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Integrated Urban Fire Risk Assessment using Analytic Hierarchy Process (AHP) and GIS: A Structural Vulnerability Analysis of Nagpur City.

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Abstract

Urban fires represent a persistent yet under-addressed risk in rapidly urbanizing cities of the Global South, where infrastructure development often lags behind population growth and land-use intensification. In Tier-2 Indian cities, historic urban cores characterized by dense built form and constrained accessibility coexist with rapidly expanding peripheral areas, creating complex patterns of structural fire vulnerability that are inadequately captured by incident-based risk assessments. Conventional approaches relying on historical fire occurrence data are inherently reactive and fail to identify latent vulnerabilities embedded within the urban fabric.

This study develops a deductive, spatially explicit Fire Vulnerability Index (FVI) for Nagpur City, India, by integrating the Analytic Hierarchy Process (AHP) with Geographic Information Systems (GIS). Five key determinants of intrinsic fire vulnerability—road network accessibility, land use and building density, land surface temperature, proximity to fire stations, and population density—were standardized and weighted using expert judgment validated through consistency analysis. The weighted criteria were spatially integrated using a weighted linear combination approach to generate a high-resolution vulnerability surface, which was subsequently aggregated to the ward level for administrative applicability.

The results reveal a pronounced core–periphery gradient in fire vulnerability, with approximately 14% of the city classified as very high vulnerability, predominantly concentrated within the historic core. Road network accessibility emerged as the most influential determinant, underscoring the critical role of last-mile access in constraining firefighting operations. The integration of land surface temperature highlights the role of urban heat islands as a risk multiplier, exacerbating fire susceptibility in dense, impervious neighborhoods. Sensitivity analysis confirms the robustness of the model, with high-risk clusters remaining spatially stable under varying weight scenarios.

By shifting fire risk assessment from retrospective hotspot mapping to proactive structural vulnerability modeling, this study provides a scalable and transferable framework for urban fire risk governance. The findings offer actionable insights for municipal planning, emphasizing the need for accessibility-oriented interventions in historic cores and regulatory enforcement in rapidly densifying peripheral areas. The proposed framework supports a transition toward resilience-oriented fire risk management in fast-growing cities of the Global South.

Keywords- Urban Fire Vulnerability; Analytic Hierarchy Process (AHP); GIS-based Risk Assessment; Fire Vulnerability Index; Urban Morphology; Land Surface Temperature; Tier-2 Cities; Disaster Risk Reduction; Nagpur City

1. INTRODUCTION

Rapid urbanization in the Global South has been one of the key factors playing an influential role in the geography of disasters. In urban centers, traditionally, the spotlight has always been on addressing the risks that come about by way of hosting large-scale disasters that are not frequent in nature, like floods and earthquakes. Recently, the risk of fire in urban centers is one of the relatively less explored themes, especially in an era where rapid urbanization is taking center stage and addressing the risks of fire in an urban setting that is not too prominent in nature is not addressed as one of the prime concerns, especially since addressing the risk of fire is naturally not supposed to be one of the concerns in the context of natural disasters that are not necessarily repeated in nature (Harakan et al., 2025; KC et al., 2024; Shekhar et al., 2022).

This lack of focus is most evident in Tier 2 classified cities within the context of a developing economy, where accelerated population growth indicates the level of regulation and infrastructure development. Morphologically, the Indian variant of such towns presents a singularly dualistic form, where the street networks are classified as historical and exhibit a rapidly agglomerating peripheral region with low intensities of planning regulation. Such a morphology presents a vastly complicated riskscape, where the traditional response system and the subsequent fire risk associated issues, which would be indicative of the more generic road network, are operationally incapable. Fire risk, within the context of the urban situation, is therefore not the product of an isolated ignition event but rather the organizational vulnerability of the built context (Phyo Wai et al., 2025; Yao et al., 2024a).

However, for the time being, a number of techniques have been incorporated within the overall context of the assessment of fire risks within an urban area. In order to be specific pertaining to the issue, it has to be mentioned that the techniques incorporated within the specific context have been retrospective in nature, i.e., the methodologies that were, in a wide range of cases, adopted for addressing the issue have been mainly dependent on the response mechanisms towards the incidents of fire occurrence. To be specific, techniques and methodologies such as the in-depth application of hotspot analysis, which in most cases includes the adoption of techniques such as Kernel Density Estimation (KDE), have been widely incorporated in this context. However, it has to be noted further that upon proper analysis of these techniques, the limitations of techniques adopted for addressing the patterns of fire occurrence become quite evident; therefore, in such an context, the overall handling of fire risks in an urban area may be identified as an approach of reactive governance (Singh et al., 2021; K. V Thakare & Tajne, 2025; K. Wang et al., 2021a).

