

A Spatial Analysis of Infrastructure Characteristics and Community Vulnerability Across India¹

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1 INTRODUCTION & SCOPE OF WORK

Infrastructure systems play a critical role in shaping community resilience and vulnerability to natural hazards. In many countries of the Global South, existing infrastructure deficits and uneven spatial development exacerbate the vulnerability of communities to disasters and climate risks (Zhang et al., 2025). While previous research recognizes infrastructure as a key component of community resilience frameworks, empirical evidence on how different infrastructure characteristics, particularly availability and access, interact to influence community vulnerability remains limited.

Infrastructure availability refers to the presence and density of regional systems such as transport networks, power transmission lines, and water resources (Henshel & Ashby, 2023), while infrastructure access relates to the ability of households to utilize essential services such as electricity, drinking water, sanitation, and clean cooking fuel (Corscadden et al., 2018). The distinction between these dimensions is particularly relevant in developing regions, where infrastructure may exist but may not be equitably accessible to households.

This study investigates the relationships between infrastructure characteristics and community vulnerability across 733 districts in India using a spatial analytical framework. The research focuses on three infrastructure dimensions: critical infrastructure availability, social infrastructure density, and household-level access to essential utilities. The objectives of the study are to: (a) develop district-level composite indicators representing infrastructure availability, infrastructure access, and community vulnerability, (b) identify spatial disparities and regional infrastructure profiles using clustering analysis, and (c) quantify the individual and synergistic relationships between infrastructure dimensions and community vulnerability through spatial regression modeling.

2 METHODOLOGY

The methodology adopted in this study is illustrated in Figure 1. It consists of four key steps: (a) data collection, processing, and categorization; (b) development of composite subnational indicators (focusing on community and infrastructure); (c) spatial analysis of subnational

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disparity in infrastructure and community capabilities; and (d) analysis of influence of infrastructure on community vulnerability profiles.

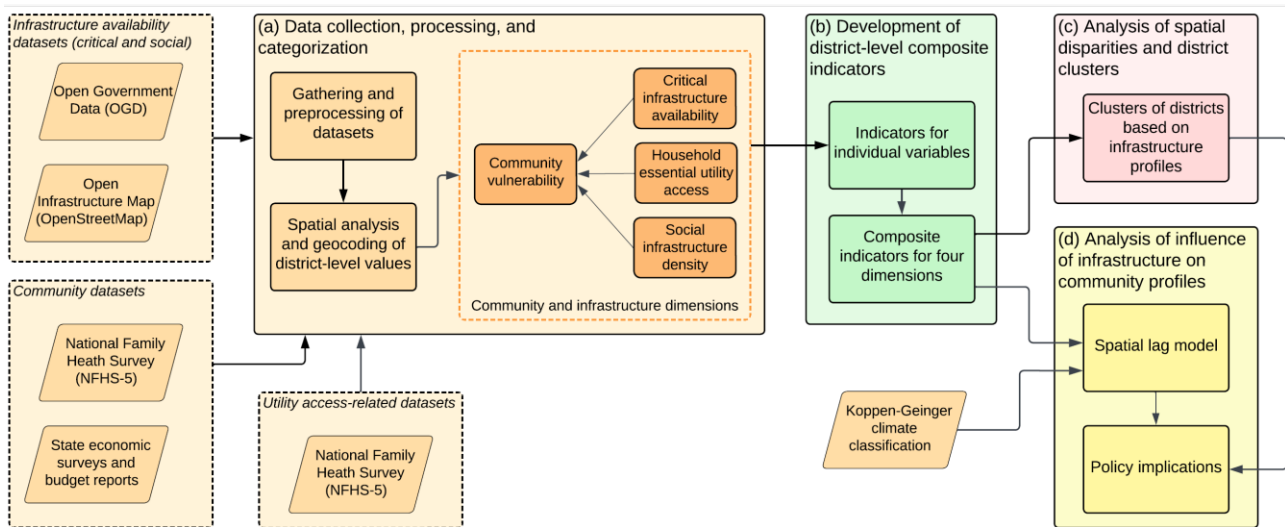


Figure 1. Methodological framework and datasets.

The core of the methodology lies in the development of a comprehensive set of indicators to capture the associations between community vulnerability and infrastructure provisions. These indicators were derived from relevant features sourced from multiple datasets, including government surveys and open-source geospatial databases, such as, the National Family Health Survey (NFHS-5) (MoHFW, 2022), ESRI India infrastructure datasets (ESRI India, 2023, 2024), OpenStreetMap, Central Ground Water Board data (CGWB, 2024), and state economic surveys. The indicators were organized into four dimensions: regional critical infrastructure availability, social infrastructure density, household access to essential services, and community vulnerability. Community vulnerability was represented using socioeconomic and health-related variables such as per capita income, female literacy, prevalence of underweight children, and health indicators, while infrastructure indicators included highway and road density, power network density, groundwater extraction levels, household access to electricity, sanitation, drinking water, and clean cooking fuel, as well as per capita availability of schools, healthcare facilities, and police stations. The indicators were standardized and integrated into composite indicators using principal component analysis (PCA), a statistical technique commonly used to reduce dimensionality and identify underlying patterns in datasets.

