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GIS-Based Assessment of Digital Connectivity in Nandurbar District, Maharashtra: A Spatial Analysis of Cellular Tower Distribution and Population

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Abstract

This research uses GIS tools to determine the spatial distribution of digital connectivity infrastructure in Nandurbar district, Maharashtra. It analyzes the location of cellular towers in relation to various demographic and geographic characteristics of the population across six tehsils. The research utilizes secondary data and analyzes 606 cellular towers located by the DoT, census data at the village level, administrative and SRTM-DEM data at 30 meters. The author uses various methods to analyze the data, including spatial analysis, calculating tower density, evaluating village level coverage, and using both Pearson and Spearman's correlation. The author finds significant spatial variation in cellular infrastructure. Tower densities for Nandurbar and Shahada tehsils are 15.73 and 15.23 towers per 100 square kilometers, respectively, while Akarani has a tower density of 2.47 towers per 100 square kilometers. Overall, the estimated coverage encompasses 63.74 percent of the study area, and 118 villages are estimated to have no coverage. There is a positive correlation between the population and location of cellular towers (Spearman's ρ = 0.487). The research identifies gaps in digital connectivity and the need to build digital connectivity infrastructure to the most remote areas of India including tribal areas.

Keywords: *Digital Connectivity, Cellular Towers, Geographic Information System, Cellular Coverage*

Introduction

Digital connectivity has become essential for social and economic development, facilitating communication, education, healthcare, and businesses, as well as other activities (Ajani, 2025). Improving digital connectivity in urban and rural areas requires a robust mobile telecommunication infrastructure (Lenormand, 2023). In particular, mobile phone (cellular) towers are essential for coverage. However, the distribution of telecommunication infrastructure is not always even and can vary because of differences in the natural and built environment (Wu et al., 2021). Geographical Information Systems (GIS) and remote sensing technologies are valuable tools for analyzing the spatial relationships of different digital infrastructures and populations. Analysis of data, such as the location of cell phone towers, the population, elevation, and slope of an area, can assist in identifying areas with a difference in digital infrastructure (Ishii et al., 2026).

GIS-based spatial analysis is advancing the planning of digital connectivity infrastructure in the Nandurbar district of Maharashtra by revealing critical geographical and demographic insights. First, geospatial mapping provides detailed information on district-level population, density, and existing infrastructure, which helps identify areas that are underserved and require improvement in connectivity. This is further complemented by spatial analysis techniques that provide insights on the relationships between the elements of the terrain and the population and help analyze the optimal placement of the infrastructure (Greenough & Nelson, 2019). Assessing the digital divide with GIS helps determine the location with the least access to digital services and further informs where to prioritize planning of digital infrastructure. Further, the analysis of the terrain along with the demand for digital infrastructure helps select the appropriate digital infrastructure and the most suitable routes that reduce environmental impact and increase service coverage and quality (Kaharu et al., 2024).

GIS-based spatial analysis helps identify optimal routes for locating digital connectivity infrastructure (Dagodzo & Patrick, 2021). Further, GIS data and its analysis help determine the feasibility of a project by assessing the potential benefits and development costs. This is critical for funding (Akmal, 2023). Finally, GIS helps address data representation concerns of the community by fostering community participation to allay fears and concerns regarding proposed digital infrastructure. Integrating GIS-based spatial analysis in planning processes is expected to result in the strategic placement of digital connectivity infrastructure in the Nandurbar District that is responsive to the needs of the populace in an environmentally friendly manner.

The GIS-based assessment of digital connectivity in Nandurbar District, Maharashtra, involves the spatial analysis of cell towers with respect to population density and settlements.