From all the above, it appears evident that the earlier research was unsuccessful in achieving the themes. However, since the older research was marked by the above characteristics, the more recent research has emphasized the significance of deductive vulnerability methods and the requirement of adopting a multi-discriminant perspective of vulnerability to fires, as opposed to trusting the statistical Project of vulnerability to fires. Furthermore, the approach would also seek to understand the development of vulnerability to fires by considering the relationships established among quantifiable spatial parameters such as the components of accessibility via roads, the intensity of the occupation of the land, the exposure to the conditions of heat stress, and the assistance. The occurrence of all these varied elements within the spatial system would allow the identification of the regions of extreme effects of fires (Granda & Ferreira, 2019; Noori et al., 2023a; Yfantidou et al., 2023).

Such an approach, in which MCDA techniques such as AHP have been found valid, forms a foundation upon which the assessment of fire vulnerability may be well implemented in urban situations that exhibit a multiplicity of non-commensurable factors and in conditions of scarcity of reliable empirical data available in the form of losses due to fire (Kirti Vijayrao Thakare, 2025; Ms. et al., 2024; K. V. Thakare & Tajne, 2025; Thakare et al., 2025). Hierarchical structures assist in decomposing the decision process, and the integration of physical, environment-related, and socio-spatial factors in an objective manner, coupled with its association with GIS, helps in the detailed modeling of vulnerability assessment (Ju et al., 2023; Meghzili et al., 2025; Nikolić et al., 2023).

This is notwithstanding the immense methodological potential that the AHP approach has to offer within the context of fire vulnerability modeling. In fact, in the specific context of fire hazard modeling of Tier-2 cities in the Indian context, which are presently confronted with tremendous spatial transformations, such an AHP approach-based study is still in the infancy stage of its exploration, mostly considering incident density in the form of urban metropolises. There is, once again, an urgent requirement to fill the critical gap in the form of infrastructure-based fire hazard vulnerability prediction models (Goswami et al., 2025a; Rani et al., 2023; Sinha et al., 2023).

This paper tries to fill this gap by presenting a Fire Vulnerability Index for Nagpur City, India, in an integrated GIS-AHP environment. Nagpur represents a typical Tier-2 city with a developing transition of a monocentric to a polycentric structure with strong contrasts between historical high-density areas and newly planned peripheral areas. In the present study, five space factors related to road network accessibility, land use and building density, land surface temperature, fire stations, and population density were used to simulate the fire vulnerability as an integrated phenomenon due to the overall morphology, rather than history-dependent fire occurrences.

The specific contribution of this study could be noted on three aspects. The first specifically refers to identifying a deductive approach on spatially explicit urban fire vulnerability assessment, including a scope outside hotspot-based post-occurrence assessment. The second refers to urban fire vulnerability assessment using a land surface temperature risk multiplier, emphasizing its utility to combine urban heat island occurrence and/or risk of building fires. The third aspect refers to deriving urban fire vulnerability assessment at a ward scale rather than only at a pixel level.

In the re-interpretation of fire risks in association with structural and environmental factors in spaces, the research aims to contribute to the paradigm of change, not in the way of reactions and attitudes towards the management of fire risks, but towards visionary and more resilient mindsets with respect to the fire risk management of spaces that show the representation of these architectural and structural manifestations. This research aims to contribute towards the template formation that is applicable to other rapidly urbanizing cities in the South.

2. DATA ACQUISITION AND SPATIAL DATABASE

2.1 Study Area Characteristics

The empirical analysis is carried out for Nagpur City, which is one of the winter capitals of the state of Maharashtra in India, located at the center of the Indian sub-continent. Geographical area of Nagpur City is approximately 229 km², and the jurisdiction area is under the area of the Nagpur Municipal Corporation (NMC). Nagpur City is divided into 10 zones and 136 election wards, which is considered to be at the highest level in the hierarchy.

In relation to the morphological characteristics, it is evident that Nagpur has all the earmarks of a large Indian Tier 2 city that is, in the current instance, in the process of rapid spatial development. For example, the historical areas in Nagpur, such as Mahal, Itwari, and Gandhibagh, are rich in the earmarks of high-density compact urban development. On the contrary, the peripheral zones of the historical center in Nagpur have all the earmarks of well-planned urban development, high coverage ratio, and development dominated by purely residential and institutional land use patterns. The fact that the city, in its spatial structure, has the earmarks of the core-periphery dichotomy makes it an appropriate case to test the hypotheses of fire vulnerability.

Topographically, therefore, it may also be understood as a flat city, given the average elevation of the city, which stands at about 310 meters above mean sea level, thus ensuring that there is no bias in the distribution of fire because of its slope. The city, therefore, also stands as a matter of study from a methodology perspective, given the prominence of fire risk vulnerability in Nagpur's urban structure.