The framework builds upon this foundation in a series of steps. The first step involved gathering and preprocessing the necessary datasets and harmonizing them at the district level to develop the indicators. In the second step, PCA was applied to generate composite indicators representing the four dimensions. In the third step, unique regional archetypes, representing distinct combinations of infrastructure characteristics, were identified using hierarchical (agglomerative) clustering analysis. Finally, spatial lag regression modelling was employed to explore the empirical relationships between community vulnerability and infrastructure provisions at the district level while accounting for spatial dependence between neighbouring districts. Interaction terms between infrastructure dimensions were also included to examine potential synergistic effects. In addition, the results from the regression model were combined with clustering analysis to derive optimal infrastructure resource allocation strategies tailored to district groups with distinct infrastructure profiles.

3 RESEARCH OUTCOMES

The results reveal significant spatial disparities in both infrastructure provisions and community vulnerability across India's districts. Spatial clustering analysis identified six distinct district archetypes characterized by different combinations of critical infrastructure availability, social infrastructure density, and household essential utility access (Figure 2). The subsequent spatial regression modelling showed that all three infrastructure dimensions are significantly

associated with community vulnerability, with household access to essential utilities emerging as the strongest determinant. Improvements in access to electricity, sanitation, drinking water, and clean cooking fuel are strongly associated with lower vulnerability levels. Critical infrastructure availability, represented by road networks, transmission infrastructure, and groundwater resources, also demonstrates a moderate vulnerability-reducing effect, while social infrastructure density (schools, healthcare facilities, and police stations) shows a smaller but consistent association with improved community outcomes.

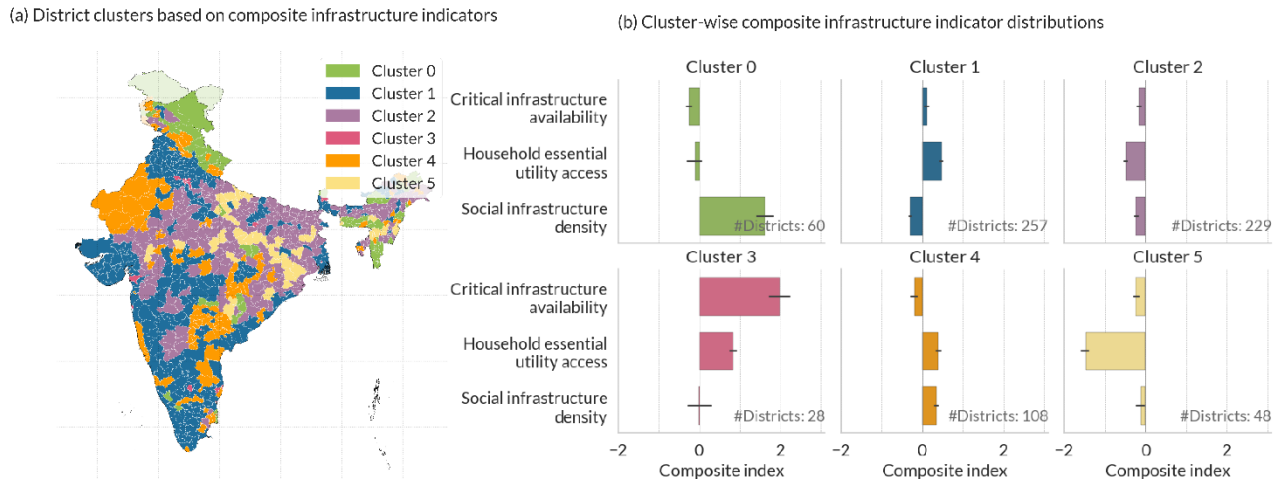


Figure 2. Agglomerative clustering results and corresponding infrastructure patterns at district-level.

The analysis also revealed synergistic interactions between infrastructure dimensions, particularly between critical infrastructure availability and household utility access. Districts with strong performance in both dimensions exhibit substantially lower predicted vulnerability, suggesting that coordinated investments in regional infrastructure networks and household-level services can generate compounded resilience benefits. The presence of spatial spillover effects further indicates that infrastructure improvements in one district may also contribute to vulnerability reduction in neighbouring districts. These findings highlight the importance of integrated and spatially coordinated infrastructure planning, where investments prioritize infrastructure-deficient regions while simultaneously improving service access to promote equitable reductions in community vulnerability.

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