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Assessing the Role of Delhi Metro on Urban and Peri-Urban Landscape Change: A GIS Perspective

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ABSTRACT

This study offers valuable insights into the relationship between metro ridership patterns and the spatial transformations around Delhi Metro stations, underscoring the role of mass transit infrastructure in shaping urban land use and ecosystem landscapes. The primary objective is to assess how high-ridership metro stations can positively influence urban development, particularly regarding socio-economic and ecological dimensions. Integrating primary survey data with ridership statistics from the Delhi Metro Rail Corporation (DMRC), the research identifies key interchange stations, such as Kashmere Gate and Rajiv Chowk, which exhibit substantial passenger volumes. Utilising GIS-based spatial analysis and remote sensing techniques, land use changes within a 500-meter buffer zone around these stations are considered, focusing on built-up areas, green cover, and open space availability. Time-series satellite imagery generates comparative maps illustrating land use changes pre- and post-introduction of metro services. The analysis reveals that high-ridership stations are linked to significant commercial densification, particularly near Rajiv Chowk, with a p-value of 0.172. Conversely, peripheral stations like Dwarka Sector 21 indicate residential growth trends, with a p-value of 0.087 for residential areas. Importantly, two land use categories—Green Space ($t = –2.33$, $p = 0.045$) and Open Space ($t = 3.57$, $p = 0.006$)—show statistically significant reductions, highlighting the ecological impacts of metro infrastructure. The findings suggest that metro systems can promote commercial clustering in urban centres while fostering residential growth in surrounding areas. Overall, the study highlights the potential of metro systems to enhance accessibility, reshape urban ecosystems, and encourage the development of compact urban forms. The implications for urban planning advocate for transit-oriented

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development (TOD) as a strategic approach to manage growth, minimise sprawl, and ensure sustainable and inclusive development.

Keywords: Metro Station; Urban Ecosystem; Landscape; Transit; GIS

1. Introduction

Urbanization and rapid population growth have exerted considerable pressure on transportation systems across cities globally, underscoring the urgent need for efficient and sustainable public transit solutions[1–3]. These challenges are not only functional and infrastructural but also ecological, as mobility systems increasingly interact with and reshape urban landscape structures. Delhi, the capital city of India, exemplifies this transformation. With a population exceeding 20 million and its status as a vital economic, cultural, and political centre[4], the city experiences mounting mobility demands. In response, the Delhi Metro—operational since 2002—has emerged as a core component of its transit infrastructure, significantly reducing traffic congestion, lowering vehicular emissions, and enhancing urban accessibility[5, 6]. However, beyond its transportation utility, the Delhi Metro has produced far-reaching spatial and ecological transformations by altering land use patterns, intensifying urban density, and reshaping the morphology and function of areas surrounding its stations[7].

Mass transit systems like the metro play a critical role not only in enabling connectivity and socio-economic development but also in influencing urban ecological structure and form[8–14]. These systems act as spatial catalysts, promoting accessibility[15, 16] and initiating land use transitions that modify the composition and configuration of urban landscapes[9, 14]. Around major transit nodes, especially high-ridership ones, previously underutilised or ecologically valuable land is often converted into densely developed commercial or residential zones[17]. The principles of Transit-Oriented Development (TOD), which emphasize high-density, mixed-use development near transit corridors, further illustrate how urban form and ecological continuity are altered by infrastructure growth[10, 11, 18–21]. While such development supports economic vitality and improved mobility, it also necessitates critical attention to ecological outcomes, such as habitat fragmentation, increased impervious surfaces, and disruption of natural flows[7]. These impacts vary according to urban planning strategies, demographic shifts, and local socio-environmental contexts.

In the National Capital Region (NCR), the Delhi Metro has served as a powerful driver of spatial transformation, prompting both planned and organic development across core urban and peri-urban zones. Studies have documented its influence on linear and nodal urban expansion, especially in areas such as Noida, Gurugram, Faridabad, and Bahadurgarh, where it has triggered real estate growth and intensified infrastructural investments[8]. Multi-temporal geospatial assessments reveal a clear decline in open and vegetated land within 0-500 m and 500-1000 m buffers around metro corridors, replaced by increasing built-up coverage in line with metro expansions and land market pressures[22]. These spatial dynamics are closely linked to socio-economic shifts, including rising land values and new investment patterns[23]. Moreover, environmental benefits from the metro have also been noted. Significant reductions in CO, NOx, and RSPM concentrations have been recorded in metro-influenced zones, attributable to a modal shift from private vehicles to public transit[24]. Socio-economically, the metro system has generated substantial public benefits, with travel time savings, accident reduction, and accessibility improvements contributing to an impressive internal rate of return of 24%—well above conventional financial returns[25]. As Delhi continues to densify, the integration of transit infrastructure with climate-resilient planning strategies such as TOD and water-sensitive urban design becomes crucial for mitigating urban heat and maintaining ecological balance[22].

Despite these observations, current research on metro systems in India remains largely focused on operational, economic, or planning aspects, with limited exploration of the broader spatial-ecological transformations induced by transit infrastructure. The specific relationship between metro ridership levels and associated land use transitions, particularly around high-functionality nodes such as interchange stations, remains underexplored. There is a significant gap in understanding how variations in ridership correlate with changes in land cover typologies, including shifts in residential, commercial, and mixed-use zones, and how these changes impact ecological continuity in the urban fabric.

Addressing these gaps requires the application of advanced spatial technologies. Geographic Information Systems (GIS) and Remote Sensing (RS) have increasingly been employed to study the ecological effects of infrastructural development. For example,[26] utilized the InVEST modelling suite alongside GIS and remote sensing data to quantify ecosystem service changes resulting from large-scale infrastructure interventions, providing a methodological foundation for long-term environmental monitoring. In the Indian context,[27] employed GIS-based multi-criteria evaluation (MCE) and satellite imagery to assess the potential for TOD in Bhopal, focusing on land use, density, and walkability. Similarly,[28] applied GIS-based spatial multi-criteria analysis to prioritize TOD zones in Alexandria, Egypt, demonstrating the efficacy of spatial tools in sustainable urban planning. In the case of Delhi, the use of primary data in combination with geospatial technologies such as remote sensing allows for high-resolution, temporal monitoring of landscape change in metro station influence zones[29, 30]. GIS tools further enable the integration, layering, and visualisation of spatial datasets, supporting proximity analysis and the identification of land cover transitions across ecological zones influenced by transit infrastructure[29, 30].

This study seeks to examine the impact of metro ridership intensity on land use and land cover (LULC) patterns around key interchange stations of the Delhi Metro. The specific objectives are:

- To analyze ridership trends at key metro interchange stations using both primary and secondary data sources.
- To investigate ecological transformations before and after the construction of metro stations using remote sensing and GIS techniques.
- To assess the ecological implications of these transformations in order to inform sustainable, transit-integrated urban planning.

The novelty of this research lies in its integrative spatial-ecological approach, which combines ridership data with geospatial analysis to uncover how metro infrastructure not only supports urban mobility but also acts as a spatial agent of ecological transformation. While prior studies have addressed operational or economic dimensions of metro systems, this study offers a new empirical framework for understanding how transit usage patterns shape land use transitions and ecological functions across Delhi's metropolitan landscape. By focusing on high-ridership interchange stations and employing a landscape ecological perspective, the study contributes original insights into the intersection of infrastructure, land use, and sustainability in rapidly urbanising contexts such as the Global South.

2. Materials and Methods

2.1. Study Area

Delhi, the capital city of India, represents a dynamic urban agglomeration and serves as a crucial hub for political, cultural, and commercial activities. Spanning approximately 1,484 square kilometres, the city is in northern India, bordered by Haryana on three sides and Uttar Pradesh to the east. Delhi's diverse topography includes the Yamuna floodplains in the east and the ridge areas in the west, which function as the city's green lungs.