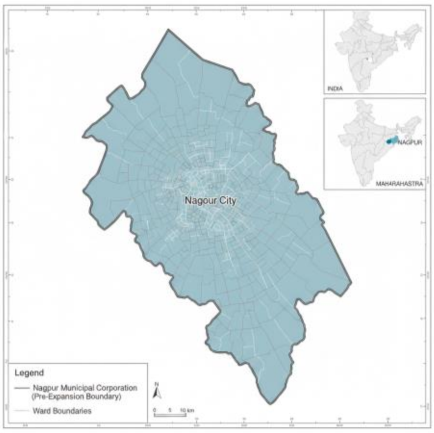

Figure 1. Geographic location of Nagpur City within India and Maharashtra State, showing the municipal boundary, administrative zones, and ward divisions used for spatial aggregation and vulnerability assessment. The figure highlights the city's central location within the Indian subcontinent and its heterogeneous urban structure, which makes it representative of rapidly urbanizing Tier-2 cities in the Global South.

2.2 Data Sources and Spatial Inventory

In order to develop a deductive Fire Vulnerability Index (FVI) model, a multi-data source spatial database was developed based on different types of administrative data, open-source geographic information systems, remote sensing imagery, and demographic analysis. Although previous research focused on fire occurrence, the focus in this research was based on indicators such as the structures or environment, considering the vulnerability factor.

These five basic spatial criteria have been developed in accordance with fire safety literature, theory of urban morphology, and expert advise from local fire authorities/planners. These highlighted basic spatial criteria identified three major aspects regarding vulnerabilities, such as accessibility, exposure, and environment stress.

Table 1 summarizes the datasets used, including their spatial resolution, source, and relevance to fire risk assessment.

Table 1. Spatial datasets used for Fire Vulnerability Index development

Parameter	**Data Type**	**Source**	**Spatial Resolution / Scale**	**Relevance to Fire Vulnerability**
Road Network	Vector (Line)	OpenStreetMap (OSM); NMC Town Planning Dept.	1:5,000	Determines emergency vehicle accessibility and evacuation efficiency
Land Use / Building Density	Raster / Vector	Sentinel-2 MSI (ESA)	10 m	Proxy for fire load, structural congestion, and land-use intensity
Land Surface Temperature (LST)	Raster	Landsat-8 OLI/TIRS (USGS)	30 m (resampled to 10 m)	Indicator of urban heat islands and thermal stress
Fire Station Locations	Vector (Point)	NMC Fire & Emergency Services	GPS-based	Used to model response distance and service gaps
Population Density	Raster	WorldPop; Census of India projections	100 m	Represents human exposure and potential casualty risk

2.3 Data Pre-processing and Harmonization

All the spatial datasets have been processed within a GIS environment, as it ensures the datasets' geometric consistency, topological correctness, and analytical compatibility. In order to avoid any kind of spatial misalignment between datasets, all the datasets have been projected into the same CRS, i.e., WGS 1984 UTM Zone 44N.

Topological cleaning operations were performed on the dataset of the road network. Instead of using distance buffers, the classification of the data was done in accordance with the effective widths of the roads, as they needed to be considered from the perspective of fire tender operations. After classifying the width of the data, there was a categorization of the data: arterial roads (> 15 m), sub-arterial roads (9 m ≤ width < 15 m), and small access roads (width < 6 m). It has been mentioned that small access roads pose bottleneck problems in accessibility to high-risk areas.

To perform the environmental characterization, the "cloud-free image" of the specified area obtained by using the "Landsat 8 OLI/TIRS" image (Path: 145, Row: 45) taken during the peak summer season, i.e., in the month of May 2024, has been taken to achieve the "maximum thermal stress." The obtained values have been further processed to achieve the "Top of Atmosphere" spectral radiance values by applying the "radiometric correction." Further, the obtained values of "Land Surface Temperature" have been obtained by using the "single channel method," which is a standard approach for "Remote Sensing" images. Additionally, a "resampling rate" of 10 inches is also being applied for "LST."

Population data, which is easy to obtain on a larger scale, is now being disaggregated according to its spatial level with data obtained from WorldPop to provide a more realistic population density curve for the ward area. The location of fire stations is determined using data from a GPS survey carried out by NMC Fire and Emergency Services.

2.4 Spatial Standardization and Hierarchical Structuring

These layers were transformed into a raster format, using a uniform cell size of 10 meters, to allow the multi-criteria spatial analysis to be performed. The cell size was 10 meters for calculations, as it ensures an optimal balance between computational precision and interpretability for urban fire management at the neighborhood scale.

Each of these criteria has been normalised into one ordinal scale of vulnerability, that extends from 1 (Very Low Vulnerability) to 5 (Very High Vulnerability). The thresholds of reclassification have been determined by using a combination of:

- National Building Code of India (Part 4: Fire and Life Safety),
- Municipal development control regulations,
- Empirical thresholds reported in prior urban fire risk studies,

The standardized layers were then organized into a hierarchical decision structure to support the Analytic Hierarchy Process (AHP), with the overall goal (fire vulnerability) at the top, followed by the five primary criteria as decision nodes. This hierarchical organization ensured methodological transparency and allowed for systematic weighting of heterogeneous spatial determinants.

