An AHP-GIS Based Approach for Optimal Metro Route Planning in Tiruchirapalli City, Tamilnadu

Suvish S
Department of Remote Sensing, Bharathidasan University, Tiruchirapalli
Email: suvisraina@gmail.com

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Abstract: This study identifies optimal metro network locations in Tiruchirapalli city to address current and future transportation challenges. The research leverages Remote Sensing, Geographic Information System (GIS), and the Analytical Hierarchical Process (AHP) to assess and prioritize key factors influencing site selection. Criteria such as population density, traffic hubs, intersections, existing road networks, land use, and slope maps are systematically analyzed. Each factor is ranked based on its importance and weighted using AHP. A GIS-based weighted overlay method integrates these ranked criteria to identify potential routes for the metro system. The study proposes five routes spanning southwest-north and east-west directions, connecting critical origin and destination stations. The findings provide a strategic framework for sustainable urban transportation planning in Tiruchirapalli, ensuring efficient connectivity while addressing the city's evolving transit demands.

Keywords: Metro network planning, Geographic Information System (GIS), Analytical Hierarchical Process (AHP), Transportation site selection

1. Introduction

Urbanization and population growth have placed immense pressure on transportation systems worldwide, necessitating innovative and sustainable solutions. Tiruchirapalli, a rapidly expanding city in Tamil Nadu, India, is facing similar challenges due to increasing traffic congestion and the strain on existing infrastructure. As a result, exploring efficient urban transit systems, such as metro networks, has become crucial to meet current and future transportation demands while supporting the city's socio-economic development (Singh & Verma, 2022).

Metro networks have demonstrated their effectiveness globally by reducing traffic congestion, minimizing environmental pollution, and improving urban connectivity. Drawing inspiration from these successes, this study investigates the feasibility of implementing a metro system in Tiruchirapalli. Employing advanced methodologies, including Remote Sensing, Geographic Information System (GIS), and Analytical Hierarchical Process (AHP), the research aims to identify optimal metro routes by analyzing critical factors such as population density, traffic hubs, land use patterns, and existing road infrastructure (Das & Sharma, 2021; Kumar et al., 2020).

The introduction of a metro network in Tiruchirapalli promises transformative benefits, including enhanced mobility, reduced reliance on private vehicles, and increased accessibility to key urban areas (World Bank, 2020). Moreover, it can serve as a catalyst for sustainable urban development, fostering economic growth and improving the overall quality of life for residents (Reddy, 2021). This study not only addresses the city's current transportation challenges but also ensures adaptability to future urban expansion by identifying routes that align with projected population growth (Mehta & Iyer, 2019).

In essence, this research contributes to urban transportation planning by offering data-driven insights into the design of a metro network tailored to Tiruchirapalli's unique needs. The findings aim to guide policymakers and urban planners in creating a robust, sustainable, and inclusive transit solution for the city.

2. Study Area

The Tiruchirappalli Metro Route Selection Study offers critical insights into the city's geographical and climatic features. Covering an area of 157.92 square kilometers and comprising 65 wards, the city is geographically positioned between 10°40′N to 10°56′N latitude and 78°36′E to 78°47′E longitude (Figure 1). Tiruchirappalli, located at the heart of Tamil Nadu, is celebrated for its cultural and historical heritage. A Google Satellite Image was used as the basemap for digitizing and analyzing the metro route selection, ensuring accurate spatial representation. According to the Census 2011, the city had a population of 847,387, with growth rates projected to range between 1.39% and 2.16% for the period from 2019 to 2030. Addressing increasing transportation demands and traffic congestion remains vital for improving urban mobility and fostering sustainable urban development.