With a population surpassing 20 million, Delhi ranks among the most populous metropolitan areas globally. Over the years, the city has undergone significant urbanization and expansion, facilitated by extensive infrastructure projects. In particular, the Delhi Metro, a contemporary mass rapid transit system, is pivotal in influencing the region's urban landscape and spatial dynamics. This research explicitly examines the Delhi Metro routes as the designated study area (**Figure 1**).

2.2. Datasets Used

This study utilises a combination of primary, secondary, and geospatial datasets to ensure a comprehensive analysis. The geospatial data was particularly instrumental in assessing temporal land use changes. A detailed overview of the datasets employed in the study is provided in **Table 1**.

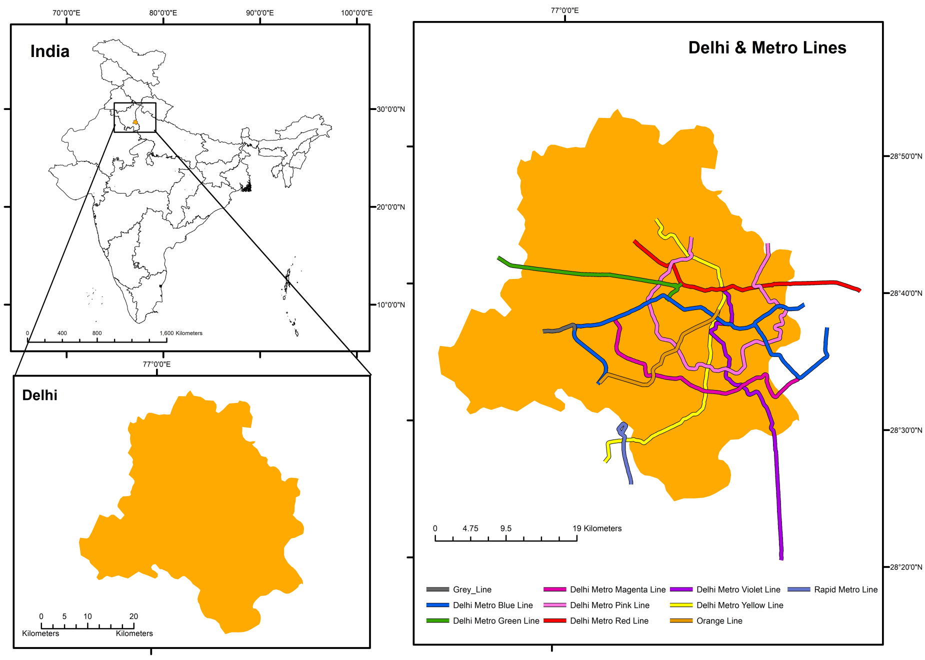


Figure 1. Study Area.

Table 1. Details of Datasets.

Details	Nature	Source
Delhi Metro Network and Station Details	Secondary	Delhi Metro Rail Corporation
Annual Metro Ridership Trends	Secondary	Delhi Metro Rail Corporation
Interchange Station Average Ridership	Primary	Collected through Surveys
Land Use Data	Geospatial	Temporal Data from Google Earth Pro (Airbus/Maxar)

2.3. Methods

This study employs geospatial tools and techniques supplemented by primary data collection through ground surveys and secondary data sourced from the Delhi Metro Rail Corporation (DMRC), government reports, published documents, and official websites. These datasets are instrumental in providing essential information regarding the growth and development of the Delhi Metro Transit System.

The methodology was initiated by selecting 25 major interchange metro stations in Delhi. According to DMRC data, there are a total of 29 interchange stations in the network, of which 25 are located within the administrative boundary of Delhi. Accordingly, all 25 interchange stations within Delhi were selected for this study (**Figure 2**). An interchange metro station is a transit hub where passengers may transfer between two or more metro lines without exiting the station premises. Primary data on ridership was gathered at these 25 stations during peak and non-peak hours to calculate average daily ridership. This analysis identified the top 10 metro stations exhibiting the highest ridership for further examination (**Figure 3**).

Comprehensive geospatial analyses, supported by ground surveys, were conducted for Delhi's top ten interchange metro stations. The methodology utilized open-source satellite datasets to assess developmental patterns and land use changes before and after the construction of the metro stations. For consistency and comparability, a 500-meter buffer zone was delineated around each station using GIS tools, enabling a systematic examination of landscape transformations within this defined spatial extent. LULC changes were analysed using temporal high-resolution satellite imagery from Google Earth Pro, corresponding to two timeframes: one preceding metro construction (determined by the year of station inauguration) and another post-operationalization (2024). Land use categories were identified through visual interpretation of the imagery, guided by existing urban land use classification standards. These classifications—detailed in **Table 2**—include built-up areas, vegetation, open spaces, institutional zones, commercial zones, and transportation infrastructure. Although the classification framework follows standard LULC typologies commonly employed in urban studies, the delineation of individual features was context-specific and tailored to the unique spatial and morphological characteristics of the Delhi urban landscape (**Table 2**). To ensure accuracy, on-site field verification was carried out using a handheld GPS device (Handheld Nautiz X6 with RTK Module), allowing for the validation and refinement of land use boundaries based on ground truth observations. In addition to spatial analysis through GIS, statistical tools such as descriptive statistics, t-tests, principal component analysis (PCA), and cluster analysis were employed to interpret land use patterns and quantify the extent of change. The percentage change in each land use category within the buffer zones was calculated, providing a robust metric to evaluate the spatial transformations induced by the metro infrastructure. The detailed methodology flowchart is depicted in **Figure 4**.

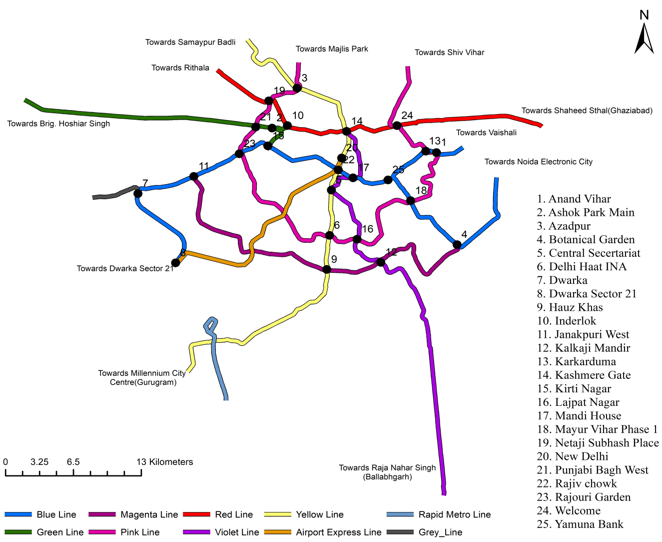


Figure 2. The Major Interchange Metro Stations.

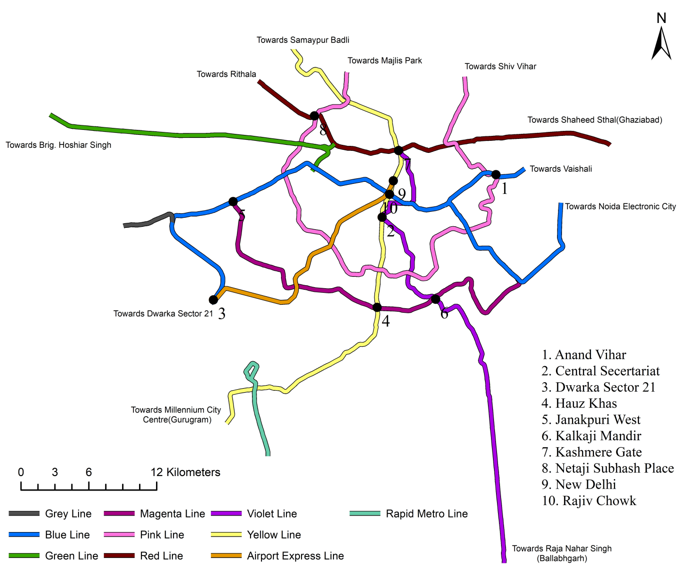


Figure 3. Selected Metro Stations.