2.5 Rationale for Data Selection

Choices in the selection of the spatial variables are oriented towards an effort to move forward from event-related modeling and towards structural vulnerability assessment. The working ability for response in emergencies can be represented by the accessibility of the roads, combustible loads and congestion can be represented by land use and density of buildings, population density represents exposure, proximity to fire stations can represent response latency, while land surface temperature represents the environmental stress, where its impacts are felt mainly in ignition and the spread of fires.

These data sets provide a thorough space-based representation of the intrinsic vulnerability to wildfires, thereby enabling predictive analyses not based on past fire-occurrence patterns.

3. METHODOLOGY

3.1 Conceptual and Analytical Framework

The present work adopts a deductive multi-criteria spatial modeling approach in determining urban fire vulnerability, considering the intrinsic urban environment. This is against the inductive approaches like Kernel Density Estimation and hotspot analysis based on frequencies of past fire events. The overall framework seeks to address fire vulnerability in terms of the general effect of all urban structural, environmental, and socio-spatial determinants regardless of past fire occurrences.

The methodological framework embraces the concepts of Remote Sensing, Geographic Information Systems, and Multi-Criteria Decision Analysis, where the main calculation tool for weights will be the Analytic Hierarchy Process. In its whole, it allows assessing heterogeneous variables in a systematic way and building a Fire Vulnerability Index based on inherent aspects of natural susceptibility, not on recorded data with respect to specific fire events. Therefore, standardization, computation of criterion weights by AHP, and a weighted linear combination technique would form part of the analytical flow (Ghorbanzadeh et al., 2019; Saidi et al., 2021; Uthappa et al., 2025).

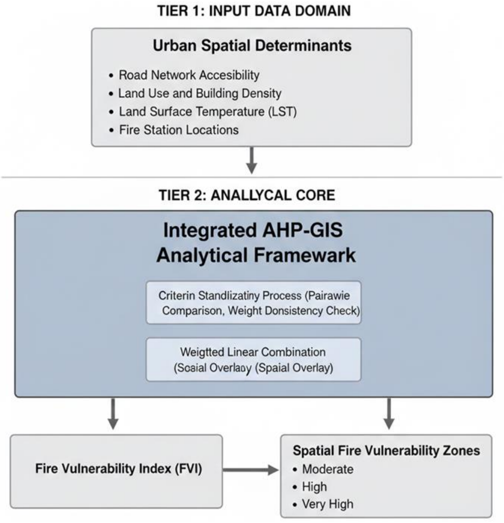

Figure 2. Schematic representation of the integrated methodological framework adopted in this study, illustrating the sequential stages of data acquisition, spatial standardization, Analytic Hierarchy Process (AHP)–based weight derivation, weighted linear combination, and generation of the Fire Vulnerability Index (FVI).

3.2 Analytic Hierarchy Process (AHP)

The application of the Analytic Hierarchy Process, which was introduced by Saaty, was used in the assessment of the relative importance of a series of factors that defined the urban landscape, thus making the urban landscape liable to fire hazards. In the choice of the AHP, it was noted that the approach would effectively handle intricacy, which was implicated in urban risk analysis, particularly instances in which the norms for the determination of the decision criteria were measured on different scales and lacked accessible historical information on the issue of fire (Goswami et al., 2025b; Noori et al., 2023b; Y. Wang et al., 2021).

3.3 Hierarchical Structuring of Criteria

The levels in the decision hierarchy for the fire vulnerability assessment were: the final objective in urban fire vulnerability, the three major criteria, i.e., the accessibility of the road network, the land use and building density, the land surface temperature, the proximity to the fire stations, the population density, with each criterion representing the various aspects of its respective dimensions regarding the accessibility, the combustible loads, the environment, and the human exposures in each dimension. The criteria were assumed substitutable with interaction among the criteria in the decision making process. It was assumed that the extreme values in any dimension could not be offset by the consequent critical values in the other dimensions (Aguirre et al., 2024a; Noori et al., 2023c).

3.4 Construction of the Pairwise Comparison Matrix

It is possible to create a matrix representing judgments regarding the relative importance of each of the chosen criteria through a technique of pairwise comparison, as illustrated by Saaty's fundamental scale, along with opinion groups of urban planners, civil engineers, and senior fire officers employed by the Nagpur Municipal Corporation. Here, every expert has to compare criterion i and criterion j rating a scale of 1 to 9, where 1 implies both criteria to be of equal importance, and 9 implies that there is extreme importance between a pair of criteria (Hysa, 2021; Wadembere & Apaco, 2020).