Nandurbar district, which includes various tribal communities, has demographic variations among its tehsils. Shahada and Nandurbar tehsils show better population densities and better infrastructure. Areas such as Akkalkuwa and Akrani have stagnation and emigration due to hilly terrain. They lack access to essential services (Torawane, 2025). The spatial distribution of settlements in Nandurbar shows several areas with lack of access and isolation. Digital connectivity will have limited use in such areas (Hange & Hange, 2021). GIS and spatial mining can optimally locate cell towers by considering changes in the elevation of terrain, population, and restricted areas, as shown in different studies (Chakali et al., 2024; Al-Hamami & Hashem, 2011). A digital elevation model (DEM) can be used to prioritize the location of cell towers to ensure that the entire area is covered and to reduce the number of towers required (Al-Hamami & Hashem, 2011; Al-Hamami & Hashem, 2011b). Using a GIS-based multi-criteria analysis (MCA), areas that are best suited to install cellular coverage can be identified to provide cellular coverage in currently underserved areas (Chakali et al., 2024). As indicated by the current cell tower placement, the growing population and urban expansion is not anticipated in the planning of cellular infrastructure (Ghani, 2026). Therefore, the use of GIS can be pivotal in developing digital connectivity in Nandurbar District, where demographic and geographical constraints are often not in alignment (Muralikrishnan et al., 2007).

Nandurbar district, in north-western Maharashtra, India, lies between 20°59′45″ and 22°01′47″ North latitudes and 73°34′33″ and 74°46′16″ East longitudes. It borders Gujarat, Madhya Pradesh, and Maharashtra's Dhule district and includes six tehsils: Nandurbar, Shahada, Taloda, Navapur, Akkalkuwa, and Akrani (Dhadgaon). Its physiographic regions include the Satpura hills, undulating plateaus, valleys, and river plains, influencing population distribution, settlement, and infrastructure. Its dense rural settlements make it a good case study for analyzing the relationship between settlement and mobile communication infrastructure.

Nandurbar district, with diverse physiographic regions, settlement types, and population densities, faces varied rural and urban digital divide challenges, making it a case study of such divides within a geographic area. This study examines the spatial distribution of mobile communication infrastructure in Nandurbar district and the relationship between tower placement, elevation, and slope. Spatial variations in digital infrastructure and cell towers will identify connectivity disparities and foster improvements in underserved areas.

The main aim of the present study is to assess the spatial distribution of digital connectivity infrastructure in Nandurbar District, Maharashtra, using GIS techniques, with particular emphasis on cell tower distribution, population characteristics, and physiographic conditions.

Objectives

1. To examine the spatial distribution and concentration of cellular towers across Nandurbar District
2. To analyze the relationship between population and cellular tower distribution.
3. To identify spatial variations in digital infrastructure availability among the six tehsils of the district.
4. To identify areas with relatively low and high cellular tower density for improved digital infrastructure planning

Database and Methodology

Database

This study uses secondary spatial and demographic data collected from various sources. Data on the location of cellular towers was obtained from the Department of Telecommunications (DoT), Government of India. To study the spatial distribution of cellular infrastructures, data on district, tehsil and village boundaries was used. Village-level population data was obtained from census of India. Elevation data was obtained from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 30-metre spatial resolution. Village level cover and use data was used to assess population accessibility and estimated cellular coverage.

Table 1. Database and Sources of Data

Database	Data source
Cellular tower locations	Department of Telecommunications (DoT)
District, tehsil and village boundaries	Administrative GIS database
Village-level population	Census of India
Elevation data	SRTM DEM (30 m)
Cellular coverage information	GIS-based coverage analysis
Road network (if used)	OpenStreetMap / GIS database

Methodology

This study applies an integrated GIS method to analyze the spatial distribution of cellular towers and digital connectivity in Nandurbar District. The base point data of cellular towers and administrative boundaries were first projected to a common coordinate reference system. Spatial Join and Point-in-Polygon analysis were performed to compute the distribution of towers in tehsils and villages respectively. Tower density was defined as the number of towers in a given geographical area of a tehsil. Using QGIS based spatial analysis, coverage of cellular towers was estimated and the areas without or limited coverage were identified. To understand the relationship between elevation and distribution of cellular towers, SRTM DEM was used. Population data at the village level were integrated to understand the population coverage of cellular towers and estimated coverage. Lastly, Pearson and Spearman correlation and rank coefficients were computed to analyze the relationship between the population distribution, availability of cellular towers and estimated coverage. Thematic maps and statistics were created to show gaps and underserved areas.

Results and Discussion

Spatial Distribution of Cellular Towers

There are large variations in digital infrastructure between the six tehsils in Nandurbar District, as shown by the spatial distribution of cellular towers. In total, 606 cellular tower locations were found within the district. The database for the towers has two categories: ground-based and roof-based towers. The distribution shows that 425 (70.13%) ground-based towers were located within the district, and 181 (29.87%) roof-based towers were located within the district. Thus, ground-based towers constitute the major component of cellular communication infrastructure in the district.