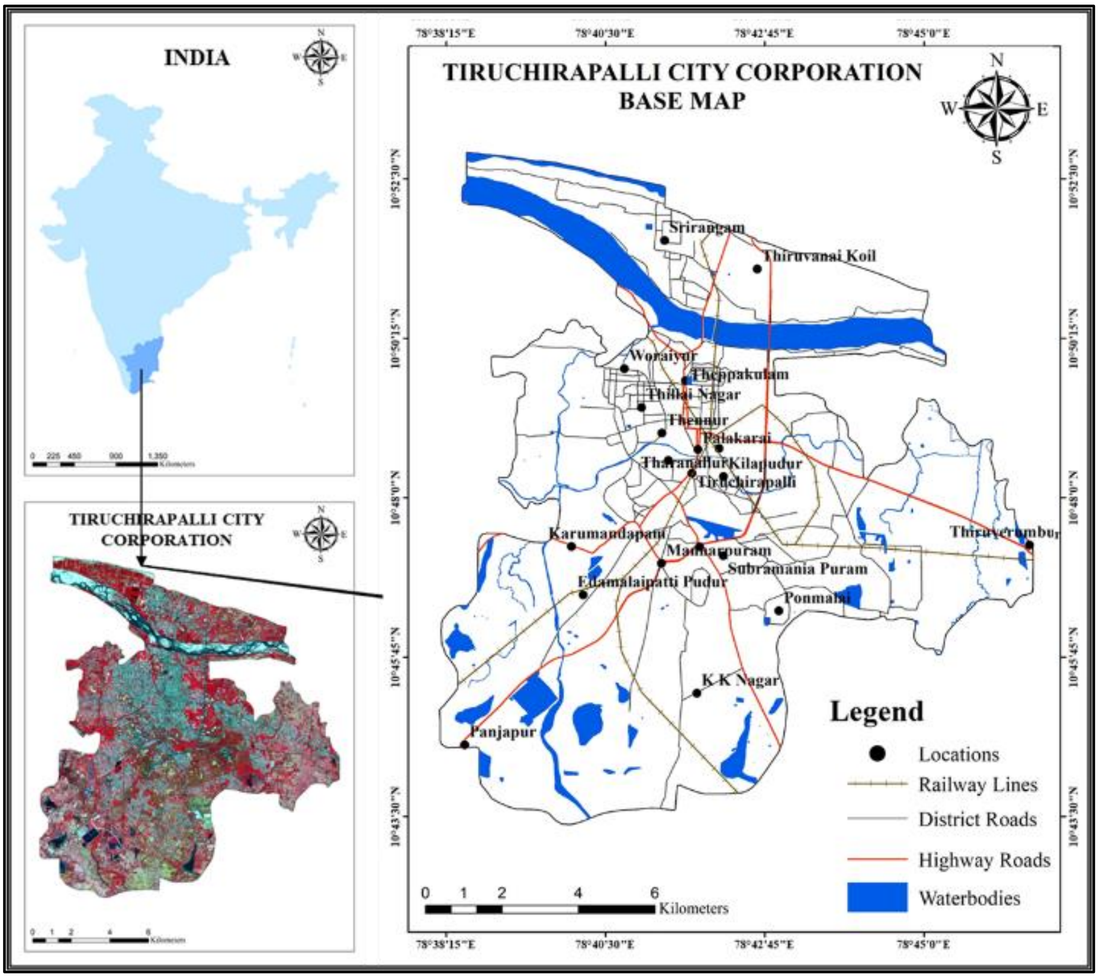

Figure 1. Study Area Map

3. Materials and Methods

The study utilized multiple datasets from various sources to ensure comprehensive spatial analysis for optimal route selection (Figure 2). Population density data was extracted from the 2011 Census Handbook (Census of India, 2011), which served as the basis for generating a population density map. Land Use/Land Cover (LULC) information was derived from Sentinel-2A satellite imagery through supervised classification techniques in GIS software. Additionally, terrain slope analysis was conducted using the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) data, which was processed with spatial analyst tools.

For proximity analysis, Google Street Map data was utilized to identify important locations, such as educational institutions, hospitals, banks, commercial hubs, railways, roads, and traffic-congested areas. Proximity zones were created using buffer distances classified into thresholds (<250 m, 250–500 m, 500–750 m, 750–1000 m, and >1000 m) to understand spatial accessibility patterns.

A weighted overlay analysis was performed to integrate multiple factors, including population density, proximity to key locations, LULC, slope, and traffic conditions. Weights were assigned to each parameter using the Analytic Hierarchy Process (AHP), and normalization ensured consistency in the decision-making process (Saaty, 1980). The resulting output identified optimal routes that minimize travel distance while maximizing accessibility to critical services, providing valuable insights for urban planning and development.