The resulting square comparison matrix $\mathrm{A} = [a_{ij}]$of order n(where $n = 5$) is defined as:

$$\mathrm{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

where a_{ij}represents the relative importance of criterion $i$over criterion j. The matrix satisfies the reciprocity condition:

$$a_{ij} = \frac{1}{a_{ji}}, a_{ii} = 1 \qquad \text{Equation 1}$$

To minimize individual bias, the final comparison values were derived by computing the geometric mean of expert judgments for each criterion pair.

Table 2. Saaty's fundamental scale for pairwise comparison

Scale Value	Definition	Interpretation in Fire Vulnerability Context
1	Equal importance	Both criteria contribute equally to fire vulnerability
3	Moderate importance	One criterion slightly outweighs another
5	Strong importance	One criterion strongly influences vulnerability
7	Very strong importance	Dominance of one criterion is evident in practice
9	Extreme importance	One criterion overwhelmingly influences vulnerability
2, 4, 6, 8	Intermediate values	Used when compromise judgments are required

3.5 Derivation of Criterion Weights

The priority weight vector $\mathrm{w} = (w_1, w_2, \ldots, w_n)$was obtained by normalizing the principal eigenvector of the comparison matrix. In practice, the weight for each criterion was approximated using the geometric mean method, expressed as:

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}} \qquad \text{Equation 2}$$

where $w_i$is the normalized weight of criterion i, $a_{ij}$is the pairwise comparison value, and $n$is the number of criteria. The resulting weights satisfy the normalization condition:

$$\sum_{i=1}^{n} w_i = 1 \qquad \text{Equation 3}$$

3.6 Consistency Assessment

To verify the logical consistency of expert judgments, a consistency assessment was performed using the Consistency Index and Consistency Ratio. The maximum eigenvalue $\lambda_{\max}$of the comparison matrix was first estimated, and the Consistency Index was calculated as:

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad \text{Equation} \quad 4$$

The Consistency Ratio was then computed as:

$$CR = \frac{CI}{RI} \qquad \text{Equation} \quad 5$$

where $RI$is the Random Index corresponding to the matrix order. For $n = 5$, the value of $RI$is 1.12. A Consistency Ratio less than 0.10 indicates acceptable consistency and confirms the reliability of the derived weights for spatial decision-making.

3.7 Spatial Aggregation and Fire Vulnerability Index Calculation

The derived criterion weights were used to complete the spatial integration by applying the Weighted Linear Combination technique with the aid of the GIS technique. All the themes were normalized into a standard of five classes and then resampled into a standard resolution of 10 meters (Akhbar et al., 2025; Chuvieco et al., 2014; Pragya et al., 2023). To determine the Fire Vulnerability Index at location (xⓜ, y), the following formula was applied:

$$FVI(x, y) = \sum_{i=1}^{n} (w_i \times X_i(x, y)) \qquad \text{Equation} \quad 6$$

where $w_i$is the AHP-derived weight of the criterion i, $X_i(x, y)$is the standardized vulnerability score of the criterion $i$at location $(x' y)$, and $n$is the total number of criteria. The resulting continuous FVI surface represents the cumulative intrinsic fire vulnerability across the study area.

3.8 Classification of Vulnerability Zones

All the values for FVI, derived from continuous implementation in the calculation of FVI mapping, were organized at a policy level in four categories: Low, Moderate, High, and Very High. This assignment utilized the Natural Breaks (Jenks) optimization technique, one of the most powerful classifiers seeking a minimum variance within each group and a maximum variance between groups (Ke et al., 2023; Li et al., 2025). This is the right tool in the case of an urban setting with potential high heterogeneity in FVI values.

Table 3. Reclassification scheme for fire vulnerability criteria

Criterion	Sub-criterion Range	Vulnerability Class	Score
Road Width	< 6 m	Very High	5
	6–9 m	High	4
	9–12 m	Moderate	3
	12–15 m	Low	2
	> 15 m	Very Low	1
Land Use / Building Density	Commercial / Industrial / Mixed-use	Very High	5
	High-density residential (informal/slums)	High	4
	Planned residential / institutional	Moderate	3
	Transport / public utilities	Low	2
	Open space / water bodies / green areas	Very Low	1

Land Surface Temperature	> 42 °C	Very High	5
	39–42 °C	High	4
	36–39 °C	Moderate	3
	33–36 °C	Low	2
	< 33 °C	Very Low	1
Distance to Fire Station	> 5 km	Very High	5
	4–5 km	High	4
	3–4 km	Moderate	3
	2–3 km	Low	2
	< 2 km	Very Low	1
Population Density	> 30,000 persons/km²	Very High	5
	20,000–30,000 persons/km²	High	4
	10,000–20,000 persons/km²	Moderate	3
	5,000–10,000 persons/km²	Low	2
	< 5,000 persons/km²	Very Low	1

3.9 Model Validation and Sensitivity Analysis

Due to the deductive nature of this proposed framework, it has been identified that the validation of the proposed results through the inclusion of quantitative techniques in a similar fashion, using predictive accuracy figures and fire incidents, it was not appropriate. However, the robustness of the proposed model was verified like sensitivity and ground-truth analyses. In order to perform the sensitivity analysis, the weight of the most influential criterion was varied in order to verify the robustness of the zones with high vulnerability (de Brito et al., 2019; Hu et al., 2021). To perform ground-truth verification, the zones identified as highly vulnerable were physically inspected.