Table 2. Category-wise Distribution of Cellular Towers

Tower category	Number	Percentage
Ground tower	425	70.13
Roof tower	181	29.87
Total	606	100.00

(Source: Analysis of cellular tower locations.)

The distribution map (Fig.1) shows cellular infrastructure is largely uneven in the Nandurbar district. Cell towers are found mainly in the central and southern settlements, especially in and around Nandurbar and Shahada. The northern and northwestern parts of the district show dispersed locations of cell towers, except for the hilly and inaccessible areas. The observation suggests that the distribution of cellular infrastructure is largely dependent on settlements and accessibility, combined with the population and physiographic factors.

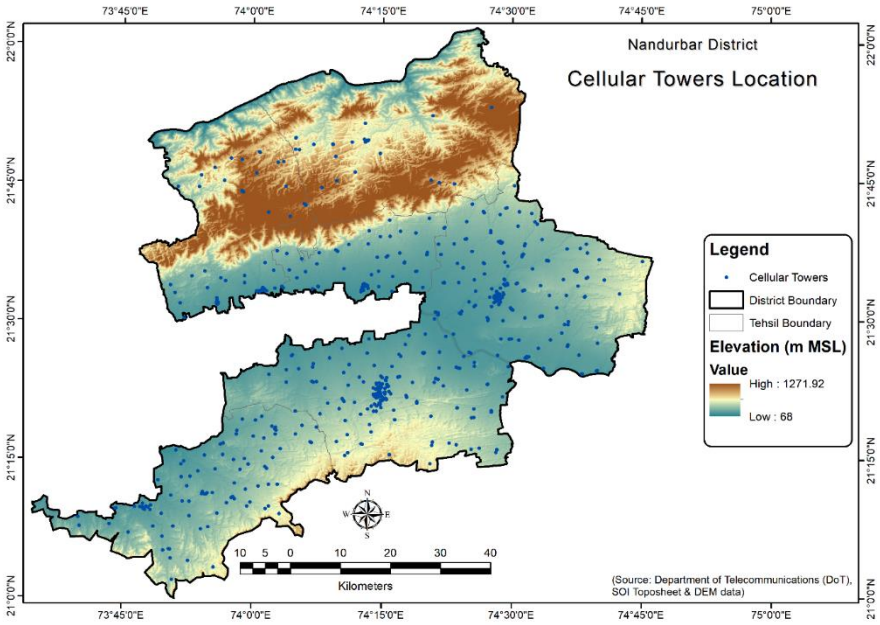

Figure 1 Spatial Distribution of Cellular Towers in Nandurbar District, Maharashtra.

Tehsil-wise Distribution and Density of Cellular Towers

Inequalities in cellular infrastructure vary from tehsil to tehsil. Shahada Tehsil has the highest (180) towers, followed by Nandurbar Tehsil (179); together they make up 59.24% of the total towers in the district. Navapur has 99 towers followed by Taloda (62) and Akkalkuwa (54). Akarani has the least, with 32 towers. The number of towers does not show us the spatial distribution. To better understand distribution, I had to calculate the density with respect to the area of each tehsil.

Table 3. Tehsil-wise Distribution and Density of Cellular Towers

Tehsil	Area (km²)	Towers	Tower density per 100 km²
Akkalkuwa	930.56	54	5.80
Akarani	1,295.04	32	2.47
Nandurbar	1,137.88	179	15.73
Navapur	952.19	99	10.40
Shahada	1,181.64	180	15.23
Taloda	454.59	62	13.64
Total	5,951.90	606	10.18*

(*Overall district density is 10.18 towers per 100 km²; the total row is not an arithmetic sum of tehsil densities.)

(Source: Calculated from cellular tower point and tehsil boundary data.)

There is a lot of variation in cellular tower density across the district. Nandurbar Tehsil has the highest tower density, at 15.73 towers in 100 km², followed by Shahada at 15.23 and Taloda at 13.64. Akarani has the lowest tower density at 2.47, followed by Akkalkuwa at 5.80. Nandurbar's tower density is approximately 6.37 times that of Akarani.