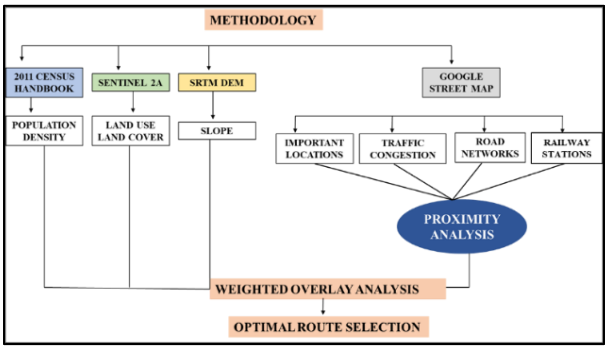

Figure 2. Methodology Flow Chart

4. Result and Discussion

4.1 Population Density

Population density for Tiruchirappalli City was calculated using data from the Census 2011 Handbook, where the total population of each ward was divided by its respective area (Figure 3). This analysis was conducted in ArcGIS, utilizing ward boundaries as the spatial framework. The calculated values were then categorized into four distinct groups: low density (<5000 people/km²), moderate-low density (5000–10,000 people/km²), moderate-high density

(10,000–15,000 people/km²), and high density (>15,000 people/km²). These density categories were visualized through a choropleth map, with darker shades representing high-density zones, primarily in central urban areas, and lighter shades depicting low-density regions in the outskirts.

This spatial representation highlights areas with varying levels of transit demand, offering valuable insights for prioritizing metro route planning and optimizing resource allocation in the city.

4.2 Important Locations/ Important Locations Proximity Map

Key locations in Tiruchirappalli, including the airport, bus stops, railway stations, schools, hospitals, commercial hubs, hotels, banks, and religious sites, were mapped (Figure 4a).

A buffer analysis was conducted, dividing the proximity into five categories: less than 250 meters, 250–500 meters, 500–750 meters, 750–1000 meters, and over 1000 meters (Figure 4b). This analysis provides valuable insights into spatial accessibility patterns and identifies areas with high foot traffic,particularly within 250 meters of bus stops.

4.3. Traffic Congestion/ Traffic Congestion Proximity Map

Traffic congestion hotspots were identified and visualized, focusing on critical road intersections and traffic signals (Figure 5a).

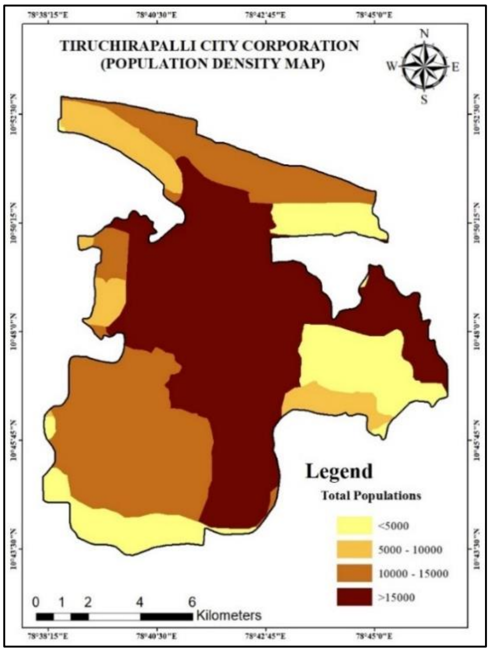

Figure 3. Population Density Map

A buffer zone analysis was performed, categorizing distances into defined ranges (<250m, 250–500m, 500–750m, 750–1000m, and >1000m) to analyze spatial patterns and proximity to congestion-prone areas (Figure 5b). The study indicates that regions within 250 meters of significant intersections are likely to face heavy traffic during peak hours. These insights can support transportation planning by guiding infrastructure improvements, implementing traffic management measures, and prioritizing resource distribution.