4. RESULTS AND DISCUSSION

4.1 Determination of Criterion Weights

The Analytic Hierarchy Process revealed a clear prioritization among the selected fire vulnerability determinants. The computed principal eigenvalue of the pairwise comparison matrix was $\lambda_{\max} = 5.34$, yielding a Consistency Ratio of 0.07, which is well below the acceptable threshold of 0.10. This confirms the internal logical coherence of expert judgments and validates the reliability of the derived weights.

The most influencing parameter for the accessibility of the road network was identified, which seemed to have the highest value in the weightage scale at 0.38 for the urban area in the determination of the vulnerability of the fire in the region. It was identified that the accessibility contributed to the difficulties experienced during the firefighting operations carried out in the confined urban region. The second major factor identified for influencing the vulnerability of the fire in the urban area was the density levels of the land and buildings, which had a lesser weightage value of 0.27, but depicted the importance of the parameter's contribution in controlling the vulnerability of the fire in the region. It has also been identified that the factor of the land surface temperature influenced the vulnerability of the fire in the region, with a weightage value of 0.16, which depicted the complete picture in the weightage scale among all the parameters in the assessment region (Aguirre et al., 2024b; Noori et al., 2023d). Other parameters influencing the vulnerability of the fire in the region included the vicinity of the location in relation to the fire stations or the population density levels, with a lesser weightage value at 0.11.

Table 4. AHP-derived criterion weights for fire vulnerability assessment

Criterion	Normalized Weight (Wi)	Percentage Influence	Rank
Road Network Accessibility	0.38	38%	1
Land Use and Building Density	0.27	27%	2
Land Surface Temperature	0.16	16%	3
Proximity to Fire Stations	0.11	11%	4
Population Density	0.08	8%	5

4.2 Spatial Distribution of Fire Vulnerability

Weighted integration of these standardized spatial layers resulted in a continuous FVI surface with marked spatial heterogeneity over Nagpur City. FVI surface classification using the Natural Breaks classifier resulted in four distinct vulnerability classes, namely Low, Moderate, High, and Very High.

Around 14.2% of the whole area formed part of the category of Very High, referring mostly to the historical area of the city. Very High Zones of Physical Vulnerability: These are zones that present street widths smaller than six meters, with continuity of facades without interruptions, high intensity of commercial activities, and land surface temperatures highly increased. The High Zones of Vulnerability add up to 25.5% of the study area and relate mostly to areas of mixed use; these are generally characterized by regular levels of congestion and relatively reduced levels of accessibility to emergency services and safety agents. The Moderate Zones of Vulnerability represent the highest percentages, 35.4%, and were generally related to planned residential areas; these offer higher width in the road network and controlled setbacks. Low Zones of Vulnerability occupy 24.9% of the whole area and are dominated mostly by institutions and open spaces, as well as road arteries.

This mode of spatial distribution obviously indicates the existence of the so-called core-periphery effect, with the level of vulnerability declining continuously as one moves away from the original urban center. This spatial distribution pattern represents a sum total of the entire history of development for the city, with the unregulated development having given rise to conditions that are not compatible with fire safety standards (K. Wang et al., 2021b; Yao et al., 2024b).