This study shows the cellular infrastructure is focused in select geographic regions of the district and not according to the overall geographic requirements of the district. The low tower density in Akarani and Akkalkuwa illustrate the need for additional cellular infrastructure in the northern and north-western regions of Nandurbar district.

Spatial Pattern of Cellular Tower Frequency

The cell tower frequency map (Fig. 2) represents communication infrastructure by density classes. The map shows that the bulk of the districts is assigned to the lowest density class, and the higher density classes are shown in more localized areas. The mapped tower frequency classes are as follows:

Table 4 The cell tower frequency

Class	Tower frequency (towers/km²)
Very low	0–1
Low	1–2
Moderate	2–3
High	3–4
Very high	4–14

The map shows localized high-density clusters around major settlements. The concentration of towers around Nandurbar and Shahada shows an urban settlement pattern, with higher density communication infrastructure near urban settlements and a dispersed pattern in the surrounding rural settlements. This may reflect difference in accessibility of communication infrastructure and services between urban and rural settlements. The mapped tower-frequency surface is not consistent with the administrative tower-density calculations in Table 4, which assess towers in relation to each Tehsil's area.

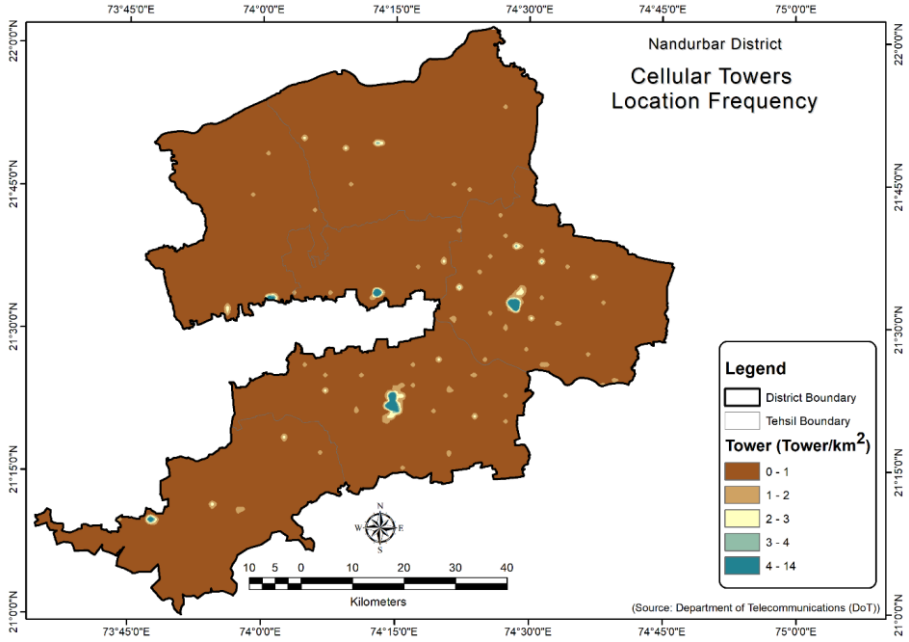

Figure 2 Spatial Pattern of Cellular Tower Frequency in Nandurbar District.

Spatial Distribution of Cellular Tower Coverage Area

A village-level dataset on cellular coverage was used to conduct an analysis on coverage. The dataset comprises of the total DEM pixels, visible pixels, estimated coverage area, and population related attributes.

Table 5. Overall Cellular Tower Coverage Statistics

Parameter	Calculated value
Total DEM pixels	797,862
Visible pixels	508,558
Non-visible pixels	289,304
Estimated coverage area (km²)	3,790.64
Overall pixel-weighted coverage (%)	63.74
Non-visible pixel percentage (%)	36.26

(Source: Analysis of tower coverage and village coverage database)

Results show that around 63.74% of the spatial pixels analyzed, fall within the estimated coverage area, and 36.26% lie outside the modeled coverage area. The spatial coverage map (Figure: Cellular Tower Coverage Area) shows geographical variation in the estimated communication coverage.