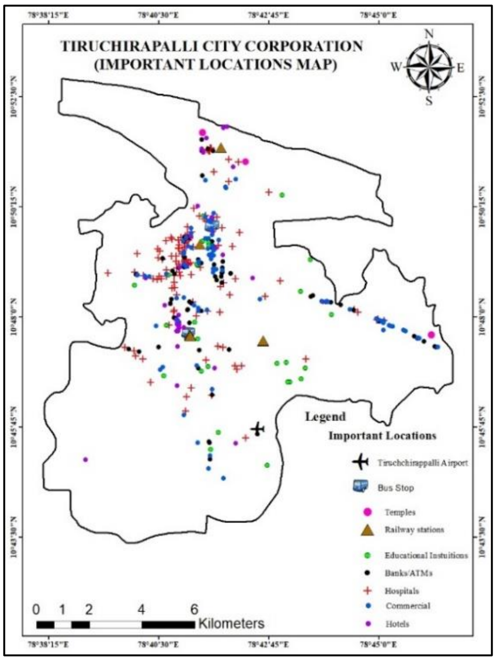

Figure 4a. Important Locations Map

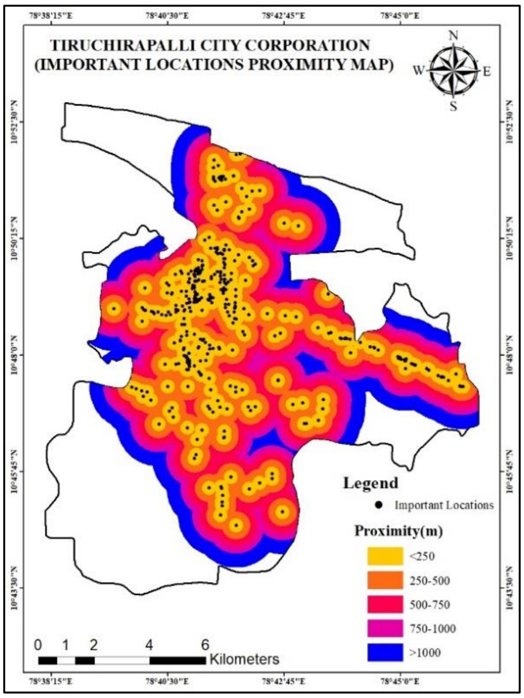

Figure 4b. Important Locations Proximity Map

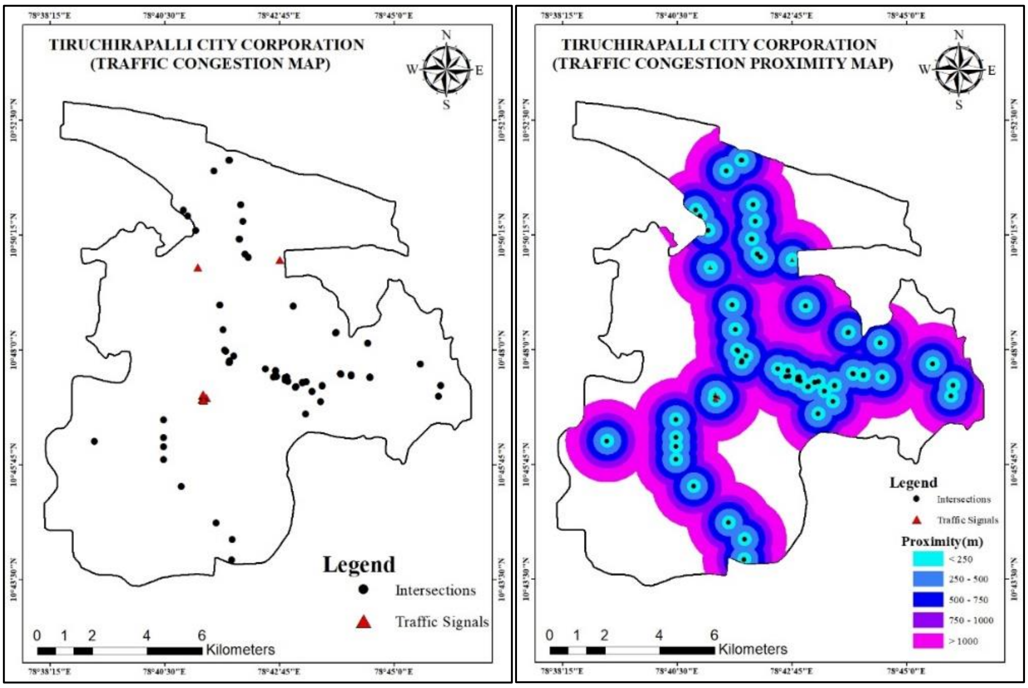

Figure 5a. Traffic Congestion Map, b. Traffic Congestion Proximity Map

4.4. Railway Stations/ Railway Stations Proximity Map
The railway station locations and network were spatially represented using vector layers (Figure 6a).

To assess accessibility, a proximity analysis was conducted around railway stations, categorizing distances into five buffer zones: <100m, 100–250m, 250–350m, 350–450m, and 450–500m (Figure 6b). These proximity zones highlight areas with varying levels of commuter influence, with regions within 250 meters experiencing higher commuter activity. This approach provides a precise evaluation of station-based accessibility, aiding in metro route planning and urban mobility assessments.

4.3. Road Networks/ Road Networks Proximity Map
Road networks, including highways and major roads, were analyzed and mapped to capture their spatial distribution across the city (Figure 7a).