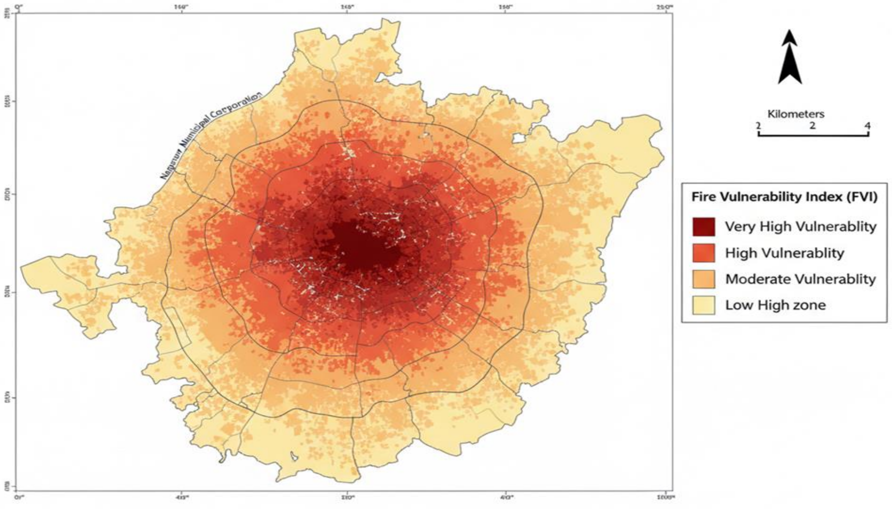

Figure 3. Spatial distribution of the Fire Vulnerability Index (FVI) across Nagpur City derived through GIS-based weighted linear combination of AHP-weighted criteria. The map classifies vulnerability into Low, Moderate, High, and Very High zones using Natural Breaks (Jenks) optimization, revealing a pronounced core–periphery gradient with extreme vulnerability concentrated in the historic city core.

Table 5. Areal distribution of fire vulnerability zones

Vulnerability Class	Area (km²)	Percentage of Total Area	Dominant Characteristics
Very High	32.5	14.2%	Narrow streets, continuous built form, high LST
High	58.4	25.5%	Mixed-use zones, moderate congestion
Moderate	81.2	35.4%	Planned residential layouts, adequate access
Low	56.9	24.9%	Open spaces, institutional areas, arterial roads

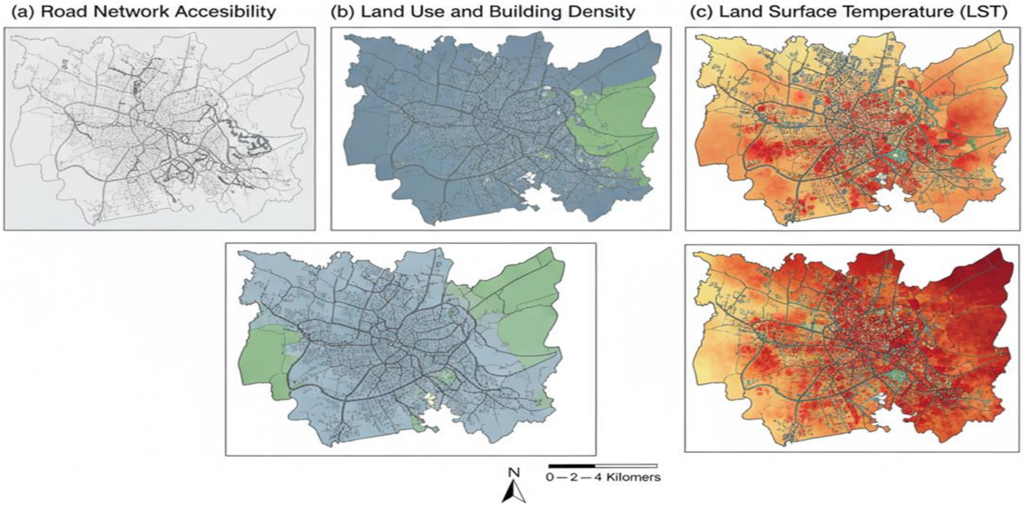

Figure 4. Spatial distribution of selected fire vulnerability determinants, including (a) road network accessibility, (b) land use and building density, and (c) land surface temperature. The overlays demonstrate strong spatial correspondence between narrow access lanes, dense mixed-use development, elevated thermal stress, and zones of high fire vulnerability.

4.3 Ward-Level Vulnerability Patterns

To draw the administratively relevant information from estimates of vulnerability, these aggregate and average the mean values of the Fire Vulnerability Index at the ward level since the pixel level shows the fact that the high-risk zones in the data cluster around the center and the eastern part of the city.

These include specific wards such as Gandhibagh, Satranjipura, Mahal, Lakadganj, and Mominpura that had always found a place in the list of most vulnerable wards. In fact, specific areas have some critical criteria laid down that ensure that the danger or risk is always there in these places comprising the highest building density, restricted availability of access roadways, unauthorized business activities, availability of combustible materials, and the aged nature of the electrical infrastructure. For instance, in Gandhibagh Ward, more than 85% of its internal road network is inaccessible to conventional fire tender vehicles.

On the other hand, as in the case of the western and southern peripheral areas, places like Civil Lines, Laxmi Nagar, and MIHAN have shown consistently lower vulnerability levels. This is because of the success of the entire process of Town Planning, i.e., wider road widths, setbacks, and the fire service access in such areas.

