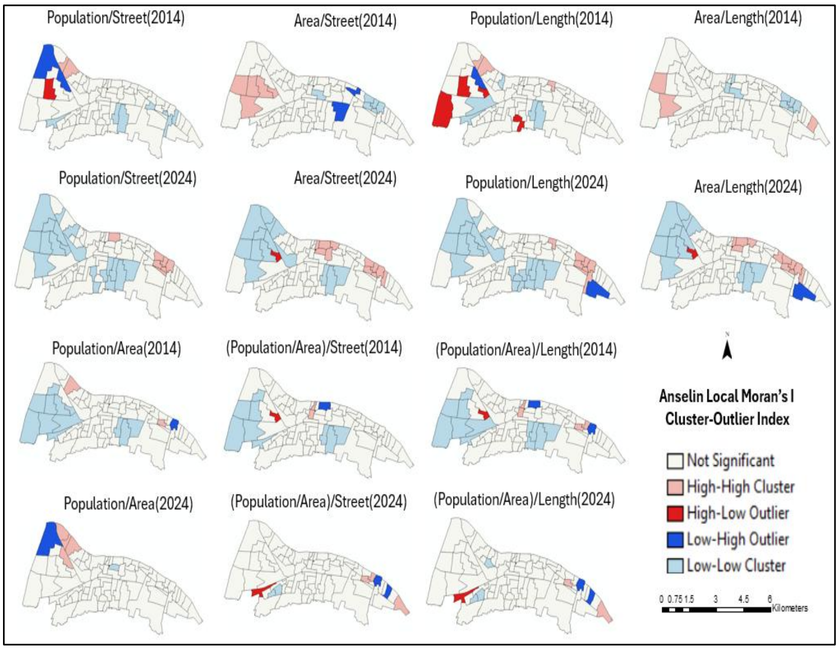
somewhat confined. Isolated High-Low and Low-High outliers, as illustrated by Ward 46 and Ward 70, have emerged as critical locations where stress either accumulates unexpectedly or resilience persists against dominant high-stress patterns, indicating the non-linear propagation of urban infrastructural stress across Patna.



Map 8 *Ward map of PMC showing (Population/Area)/by length of Streets*

A comparative analysis spanning from 2014 to 2024 reveals a notable expansion of urban street stress zones within the Patna Municipal Corporation, aligning with established patterns of urban sprawl. Wards classified as Low-Low coldspots in 2014 have gradually shifted to neutral or High-High stress classifications by 2024, particularly along major transport routes such as Bailey Road, Patliputra Colony extensions, and the Saguna Mor axis. This spatial change underscores the crucial need for infrastructural foresight, which requires planners to anticipate not only existing hotspots but also potential corridors for stress propagation.

Spatial analysis reveals that the inner circles, such as Gandhi Maidan, Kankarbagh, and Bakerganj, exhibit a high concentration of High-High stressed wards. Intermediate circles of Boring Road, Rajendra Nagar, and Ashok Nagar indicate a transition area with both steady areas and newly developed hotspots. The external circles of Danapur, Phulwari, and Sampatchak mostly show Low-Low statuses, but spot localized High-Low outliers, indicating the primary phases of stress development in peripheral areas.
The spatial distribution of urban street stress reveals significant structural inequities: old centers face extreme latencies due to archaic street networks, whereas peri-urban centers hold promise for sustainable development through the enactment of proactive planning interventions. Anselin's Local Moran’s I classification indicates that High-High clusters require immediate measures, such as street widening, pedestrianization, and prioritizing transit. High-Low as well as Low-High outliers serve as crucial buffers through localized intervention for the prevention of systemic urban dysfunctions.
Z-score normalization-spatial autocorrelation combination plays a vital role in finding the intrinsic 'stress anatomy' of Patna at the detailed ward level. Urban stress zoning maps provide valuable inputs for data-driven master planning, infrastructure prioritization, and building resilience, thereby ensuring sustainable and comprehensive urbanization of Patna.



Map 9: Ward-wise Analysis of Cluster and Outlier Distribution of Street Parameter Stress in Patna Municipal Corporation for the Years 2014 and 2024

Conclusion

The analysis assessed the spatial variation of urban stress linked to the street network of the Patna Municipal Corporation over the past decade, employing Z-score normalization and Anselin Local Moran's I for evaluation. The findings provide a crucial understanding of shifting infrastructural patterns and the emergence of new stress zones.

A notable observation is the substantial rise in High-High stress clusters, which have escalated from 18.6% of wards in 2014 to 28% in 2024, with a primary concentration in Bakarganj, Gandhi Maidan, and Kankarbagh. The fundamental aspects illustrate the cumulative impacts of past infrastructure constraints, rapid urban growth, and limited road network expansion. Simultaneously, Low-Low clusters decreased from 34.6% to 25.3%, suggesting that previously stable peripheral regions are slowly evolving into areas experiencing increased infrastructural strain. High-Low (6.6%) and Low-High (5.3%) outliers underscore specific vulnerabilities and resilient areas, serving as early warning signals that can guide focused planning efforts.

Spatial patterns indicate that stress has spread outward from the traditional urban core into the developing peri-urban corridors along Bailey Road, Patliputra Colony extensions, and the Saguna Mor axis. These shifts underscore the pressing need for forward-thinking infrastructure planning and adaptable management strategies that anticipate future congestion rather than merely responding to current issues.

The study provides a detailed insight into the urban stress dynamics of Patna by integrating demographic load, spatial coverage, and street network indicators into composite indices. The results highlight the necessity for prompt infrastructural interventions in High-High clusters, including road widening, enhanced pedestrian amenities, and a focus on public transit options. Low-Low clusters offer avenues for sustainable development, whereas spatial outliers highlight regions where proactive measures can avert systemic urban decline.

This comprehensive spatial analysis provides a model that can be applied to other cities experiencing rapid urbanization globally. This illustrates the potential of integrating GIS-based spatial analysis with statistical methods to inform infrastructure investment priorities, enhance urban resilience, and facilitate evidence-based planning for sustainable urban development.

Suggestion

Improving Patna's Street network is essential to ease the growing pressure on its urban infrastructure. The most congested core areas, identified as High-High clusters, need targeted interventions such as widening roads, better traffic management, and creating safer spaces for pedestrians. At the same time, the city's less developed outskirts, classified as Low-Low clusters, should be safeguarded through smart zoning regulations to prevent haphazard growth in the future. Regularly tracking unusual patterns, such as High-Low and Low-High outliers, enables timely responses that strengthen the city's overall resilience. As Patna continues to expand, urban planning must integrate well-designed street networks that match expected population growth. To support this, periodic evaluations using consistent spatial indicators should become a routine part of city governance, ensuring that decisions remain adaptive, data-driven, and responsive to changing needs.

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