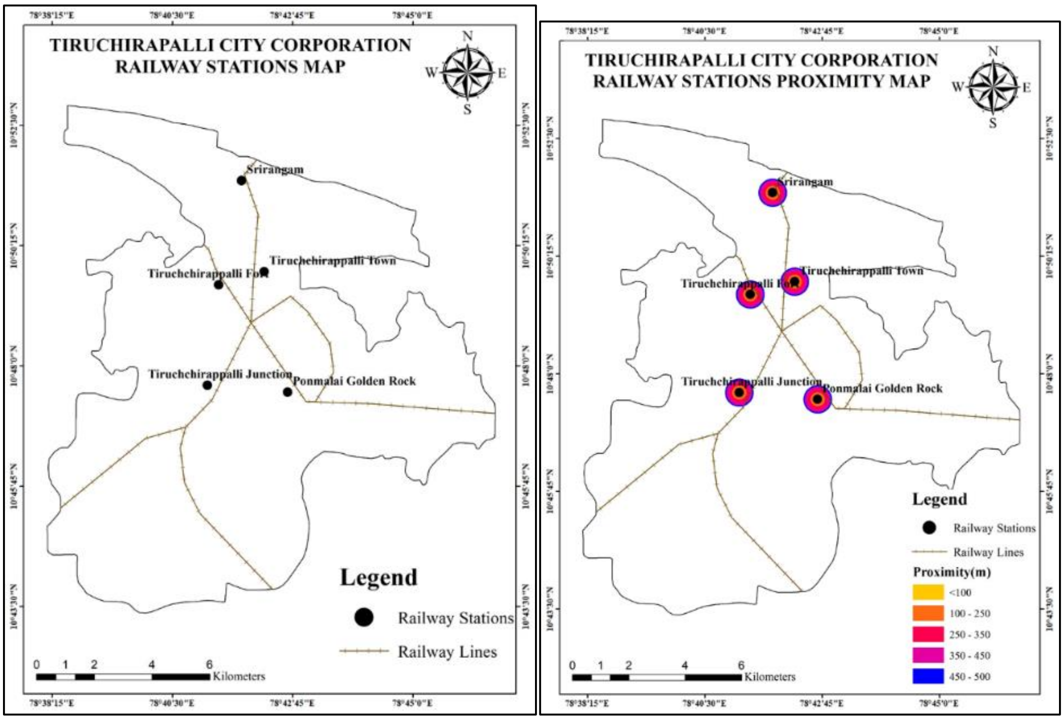

Figure 6a. Railway Stations Map, 6b. Railway Stations Proximity Map

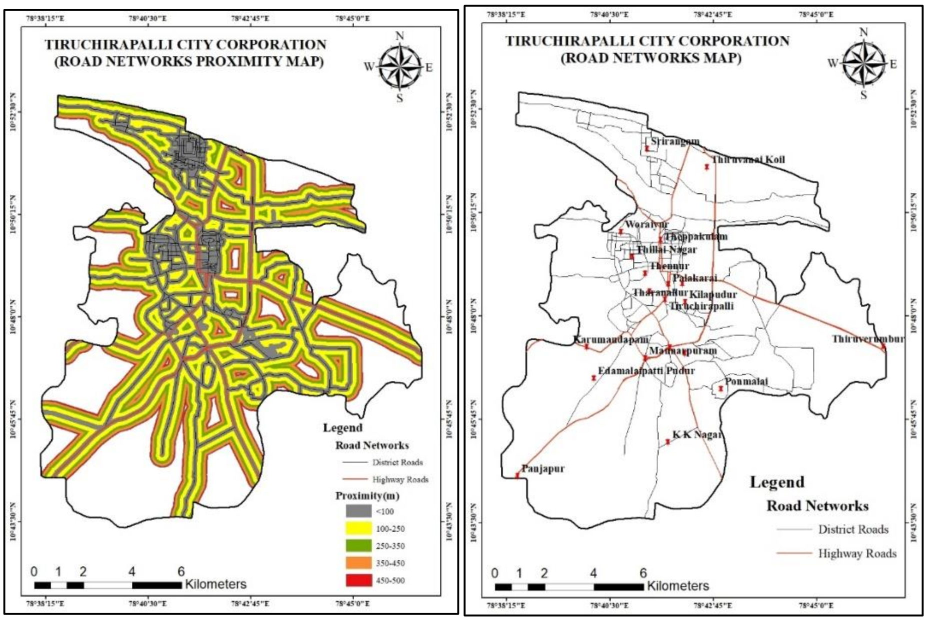

Figure 7a. Road Network Map, 7b. Road Network Proximity Map

A proximity map was also created to evaluate the interaction between road networks and nearby amenities such as schools, hospitals, commercial zones, and residential areas. Buffer zones were delineated at specific distances (<100m, 100–250m, 250–350m, 350–450m, and 450–500m) to assess the impact of road infrastructure on surrounding locations (Figure 7b).