Table 2. Land Use Categories (Source: Adapted from Master Plan for Delhi 2021 (pp. 275–276), by the Delhi Development Authority, 2021.)[31].

S.No	Land use	Features
1	Residential	Residential area; Foreign Mission
2	Commercial	Retail Shopping, General Business and Commerce, District Centre, Community Centre, Non-Hierarchical Commercial Centre. Wholesale, Warehousing, Cold Storage and Oil Depot Hotels
3	Industrial	Manufacturing, Service, and Repair Industry.
4	Transportation	Airport Terminal / Depot - Rail / MRTS / Bus / Truck T3 Circulation - Rail / MRTS / Road
5	Administrative (Government)	President Estate and Parliament House Government Office / Courts Government Land (use undetermined)
6	Institutional (Public and semi-public facilities)	Hospital, Education and Research University / University centre, College, / Police Headquarters / Police Lines, Fire Stations / Disaster Management Centres, Religious, Burial Ground / Cremation. Transmission Site / Centre Sports Facilities / Complex / Stadium / Sports Centre.
7	Green belt/Green space	Plant Nursery Green Belt / Agricultural Green
8	Waterbody	River and Waterbody
9	Mixed	A use zone in the Land Use Plan could be indicated as having more than one use zone.
10	Open space	Vacant land, Barren Land
11	Others	Religious areas, cremation grounds, and any other use that does not fall under the above categories.

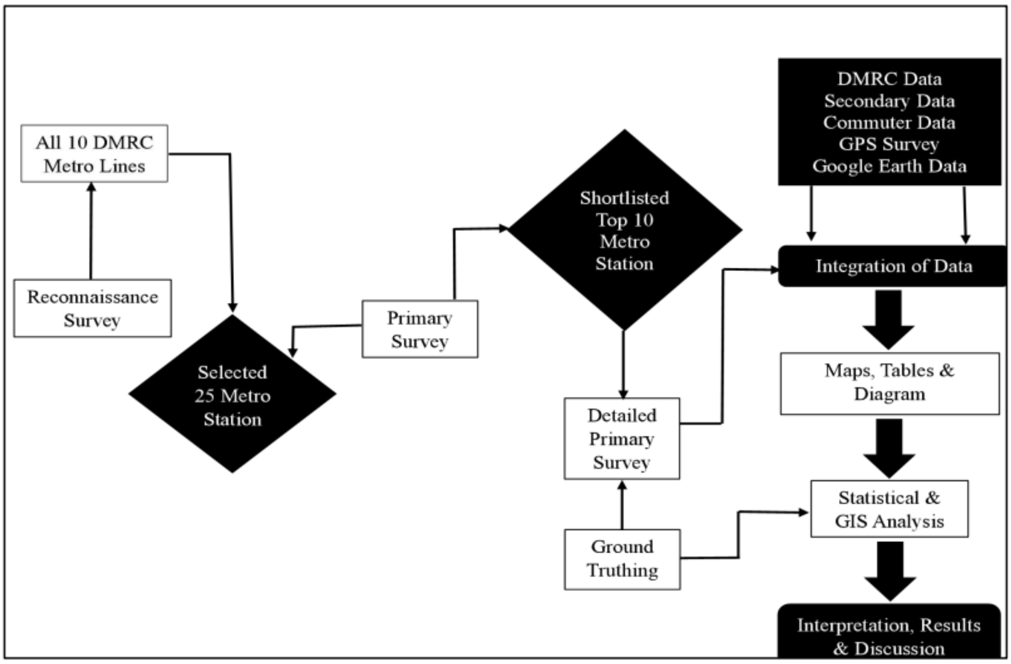


Figure 4. Detailed Methodology Flowchart.

3. Results and Discussions

3.1. Delhi Metro Ridership

The annual ridership data for the Delhi Metro demonstrates significant trends over time, shaped by infrastructure development and external socio-economic factors. The ridership trends from 2013 to 2022 are illustrated in **Figure 5**. The data for 2023 and 2024 is not yet available in the public domain from the DMRC, and therefore, the latest available data up to 2022 has been utilised for this study.

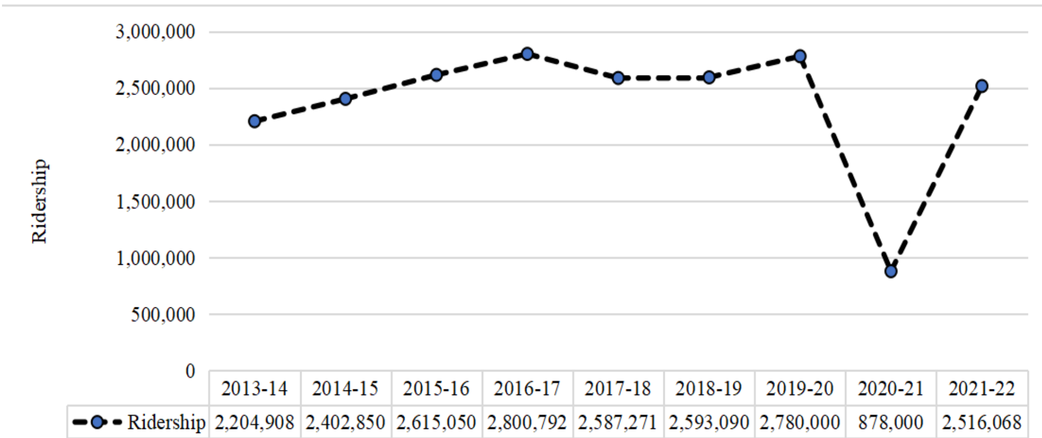


Figure 5. Ridership trends of Delhi Metro (Source: DMRC Archives).

The ridership of the Delhi Metro exhibited a consistent increase from an average daily ridership of 22,04,908 in the fiscal year 2013–2014 to a peak of 28,00,792 in 2016–2017, demonstrating its growing significance as a primary mode of urban transportation. However, a decline was recorded in the following years, with ridership falling to 25,87,271 in 2017–2018, followed by a marginal increase to 25,93,090 in 2018–2019. A substantial rise was again observed in 2019–2020, with ridership reaching 27,80,000, before a dramatic drop occurred in 2020–2021, with the figure plummeting to 8,78,000 due to the COVID-19 pandemic and related restrictions. Signs of recovery became evident in 2021–2022, as ridership rebounded to 25,16,068, reflecting renewed public reliance on metro transit and a return toward pre-pandemic commuting patterns. This data highlights the crucial role of the Delhi Metro in the city's transportation framework, as it serves as a key backbone for daily commuting and significantly alleviates traffic congestion on roadways. Its extensive accessibility and connectivity to vital urban and suburban areas underscore its status as an indispensable element of the city's infrastructure. The Metro's presence has been instrumental in shaping urban development and transforming landscape patterns, including promoting TOD, stimulating real estate growth along Metro corridors, and encouraging more sustainable and compact urban designs.

3.2. Metro Interchange Ridership Analysis

A comprehensive survey was conducted at 25 interchange metro stations to analyze ridership patterns during peak and non-peak hours. Peak hours were defined as 8:00 AM to 12:00 Noon and 5:00 PM to 9:00 PM, corresponding with office timings and periods of high travel demand. Non-peak hours included early mornings, mid-day, and late evenings, reflecting reduced commuter flow.