The central and southern part of the district show relatively better communication coverage, whereas the northern and north-western part of the district show relatively poor communication coverage. This may be attributed to the physical characteristics of the study area, such as elevation differences and settlement dispersal. Coverage may also be affected by the geographical relief of the study area. The coverage estimated and shown on the map, however, should be interpreted with caution. Verification of coverage and availability of mobile signals is required.

Tehsil-wise Variation in Estimated Cellular Coverage

The tehsil-wise coverage analysis provides further evidence of geographical inequalities in cellular connectivity.

Table 6. Tehsil-wise Estimated Cellular Coverage

Tehsil	Estimated coverage area (km²)
Akkalkuwa	370.43
Akarani	215.79
Nandurbar	987.56
Navapur	756.74
Shahada	1,067.90
Taloda	392.22
Total	3,790.64

(Source: Author's calculation from the village-level coverage dataset.)

Estimates show Shahada covers 90.32% of the communicated area, followed by Taloda (87.11%) and Nandurbar (86.78%). The lowest coverage is shown by Akarani (16.67%) and Akkalkuwa (39.89%). The difference between Shahada and Akarani shows spatial communication coverage inequalities. Coverage inequalities may be due to dispersed settlement in remote and rugged areas. Coverage may also be due to the lack of communication and associated infrastructure.

Areas with coverage may be due to the concentration of communication and/or accessible settlements and/or population as seen in Shahada and Nandurbar. Based on the results, planners of communication networks should consider the physical environment of the area and the accessibility of the population of the area.

Village-level Variation in Cellular Coverage

To understand distribution of digital connectivity at grassroots level, a village coverage dataset was generated using unique village identification codes. A total of 971 unique villages were identified in the filtered dataset. Coverage at the village level was classified into four categories:

Table 7. Village-wise Classification Based on Estimated Cellular Coverage

Coverage category	Number of villages	Percentage
No coverage (0%)	118	12.15
Very low coverage (0.01–50%)	111	11.43
Moderate coverage (50.01–75%)	61	6.28
High coverage (75.01–100%)	681	70.13
Total	971	100.00

(Source: Aggregation of village-level coverage attributes.)

The results show that 70.13% of the studied villages were in the high-coverage category. On the other hand, coverage estimates were not available for 118 villages (12.15%), and for 111 villages (11.43%), the coverage was less than 50%. Hence, 229 villages (23.58%) have either no coverage or very low coverage, revealing a spatial dimension of the digital divide for the rural settlements due to limitation of estimated cellular coverage.

This situation is well illustrated by Akarani where 82 villages have no coverage. Likewise, Akkalkuwa has 26 villages with no coverage. However, none of the villages in Nandurbar and Shahada have no coverage (in the samples studied). This indicates that average digital connectivity for each district could mask significant variation in village and tehsil level digital connectivity within the same district.

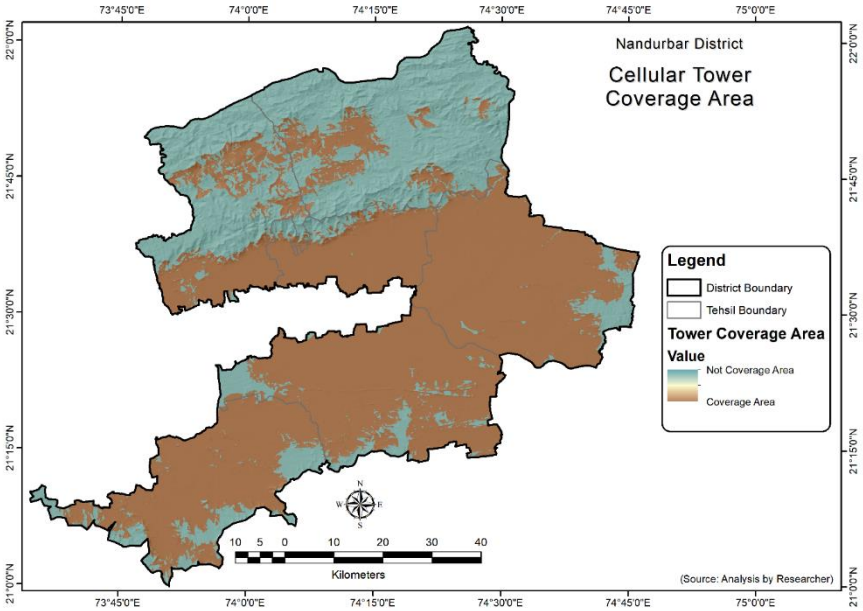

Figure 3 Spatial Distribution of Estimated Cellular Tower Coverage Areas in Nandurbar District.