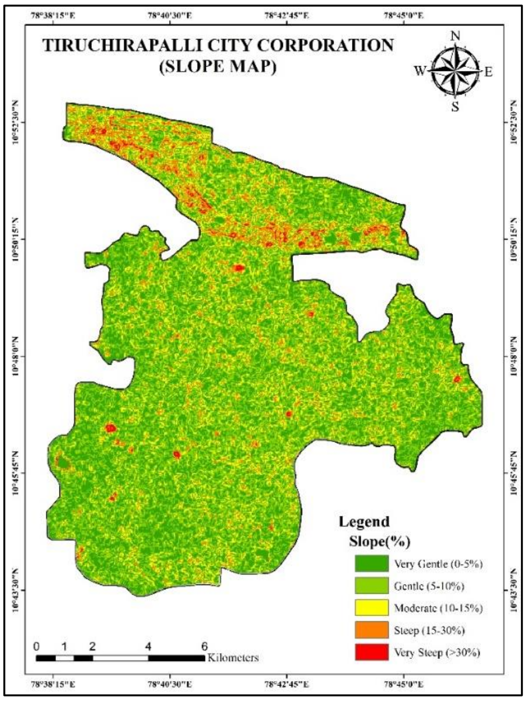

Figure 8. Slope Map

4.4. Slope Map

Slope is a crucial factor in determining the optimal route for metro train networks, as it significantly impacts construction feasibility, operational efficiency, and cost. A slope map of the study area was prepared using SRTM DEM data, where slope is defined as "the maximum rate of change in elevation between a cell and its neighbors" (Burrough, 1986) (Figure 8). Based on the slope, the study area was classified into five categories. Regions with a slope of 0–5% are categorized as "very good" for metro route alignment due to their flat terrain, minimizing construction complexity and cost.

Areas with a slope of 5–10% are considered "good" as they feature slightly undulating terrain, which can still accommodate metro routes with minor adjustments. Zones with a slope of 10–15% are classified as "moderate," where careful planning and engineering interventions are required to ensure stability and efficiency. Slopes between 15–30% are categorized as "poor" due to steep gradients that increase construction challenges and costs. Finally, areas with slopes exceeding 30% are classified as "very poor" and are unsuitable for metro route development because of the significant technical and financial constraints associated with such steep terrains. This slope-based analysis is integral to designing an efficient and cost-effective metro train network that prioritizes safety, sustainability, and feasibility.

4.3. Land Use/ Land Cover Map

The land use/land cover (LULC) map, derived from Sentinel-2A multi-spectral imagery, provides critical insights for determining optimal metro train routes. A supervised classification method, based on the Level-2 NRSC classification system (NRSC, 2011), was applied to categorize the land use patterns into built-up areas, cropland, current fallow land, land with scrub, land without scrub, dense vegetation, and waterbodies (Figure 9). Understanding LULC is essential for metro route alignment, as it aids in identifying suitable corridors that minimize environmental disruption, reduce construction costs, and avoid ecologically sensitive zones.

The Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a widely recognized decision-making framework that is effective for addressing multi-criteria decision-making challenges.

Developed by Professor Thomas L. Saaty in the 1970s, AHP simplifies complex problems by structuring them into a hierarchical model and comparing the significance of criteria in pairs (Saaty, 2005) (Table 1).

Table 1. Saaty's Pairwise Comparison Matrix

Intensity of importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or Slight	
3	Moderate Importance	Experience and judgment slightly favour one activity over another
4	Moderate Plus	
5	Strong Importance	Experience and judgment strongly favour one activity over another
6	Strong Plus	
7	Very Strong	An activity is favoured very strongly over another
8	Very, very Strong	
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation

The process begins by decomposing the problem into a hierarchy that outlines the key parameters or criteria relevant to the study objective. These criteria are then evaluated against each other using a pairwise comparison matrix (Pij), which quantifies their relative importance. The comparison relies on a standardized scale (Saaty, 1977; Saaty & Vargas, 1991), ranging from 1 to 9 to express the intensity of preference between criteria. The matrix columns are summed, and scale weights (SW) are determined.