The counting was performed manually at entry and exit gates by field surveyors using tally counters. Surveys were conducted over three consecutive working days at each station to ensure consistency and eliminate anomalies caused by day-to-day variations. For each day, observations were made across the operational window from 08:00 AM to 09:00 PM, with data recorded at hourly intervals. Data from these manual counts were compiled and analysed using Microsoft Excel and SPSS. The hourly ridership data was compiled and summed to calculate the total ridership for each day. These daily totals were then averaged across the three days to determine the mean daily ridership per station. The results facilitated a robust understanding of station-wise commuter patterns and were instrumental in identifying the top ten most trafficked interchange stations for further geospatial analysis (**Figure 6**).

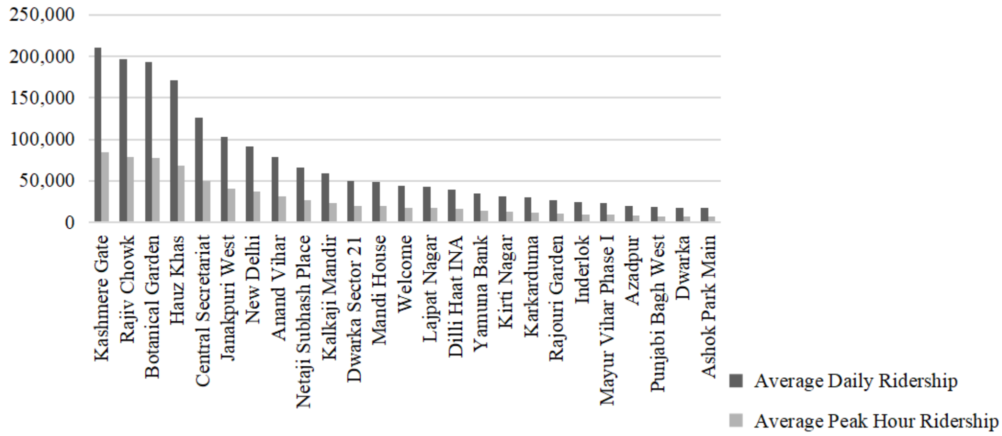


Figure 6. Average Approximate Ridership Data of 25 Interchange Metro Stations (Source: Primary Survey).

The ridership data for various Delhi Metro stations provides significant insights into commuter traffic patterns throughout the city. Kashmere Gate and Rajiv Chowk are the busiest stations, with average daily ridership figures of 210,404 and 196,306 passengers, respectively. During peak hours, Kashmere Gate accommodates up to 84,162 passengers, while Rajiv Chowk serves approximately 78,522 passengers. This substantial ridership underscores their functions as key interchange stations, facilitating efficient transfers between multiple metro lines and connecting commuters to commercial, residential, and institutional sectors.

Other stations, including the Botanical Garden, Hauz Khas, and Central Secretariat, also demonstrate considerable ridership. Botanical Garden records an average daily ridership of 193,521, and Hauz Khas reports 170,987 daily passengers. These stations are strategically situated in well-connected areas, serving transit commuters and individuals travelling to essential educational, governmental, and commercial locations. The moderate peak hour ridership observed at these stations highlights their importance in facilitating adequate urban mobility despite not attracting the same traffic volume as the primary interchange hubs.

Stations in more peripheral or less densely populated areas, such as Ashok Park Main, Dwarka, and Punjabi Bagh West, exhibit relatively lower ridership figures. Specifically, Ashok Park Main registers approximately 17,406 daily riders, while Dwarka records about 17,993 daily riders. Although these figures are significant, they reflect a lower density of commuter traffic in these regions. This phenomenon can be attributed to several factors, including the distance from central commercial or business districts, lower population density in residential areas, and less developed public transportation infrastructure compared to more central locations. Following the ridership data collection from 25 metro stations, the top 10 stations were identified for further analysis. These stations include Kashmere Gate, Rajiv Chowk, Hauz Khas, Central Secretariat, Janakpuri West, New Delhi, Anand Vihar, Netaji Subhash Place, Kalkaji Mandir, and Dwarka Sector 21. The Botanical Garden Metro Station was excluded from this study due to its location in the Noida region, in contrast to the remaining stations, which are situated within Delhi. The selected ten metro stations were subsequently analyzed using geospatial tools and techniques to investigate the developmental patterns emerging in their surrounding areas.

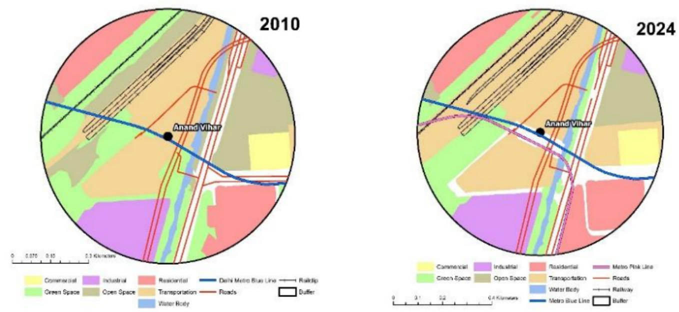
3.3. Results of Land Use Analysis

The GIS-based analysis of the 500-meter buffer zones surrounding the top ten selected metro stations in Delhi reveals significant changes in land use patterns before and after the construction of the metro system. This study utilized high-resolution temporal satellite imagery sourced from Google Earth Pro (Airbus/Maxar) for two distinct periods—prior to the opening of each station and post-2022—to capture and analyse these transformations. Using visual interpretation techniques and digitisation in the Arcgis software, comprehensive land use maps were generated to assess spatial and categorical changes within these zones.

To ensure accuracy, the land use classification—comprising built-up, commercial, institutional, transportation, green/open spaces, and vegetation—was supported through field surveys and GPS-based ground validation. As illustrated in **Figure 7(a-j)**, the findings indicate a consistent reduction in open spaces, expansion in commercial and transportation areas, and variable trends in residential and institutional categories. To establish a clear association between land use changes and metro line development, the analysis focused exclusively on a 500-meter fixed-radius buffer around each interchange station, a methodological approach commonly employed in transit-oriented development (TOD) research. This spatial concentration allows for isolating metro-induced effects from broader urban expansion trends. Although other factors, such as general urban growth, government policies, or real estate dynamics, may also influence land use change, the consistent spatial pattern of intensified development adjacent to metro infrastructure strongly supports the hypothesis that the metro has played a catalytic role in shaping these transformations.

Table 3 presents a comprehensive overview of the percentage distribution of various land use categories within the defined buffer zones before and after the metro stations became operational, thereby reinforcing the connection between transit infrastructure and surrounding urban development. These percentages were calculated using area statistics derived from manual digitisation of land use features within a 500-meter buffer around each metro station. Each land use polygon was digitised manually using GIS software, and its corresponding area (in square meters) was calculated. The percentage for each category was then computed by dividing the area of that category by the total buffer area and multiplying by 100. This method allowed for a consistent and accurate assessment of land use distribution and changes over time.

a: Anand Vihar



b: Central Secretariat

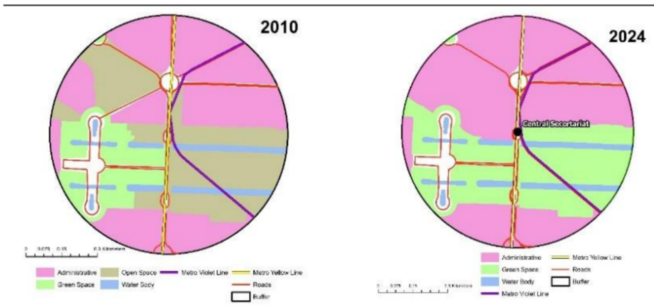
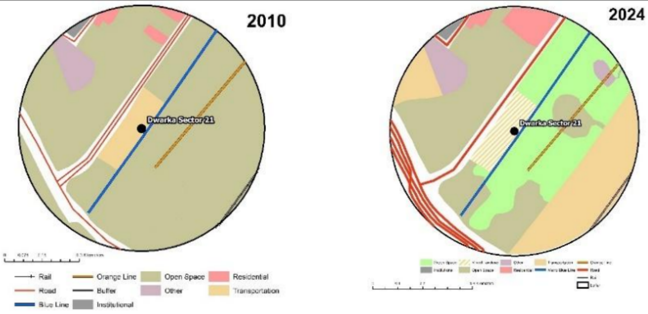