4.7 Relationship Between Population Distribution and Cellular Tower Distribution

The study analyzed the relationship between the distribution of population and cellular tower infrastructure at the village level using population attributes and the spatial location of cellular towers. The 2011 census-linked village population field was used as the population attribute. To identify the number of towers located within the village boundaries, the cellular tower points were spatially joined to village boundaries. Correlation analysis was performed using both the Pearson's correlation coefficient and Spearman's rank correlation coefficient.

There is a positive relationship between population and the number of cell towers. The Pearson correlation between population and tower count was 0.211, which suggests a positive, weak linear relationship. However, Spearman's rank correlation between the two factors was 0.487, and thus positive, weak monotonic relationship. This is likely reflective of the size and settlement location of the infrastructure.

Table 8. Correlation Between Population and Cellular Tower Distribution

Variables	Pearson's r	Spearman's ρ	Significance
Population and tower count	0.211	0.487	p less than 0.001
Population and coverage percentage	0.173	0.155	p less than 0.001
Tower count and coverage percentage	0.179	0.312	p less than 0.001
Population and estimated covered population	0.167	0.718	p less than 0.001

Sample size: 971 villages. All correlations were statistically significant at the 0.001 level.

(Source: Statistical analysis of village population, tower locations and coverage attributes.)

A relatively weak positive relationship was shown between population and coverage percentage (Pearson's r = 0.173). A positive relationship was also shown between tower count and coverage percentage (Spearman's ρ = 0.312). Thus, villages with a greater number of towers had a greater estimated coverage.

The strongest rank correlation was shown between the population and estimated covered population (Spearman's ρ = 0.718), and therefore suggests that the estimated covered population distribution is reflective of the population distribution of a given area.

It can be concluded that the study population, in this case, Refugees, affects the spatial distribution of cellular infrastructures. However, this is not always the case, and it can be assumed other geographic conditions, such as the local environment, accessibility, and settlement and infrastructure layout, also play a role in shaping the geospatial distribution of the study population.

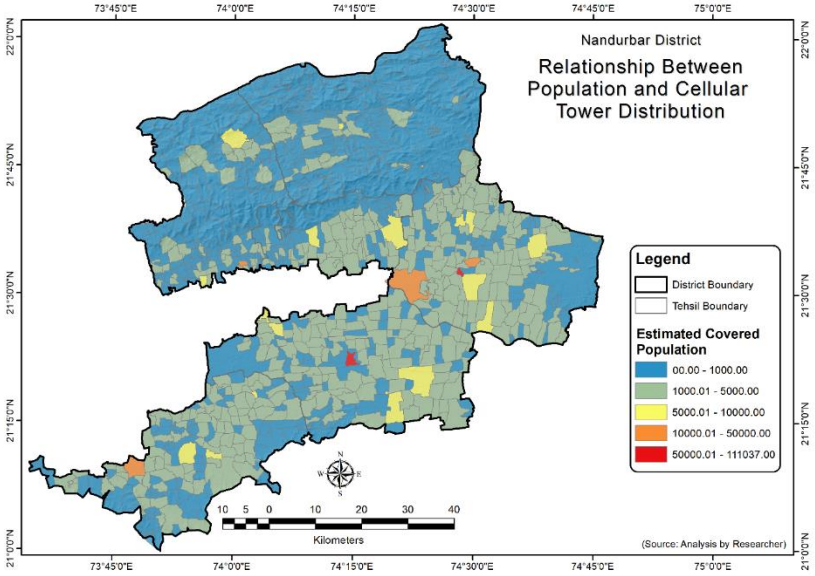

Figure 4 Spatial Relationship Between Population Distribution and Estimated Cellular Tower Coverage in Nandurbar District.