A normalized pairwise matrix is generated by dividing each matrix element by its respective scale weight. Subsequently, row averages are computed to derive the geometric mean (GM). To ensure consistency in the matrix, the consistency ratio (CR) is calculated using the formula:

$$\mathbf{CR} = \mathbf{CI} / \mathbf{RI} \; (< \mathbf{0.1}) \qquad (1)$$

Here, CI refers to the consistency index, and RI denotes the random inconsistency index.If CR exceeds 0.1, the decision-making process requires reassessment to ensure the matrix's reliability. To compute the CI, the maximum eigenvalue (λmax) of the pairwise matrix is determined using the formula:

$$\mathbf{CI} = (\boldsymbol{\lambda}\mathbf{max} - \mathbf{n})/\mathbf{n} - \mathbf{1} \qquad (2)$$

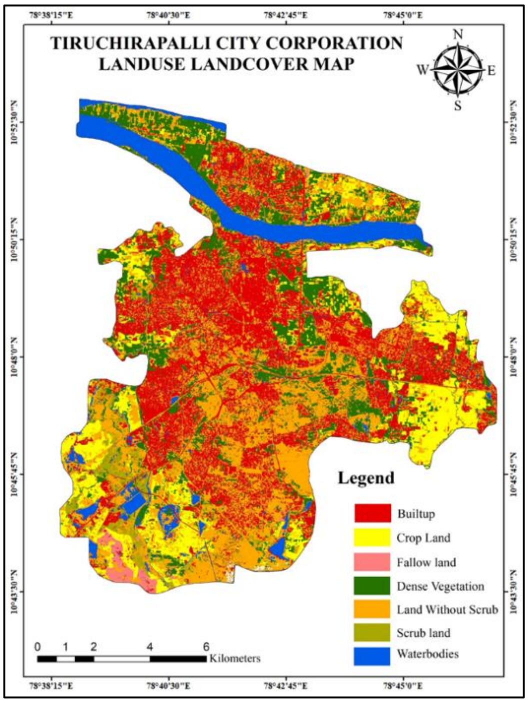

Figure 9. LULC MAP

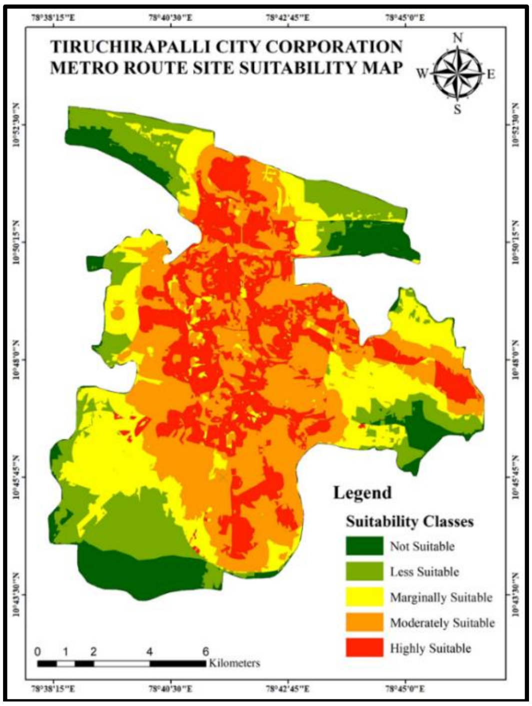

Figure 10. Metro Route Suitability Map

where λmax represents the largest eigenvalue of the matrix and nnn is the number of criteria. By verifying the CR value, the consistency of decisions is ensured, and the matrix becomes acceptable for further analysis. This rigorous process guarantees the reliability of the decisions made.

Evaluation of Multi-Criteria for Optimal Metro Route Selection

The evaluation of optimal metro routes for Tiruchirapalli city involved a detailed analysis using a combination of the Analytical Hierarchy Process (AHP) and geospatial technology. This approach enabled a comprehensive and data-driven assessment of various critical parameters (table 2). Population density was a key factor, with higher-density areas prioritized to maximize accessibility and cater to a larger commuter base. The study also considered key locations such as government offices, educational institutions, hospitals, markets, and industrial hubs, ensuring the metro system would connect vital areas of economic and social significance.