Figure 7. *Cont.*

c: Dwarka Sector 21



d: Hauz Khas

e: Janakpuri West

f: Kalkaji Mandir

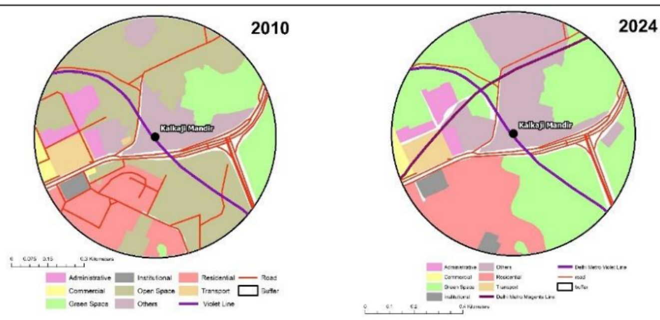


Figure 7. *Cont.*

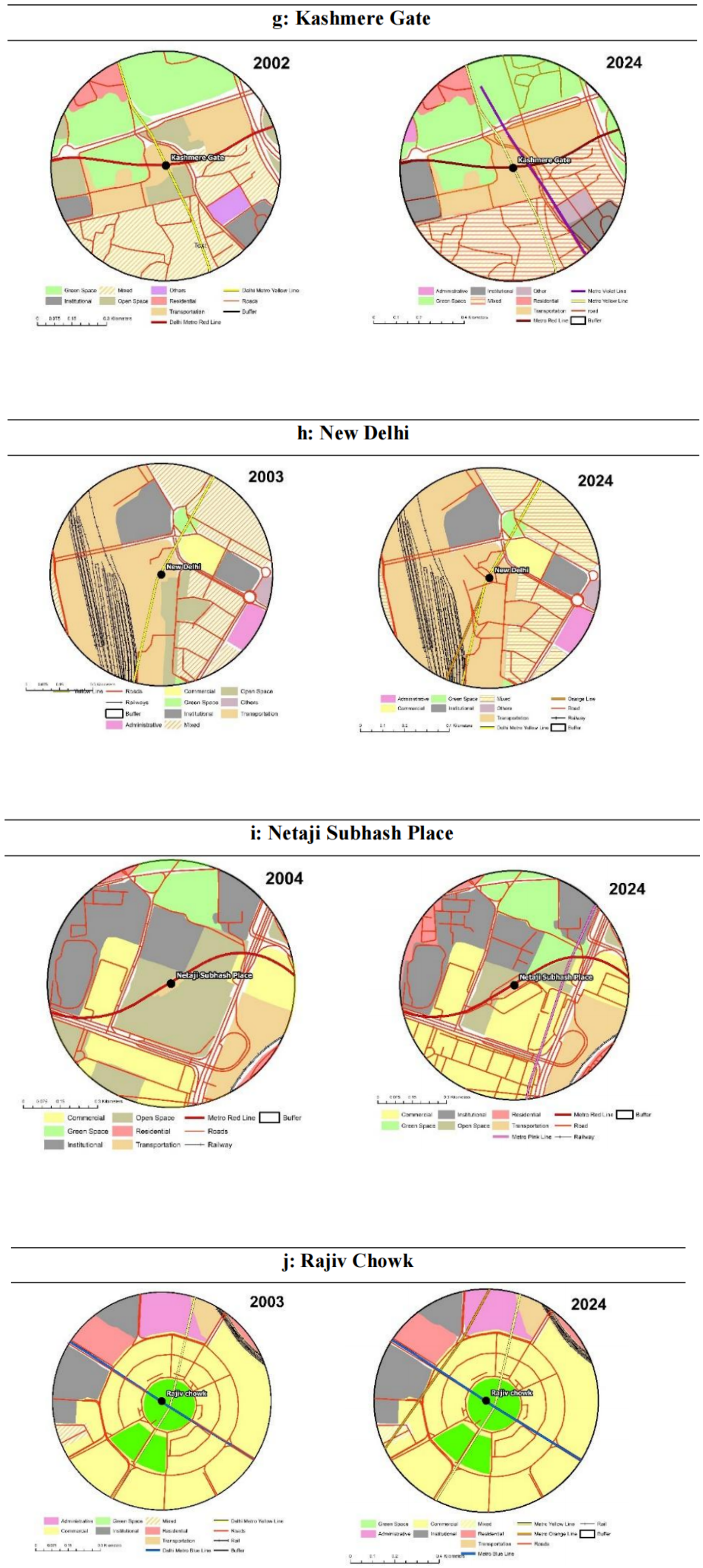


Figure 7. (a-j). Landscape Change Maps for Pre- and Post-Metro Station Construction.

Table 3. Land Use pre- and Post-Metro Station Construction (in Percentage).

	Rajiv Chowk		New Delhi		Kashmere Gate		Central Secretariat		Hauz Khas	
	Old	**2024**	**Old**	**2024**	**Old**	**2024**	**Old**	**2024**	**Old**	**2024**
Residential	5.2	5.2	0.0	0.0	3.6	3.5	0.0	0.0	66.4	67.3
Commercial	66.1	66.1	3.3	3.3	0.0	0.0	0.0	0.0	3.8	4.1
Industrial	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transportation	3.4	3.4	47.7	54.5	15.3	22.9	0.0	0.0	0.0	0.0
Administrative	6.4	6.4	2.6	2.6	0.5	0.5	45.6	59.4	0.0	0.0
Institutional	7.4	7.4	9.5	9.5	5.4	8.3	0.0	0.0	4.8	6.4
Green Space	10.3	10.3	1.4	1.4	27.2	26.8	16.0	33.1	14.9	19.2
Waterbody	0.0	0.0	0.0	0.0	0.0	0.0	5.3	5.3	0.0	0.0
Mixed	1.3	1.3	27.7	27.7	35.5	34.7	0.0	0.0	0.0	1.1
Open Space	0.0	0.0	6.8	0.6	10.2	1.5	33.1	2.4	10.0	1.9
Others	0.0	0.0	1.1	1.0	2.3	2.3	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Kalkaji Mandir		**Anand Vihar**		**Netaji Subhash Pl.**		**Janakpuri West**		**Dwarka Sec 21**	
	Old	**2024**	**Old**	**2024**	**Old**	**2024**	**Old**	**2024**	**Old**	**2024**
Residential	14.6	18.0	10.3	15.5	1.3	1.3	53.9	53.8	1.7	3.7
Commercial	1.4	1.2	2.5	3.3	22.3	39.6	7.0	16.2	0.0	0.0
Industrial	0.0	0.0	7.6	7.6	0.0	0.0	0.0	0.0	0.0	0.0
Transportation	3.1	3.2	39.7	43.2	10.4	10.4	0.0	0.0	7.3	23.5
Administrative	3.7	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Institutional	1.2	2.0	0.0	0.0	29.0	29.3	3.8	5.3	0.4	0.4
Green Space	13.4	46.1	19.8	16.2	8.9	12.2	15.4	22.6	3.1	27.4
Waterbody	0.0	0.0	2.4	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Mixed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Open Space	49.9	1.3	17.8	10.0	28.0	7.8	12.8	1.3	84.6	37.9
Others	12.6	24.6	0.0	0.0	0.0	0.0	7.1	0.9	3.1	4.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Sources: Satellite-based data.