Geographical Influence of Elevation and Physiographic Characteristics on Digital Connectivity

The relationship between cellular tower locations and physiographic factors was studied through an elevation-based distribution map with the integration of cellular tower and elevation data from the digital elevation model (DEM). Towers are located in different elevation zones, but are more concentrated in the central and southern parts of the district. Towers in the more rugged, elevated northern and northwestern parts of Nandurbar district are more disperse in location.

The elevation map shows the district has an elevation ranging from 68 meters to 1,271.92 meters above Mean Sea Level (MSL). The northern mountainous region of the district, and particularly Nandurbar taluka, is challenging for improving cellular communication. This may be attributed to obstructions in terrain and settlements, slope, and

elevation. Radio signals propagate differently in various physiographic regions, and these factors should be considered in planning of cellular towers.

However, in this analysis, a geographical association has been established rather than a statistically significant elevation-tower relationship. To establish a statistically significant elevation-tower relationship, the density of towers across varying elevation and slope classes should be studied.

Relationship Between Estimated Covered Population and Geographical Distribution

The population–cellular tower distribution map (Fig) illustrates the spatial variation in the estimated covered population across the villages in the Nandurbar district. The map classifies villages into five estimated population coverage categories:

Table 9 The population–cellular tower distribution

Category	Estimated covered population
Very low	0–1,000
Low	1,000.01–5,000
Moderate	5,000.01–10,000
High	10,000.01–50,000
Very high	50,000.01–111,037

Where population is more centrally located, i.e., in the district's southern and central areas, higher population values are estimated, for example, in and around Nandurbar and Shahada Tehsil. The peripheral areas contain the more remote and smaller settlements. This implies that the population is not evenly distributed, and that infrastructure and availability of digital networks shape digital connectivity. The estimations show that even if a population is not directly connected to the network, it could be counted by the model and shown in the coverage estimates.

Implications and Limitations of the Study

Implications for Digital Infrastructure Planning

Based on the spatial findings, the following measures are suggested.

1. Priority Infrastructure Development: Akarani and Akkalkuwa tehsil should receive priority consideration because of relatively lower tower density and estimated coverage.
2. Identification of Underserved Villages: The 118 villages with zero estimated coverage should receive priority consideration for detailed assessment of network feasibility.
3. Terrain-based Infrastructure Planning: When identifying potential sites for new cellular towers, DEM, slope and terrain obstruction analysis should be incorporated.
4. Population-based Infrastructure Allocation: Future tower locations should be based on the combination of the population and settlement density and the existing infrastructure.
5. Improving Rural Connectivity: Priority should be given for remote tribal and hill settlements for reducing geographical disparity in access to digital services.
6. Integrated Digital Development: Planning for cellular connectivity should be integrated with planning for other transport and social infrastructure.

Limitations of the Study

The following limitations should be acknowledged in this study. The analysis used the supplied tower point dataset, representing tower locations as they were collected. Estimated coverage was taken from the supplied spatial dataset and should not be considered as measured network signal coverage. The analysis does not distinguish between 2G, 3G, 4G, and 5G. Population data utilizes census-linked village attributes, whereas estimated covered population is a model-derived variable. Elevation map shows physiographic variation; however, a separate analysis is required to show the relationship to tower distribution. Actual network performance depends on a number of factors, e.g., operator capacity, antenna orientation, frequency bands, interference, and congestion, which is not captured in the supplied datasets.

Conclusion

This study demonstrates important differences in the distribution of cellular towers and estimated digital connectivity in Nandurbar District, Maharashtra. Analysis of 606 cellular towers in GIS shows that communication infrastructure is more in Nandurbar and Shahada Tehsils and less in Akarani and Akkalkuwa Tehsils. Estimated spatial coverage is 63.74% of the studied area and 36.26% is beyond the modeled coverage. At the village level, 118 villages are shown to have no estimated coverage and, therefore, show inequity in digital connectivity. Cellular towers are seen to be more in the populated areas. Untouched rural and remote areas in the north and northwest of the district may be underserved due to challenges of difficult and rugged terrain. Based on this, it may be considered that efforts be made to focus more on cellular infrastructure in remote, tribal and mountainous areas of the district. In addition, while planning for cellular infrastructure in Nandurbar District, it is recommended to carry out an integration of GIS coverage analysis of communication infrastructure, population distribution and physiography in the district.

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

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