Traffic congestion zones were carefully analyzed to incorporate heavily congested areas into the network, aiming to alleviate road traffic and reduce travel times. Proximity to existing railways and road networks was another important parameter, facilitating smooth intermodal connectivity and improving transportation efficiency. Terrain analysis, particularly slope, was conducted to avoid steep gradients that could complicate construction and increase operational costs. Additionally, land use and land cover (LULC) were evaluated to ensure environmentally sustainable and technically feasible routes. These parameters (Table 3) were integrated into the GIS environment, where the final classification categorized the city into five suitability levels: not suitable, less suitable, marginally suitable, moderately suitable, and highly suitable. This multi-criteria evaluation provided a structured, objective, and efficient methodology for identifying optimal metro routes, ensuring the proposed system meets the city's current and future needs.

5. Conclusions

This GIS-based analysis for metro route planning in Tiruchirapalli city has demonstrated the potential of integrating spatial technologies for strategic transportation planning.

By assessing factors such as population distribution, traffic patterns, road and railway networks, and urban growth trends, the study identified optimal routes for the proposed metro system. The utilization of GIS tools enabled precise and efficient decision-making, paving the way for sustainable and effective urban infrastructure development.

The proposed metro routes (Figure 10-11) are anticipated to improve urban connectivity, alleviate traffic congestion, and foster sustainable growth in Tiruchirapalli.

Table 2. Pairwise Comparison Matrix

Parameters	Population Density	Important location	Traffic Congestion	Railway Stations	Road Networks	LULC	Slope
Population	1	2	3	4	5	6	7
Important location	0.5	1	2	3	4	5	6
Traffic	0.33	0.5	1	2	3	4	5
Railway Stations	0.25	0.33	0.5	1	2	3	4
Road	0.2	0.25	0.33	0.5	1	2	3
LULC	0.17	0.2	0.25	0.33	0.5	1	2
Slope	0.14	0.17	0.2	0.25	0.33	0.5	1

Table 3. Normalized Pairwise Comparison Matrix

Parameters	Population Density	Important location	Traffic Congestion	Railway Stations	Road Networks	LULC	Slope	Criteria Weights
Population	0.39	0.45	0.41	0.36	0.32	0.28	0.25	0.35
Important location	0.19	0.22	0.27	0.27	0.25	0.23	0.21	0.24
Traffic	0.13	0.11	0.14	0.18	0.19	0.19	0.18	0.16
Railway	0.10	0.07	0.07	0.09	0.13	0.14	0.14	0.11
Road	0.08	0.06	0.05	0.05	0.06	0.09	0.11	0.07
LULC	0.07	0.04	0.03	0.03	0.03	0.05	0.07	0.05
Slope	0.05	0.04	0.03	0.02	0.02	0.02	0.04	0.03

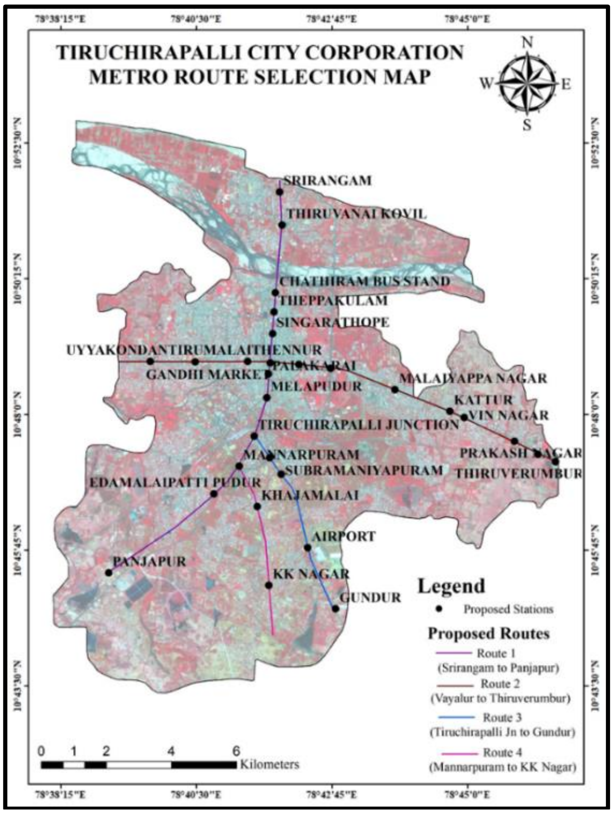

Figure 11. Metro Route Selection Map

This research underscores the critical role of advanced geospatial analysis in modern urban planning, ensuring that infrastructure projects are aligned with the city's evolving needs. The successful implementation of these recommendations will enhance transportation access, elevate the quality of life for residents, and position Tiruchirapalli as a model for progressive urban development.

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