3.4. Station-Wise Analysis of Landscape Change

The expansion of the Delhi Metro has not only improved urban mobility but has also served as a catalyst for significant changes in land use and spatial restructuring within the surrounding urban area. These transformations include alterations in green cover, open space layout, infrastructure density, and functional zoning. The following cases present a comparative spatial analysis of selected interchange stations, illustrating the complex ways transit infrastructure interacts with existing land cover patterns and leads to new spatial arrangements.

Anand Vihar Metro Station:

Since its establishment in 2010, Anand Vihar has become an essential multimodal hub, integrating the Blue and Pink Lines with railway and bus terminals. Before the metro development, the area had a notable amount of green spaces, which comprised 19.84% of the total area, and open land made up 17.8%. Transport-related infrastructure accounted for 39.68%. After the metro's development, the share of transport infrastructure increased to 43.16%, coinciding with a decrease in green and open spaces. Additionally, the proportion of residential land use rose to 15.52%, while commercial land use increased to 3.31%. These changes reflect a rise in land use intensity and functional diversification around the transit hub.

Central Secretariat Metro Station:

This interchange station, inaugurated in 2005, provides critical connectivity to Delhi's administrative core via the Yellow and Violet Lines. Initially, land use was dominated by administrative functions (45.62%), open spaces (33.08%), and a significant green cover (15.95%). Following metro integration, administrative use expanded to 59.40%, and green areas increased to 33.08%, while open spaces contracted significantly to 2.36%. This shift can be attributed to state-led redevelopment, particularly under the Central Vista Project, resulting in a more controlled and purpose-specific landscape configuration.

Dwarka Sector 21 Metro Station:

Located on the Blue Line and Airport Express corridor, this station illustrates a transition from peripheral openness to structured development. Before the metro construction, open land constituted 84.58% of the surrounding area. Following the station's inauguration in 2011, transport infrastructure increased to 23.49% and green cover improved to 27.39%, indicating a planned conversion of open tracts into functional and vegetated spaces. Open areas decreased to 37.94%, reflecting the spatial implications of transit-induced urban expansion.

Hauz Khas Metro Station:

As an interchange between the Yellow and Magenta Lines, Hauz Khas exemplifies localized intensification in a pre-established residential setting. Residential land use slightly increased from 66.42% to 67.27%, while green space saw a noticeable rise from 14.91% to 19.23%. The emergence of commercial use (4.12%) highlights a shift toward mixed land utilization. This case underscores a moderate reconfiguration of landscape function, maintaining residential dominance while integrating ancillary uses.

Janakpuri West Metro Station:

An interchange node on the Blue and Magenta Lines, Janakpuri West has seen an increase in green cover from 15.35% to 22.63%, alongside a significant rise in commercial land use from 6.99% to 16.15%. Residential use remained stable at approximately 54%. These changes suggest a dual transformation—landscape enhancement through increased vegetation and economic intensification through commercial expansion—indicative of balanced spatial planning.

Kalkaji Mandir Metro Station:

Located near prominent religious landmarks, Kalkaji Mandir has undergone a substantial land use transformation. Green cover expanded markedly from 13.44% to 46.06%, while open space declined from 49.91% to 1.33%. Residential use also increased from 14.61% to 17.95%. The significant reduction in unprogrammed open land indicates a shift toward more controlled land use arrangements, with a focus on enhancing formal green spaces and consolidating built-up functions.

Kashmere Gate Metro Station:

This major interchange serves three lines and bridges the older and newer parts of the city. Pre-metro land use included 27.16% green spaces and 35.50% mixed-use zones. Following metro development, transport infrastructure rose to 22.94%, and institutional use increased to 8.34%. Open space was reduced to 1.5%, while mixed-use functions remained largely unchanged. The transition reflects a densification of core urban functions, reinforcing the role of the station as a high-capacity mobility and service hub.

New Delhi Metro Station:

Strategically located near the city's primary railway terminal, New Delhi Metro Station has seen transport infrastructure expand from 47.7% to 54.05%, while open space declined from 6.8% to 0.55%. Institutional and mixed-use areas remained consistent. The spatial intensification around this station demonstrates the prioritization of intermodal connectivity over landscape heterogeneity, with minimal provision for unstructured or vegetated space.

Netaji Subhash Place Metro Station:

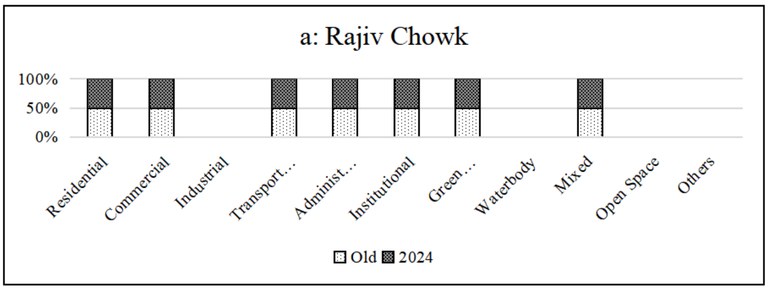
An interchange between the Red and Pink Lines, this station area has transitioned into a commercial hub. Institutional land declined as commercial use increased from pre-existing levels to 39.6%, while open space reduced from 28.0% to 7.8%. Green space showed a modest increase to 12.2%. The transformation signals a shift toward market-driven redevelopment, where commercial growth is accompanied by incremental increases in green infrastructure, albeit at the cost of spatial openness.

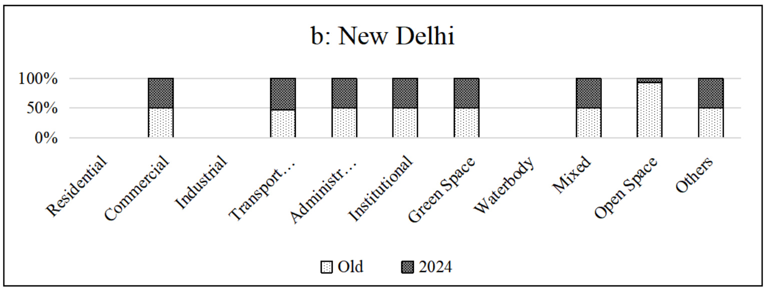
Rajiv Chowk Metro Station:

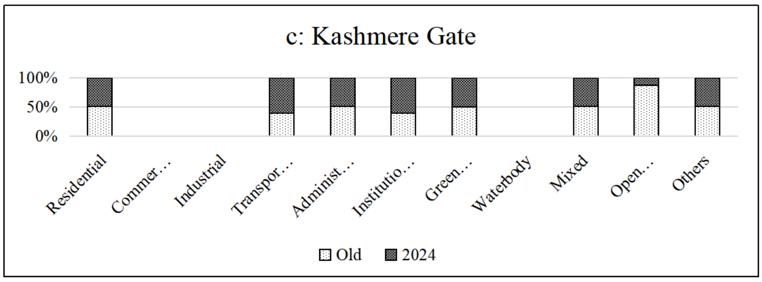
Situated in Connaught Place, one of Delhi's oldest and most commercially active zones, this station area has maintained its pre-existing structure. Commercial land use remains dominant at 66.1%, and green space continues at

10.3%, reflecting minimal change post-metro. This stability indicates a saturation point in terms of land use transformation, where the built environment was already optimised for high-density, high-activity use before the metro's integration.

The stacked column charts (**Figure 8a-j**) provide a comparative visualization of land use distribution before and after the construction of metro infrastructure at selected stations across Delhi. Each pair of columns represents the land use composition before and after metro construction, segmented into residential, commercial, institutional, green spaces, and other categories, enabling a temporal and spatial comparison.







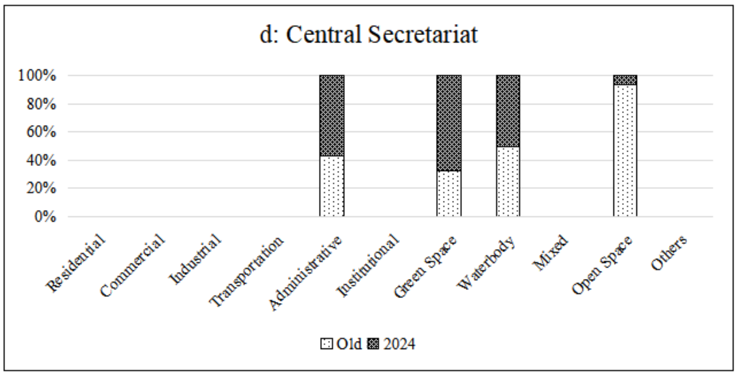


Figure 8. *Cont.*

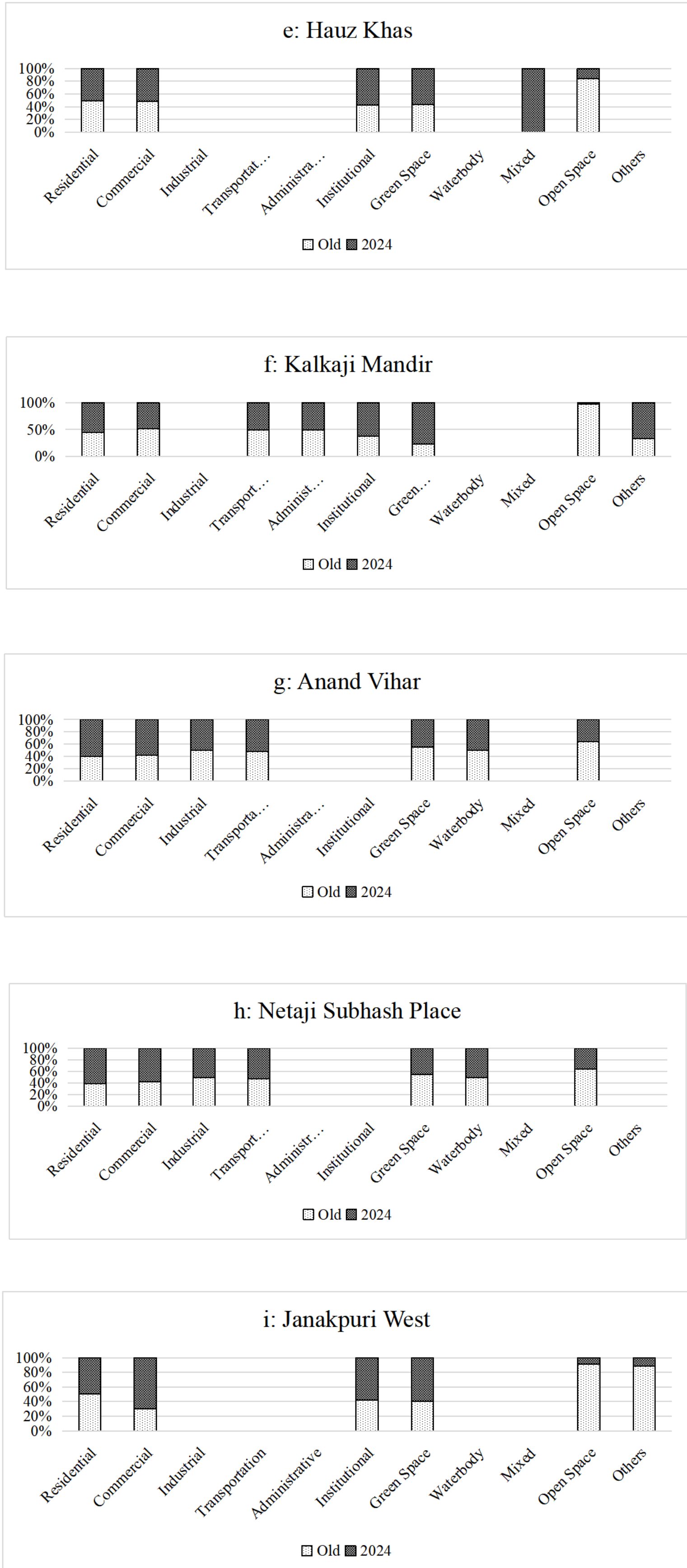


Figure 8. *Cont.*

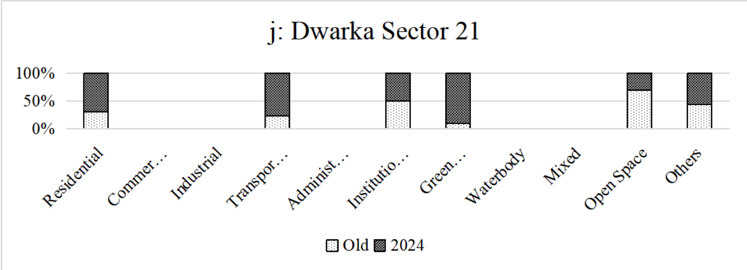


Figure 8. Stacked Bar Charts of Land Use Change.

Based on the stacked column chart analysis, land use changes around the ten selected Delhi Metro stations reveal distinct patterns of transformation before and after metro construction. Central stations such as Rajiv Chowk and New Delhi maintained high commercial land use (66.1% and 3.3% respectively), with negligible changes, reflecting their enduring roles as commercial and transit hubs. Kashmere Gate experienced a significant rise in transportation infrastructure (from 15.3% to 22.9%) and institutional land use (from 5.4% to 8.3%), highlighting its growing prominence as an interchange and civic node. Central Secretariat showed a remarkable increase in green space (from 16.0% to 33.1%) and administrative use (from 45.6% to 59.4%), aligning with national redevelopment efforts under the Central Vista Project. In South Delhi, Hauz Khas exhibited slight increases in residential and institutional areas, while Kalkaji Mandir saw a dramatic rise in green space (from 13.4% to 46.1%) and "Others" category (from 12.6% to 24.6%), suggesting ecological improvements and increased public amenities. Anand Vihar demonstrated a modest shift from open space (17.8%) towards increased green (19.8%) and residential areas (from 10.3% to 15.5%), reflecting its transformation into a multi-modal residential hub. At Netaji Subhash Place, commercial land use rose significantly (from 22.3% to 39.6%), indicating its emergence as a business centre. Peripheral stations such as Janakpuri West and Dwarka Sector 21 exhibited substantial reductions in open spaces (from 12.8% to 1.3% and 84.6% to 37.9%, respectively) and concurrent increases in green and residential areas, highlighting a transition from underdeveloped landscapes to structured, livable suburban environments. These findings confirm that metro development induces both densification and functional diversification, varying by location and urban hierarchy.

3.5. Paired t-Test Analysis

To assess the statistical significance of land use changes associated with the construction of metro stations in Delhi, a paired sample t-test was conducted for each land use category using pre- and post-construction data within 500-meter buffer zones around selected metro stations. This test aimed to determine whether the observed differences in land use values before and after the metro development were statistically meaningful (**Table 4**).

Among all categories, the analysis revealed statistically significant changes in only two land use types: Green Space and Open Space. The t-statistic for Green Space was -2.33 with a p-value of 0.045, and for Open Space, it was 3.57 with a p-value of 0.006. These results suggest a notable and statistically confirmed reduction in both green and open spaces following the construction of metro infrastructure. This indicates that the expansion of metro facilities, including stations, tracks, and associated developments, may have occurred at the cost of natural and undeveloped land. These two categories, therefore, represent the most robust evidence of metro-induced transformation in the urban landscape and warrant particular attention in the discussion of land use impacts.

Other categories, such as Institutional ($p = 0.054$), Transportation ($p = 0.079$), and Residential ($p = 0.087$) showed p-values marginally above the conventional significance threshold of 0.05. These results are considered "approaching significance" and suggest a trend toward change, but do not provide sufficient statistical evidence to conclusively assert a shift. While they hint at the possibility of emerging patterns influenced by metro development, such as re-zoning for residential or transport use, these trends remain tentative and should be interpreted with caution. All other land use types—including Commercial (p = 0.172), Administrative, Mixed, Waterbody, Industrial, and Others—recorded p-values well above 0.1, indicating no statistically significant change associated with metro construction. While these categories may have experienced physical changes, the lack of statistical significance implies that such shifts are either minimal or influenced by a broader range of urban dynamics unrelated to metro expansion.

Table 4. t-test Statistics and Inference of the Land use data.

Land Use Category	t-Statistic	p-Value	Inference
Green Space	−2.33	0.045	Statistically significant change (decrease in green space)
Commercial	−1.48	0.172	No statistically significant change
Institutional	−2.22	0.054	Approaching significance (potential decrease)
Mixed	−1.01	0.340	No statistically significant change
Administrative	−1.00	0.343	No statistically significant change
Transportation	−1.98	0.079	Approaching significance (potential decrease)
Residential	−1.92	0.087	Approaching significance (potential decrease)
Open Space	3.57	0.006	Statistically significant change (decrease in open spaces)
Others	−0.40	0.701	No statistically significant change
Waterbody	0.62	0.552	No statistically significant change
Industrial	−1.00	0.343	No statistically significant change

The paired t-test results demonstrate that the Delhi Metro's development has had a statistically significant impact, specifically on Green and Open Spaces, reflecting the trade-offs between infrastructure expansion and the reduction of environmental or vacant land. Other land use categories showed either non-significant or marginal changes, suggesting that metro development is only one of several forces influencing urban land use and should be studied in conjunction with factors such as population growth, government policy shifts, and real estate trends.

4. Conclusions

This study systematically examined the impact of metro infrastructure on urban land use patterns in Delhi by analyzing spatial transformations within a 500-meter buffer around ten strategically selected metro stations. The findings underscore the pivotal role that mass transit infrastructure plays in reshaping urban form and land allocation. Through paired sample t-tests, the study revealed statistically significant reductions in Green Space (t = –2.33, p = 0.045) and Open Space (t = 3.57, p = 0.006), highlighting the extent to which metro-related construction activities and associated developments encroach upon natural and undeveloped areas. Additionally, land use categories such as Institutional (p = 0.054), Transportation (p = 0.079), and Residential (p = 0.087) showed changes approaching significance, suggesting emerging trends likely influenced by improved accessibility and urban densification near transit corridors. In contrast, categories such as Commercial, Administrative, Mixed, Waterbody, and Industrial showed no statistically significant change, indicating either stability or that any transformations in these categories are influenced by broader urban dynamics beyond the metro system alone. The study reveals that the functional (e.g., administrative, commercial, residential) and locational (e.g., core city vs. peripheral) characteristics of metro stations are critical determinants of the type and extent of land use change. For instance, centrally located stations such as Rajiv Chowk and New Delhi, due to their high commuter volume and existing infrastructure, have reinforced their roles as commercial and transit hubs, with marginal land use change but sustained dominance in transportation and commercial functions. In contrast, stations like Dwarka Sector 21 and Janakpuri West, situated on the urban fringe, have experienced significant residential development, indicating a shift toward decentralised urban expansion and peri-urban growth. The stations, such as Central Secretariat, have demonstrated increases in institutional and green land uses, aligning with their administrative character and reflecting state-led spatial reorganisation. These findings support the idea that metro stations not only respond to existing urban functions but also help reinforce and reshape them, producing differentiated spatial outcomes based on their functional context.

The paired sample t-test analysis further confirms that among all land use categories, green space and open space witnessed statistically significant declines post-metro construction. These findings raise important concerns about ecological sustainability, as the reduction in vegetated and unbuilt areas may undermine the city's urban resilience and environmental quality. While other categories such as residential, institutional, and transportation land uses show trends of increasing change, these remain statistically non-significant or borderline, suggesting more nuanced or location-specific impacts that warrant further longitudinal studies.

From an urban ecology and sustainability perspective, the loss of green and open spaces illustrates a trade-off between infrastructure development and environmental stewardship. Such transformations may have implications for urban microclimates, biodiversity, and thermal comfort—elements central to sustainable urban living. Therefore, while the Delhi Metro has undeniably contributed to improved mobility and transit-oriented development, the accompanying land use shifts necessitate careful planning interventions to balance growth with ecological preservation.

The present study aligns closely with the findings of previous international and Indian research. Xuexin Yan et al observed that metro construction leads to significant land use transformation, particularly the conversion of non-construction land into construction land [11]. Similarly, this study found considerable reductions in open spaces across most stations, most notably at Dwarka Sector 21, Kalkaji Mandir, and Central Secretariat- replaced by green, residential, or transport infrastructure. The increased transportation-related land use in areas such as New Delhi and Kashmere Gate resonates with the assertion by Roukouni et al that metro infrastructure improves accessibility and alters surrounding trip characteristics [10]. The study also confirms the findings from the Chennai case [21], which documented a rise in commercial activities near metro corridors, as seen in stations like Netaji Subhash Place and Janakpuri West [21]. The predictive modeling by Fu et al. emphasizes that point of interest (POI) density and station accessibility play vital roles in shaping urban land use, paralleling this study's observation of green space increases near culturally and infrastructurally significant locations [20]. Overall, these comparisons reinforce the broader conclusion that metro development in urban centers catalyzes land use shifts toward more structured, accessible, and commercially viable environments, with spatial outcomes varying according to the surrounding urban morphology and pre-existing infrastructure.

Nevertheless, the research is not without limitations. The analysis was based on only two temporal points—before and after metro construction—without capturing continuous change over time, which limits the ability to understand the full trajectory of urban transformation. The attribution of land use change solely to metro development is also constrained by the presence of other urban drivers such as housing demand, planning regulations, and economic activities. The manual digitisation of land use features, although carefully executed, is inherently subjective and may introduce classification inconsistencies. Future research can address these gaps by incorporating time-series satellite data to examine the rate and progression of land use change over different phases of metro development. Adopting automated classification methods and machine learning tools can enhance accuracy and reduce observer bias in spatial data analysis. Further, integrating socio-economic variables—such as land value appreciation, population density, and employment clustering—can offer a more comprehensive understanding of the socio-spatial outcomes of metro expansion. Comparative studies with other Indian or global cities experiencing similar transit-driven growth could help generalise findings and inform policy at broader scales.

In conclusion, this research demonstrates that metro infrastructure in Delhi serves as a key driver of land use transformation, particularly through the conversion of green and open spaces into built environments. These findings call for integrated urban planning approaches that align transport infrastructure development with ecological conservation and inclusive urban design. A deliberate emphasis on spatial equity, sustainable development, and environmental stewardship in future metro expansions can help build more resilient, connected, and livable cities.

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Institutional Review Board Statement

This study did not involve direct interaction with human subjects. It relied on secondary data and observational methods, including ridership statistics and spatial analysis, which do not require informed consent or ethical review from an Institutional Review Board.

Informed Consent Statement

As this study did not involve direct interaction with human participants, informed consent was not required.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request. Ridership data was sourced from the Delhi Metro Rail Corporation (DMRC), and land use data was derived from publicly available satellite imagery.

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Conflict of Interest

The author declares that they have no conflicts of interest regarding the publication of the paper.

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