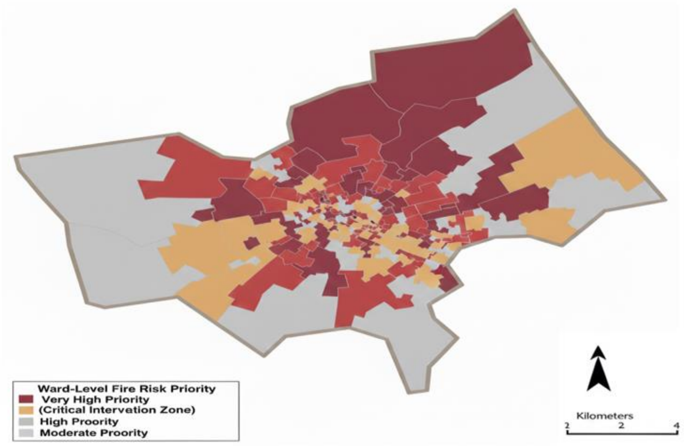

Figure 5. Ward-level aggregation of the Fire Vulnerability Index showing relative vulnerability patterns across 136 election wards of Nagpur City. High and very high vulnerability wards are predominantly concentrated in the central and eastern zones, reflecting the influence of dense built form, narrow street networks, and limited emergency accessibility.

4.4 Validation and Sensitivity Analysis

A sensitivity analysis has been carried out, and it can be seen that the results only prove the robustness of our proposed Fire Vulnerability Index, especially because with our proposed model, where the accessibility weight for the existing route network was subjected to variation at ±10%, its spatial distribution revealed a variation of less than 4% at the Area of Very High Vulnerability level. Furthermore, with respect to the levels of variation maintained at ±20%, the proposed model has been tested, and it has been observed that the spatial variation for critical clusters has been achieved only at quite a stable level.

The correctness of the ground truth is further validated to ascertain the appropriateness of the model. In fact, the ground inspection in ten locations, as identified by the model, as Very High Vulnerability Zones, has confirmed the existence of acutely hazardous conditions in nine locations, which correspond to the areas of illegal street encroachments, access route blockages, absence of fire hydrants in working condition, and highly fire-prone nature of the commercial activities. This suggests that the model gives a very good approximation of the real-world vulnerability, considering the deductive nature of the model.

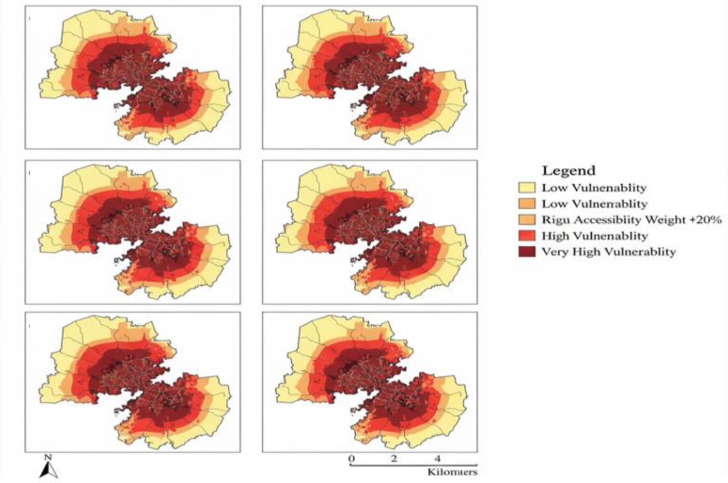

Figure 6. Results of sensitivity analysis illustrating the spatial stability of very high fire vulnerability zones under ±10% and ±20% variations in the weight assigned to road network accessibility. The persistence of core high-risk clusters indicates robustness of the AHP-based Fire Vulnerability Index.

4.5 Urban Morphology as a Determinant of Fire Risk

Such results highlight a basic but significant observation which is that the “fundamental reason” for fire vulnerability in urban areas in Nagpur is more related to ignition than to morphological constraints, in so far as the coincidence in the Very High fire vulnerability zones in historic urban neighborhoods may indicate some form of “lock-in” in so far as the initial street network constrains the potential of firefighting infrastructure. In these areas, the potential of firefighting infrastructure is severely constrained, notwithstanding the presence of fire stations and human resources.

This level of weighting also further supports the underlying premise of accessibility being a primary measure of the underlying constraint for infrastructure response times. As a further analysis of a basic tool for fire service planning, it was determined that buffer proximity analysis is also inadequate for dense urbanized areas, primarily because, as was determined and shown above, accessibility is actually a primary constraint for scenarios.

4.6 Thermal Stress as a Risk Multiplier

Furthermore, it can also be deduced that the inclusion of the information pertaining to land surface temperatures highlighted the level of association present around the level of fire vulnerabilities and urban heat islands. The areas that were recognized by the land surface temperatures, with temperatures higher than 42°C, indicate some similarity with the areas recognized as ones having some characteristic and definitions of urban areas with no impervious surfaces, with absolutely no kind of vegetative cover at all. The higher the temperatures, the higher the possibilities and the quicker they deteriorate, leading to fires.

This interplay between thermal components and structural elements reveals the presence of a concept in which the environment, rather than affecting the location, is acting as a multiplier of the risk to the vulnerable environment. The results demonstrate that GIs, as well as strategies to mitigate urban heat, are for the environment and for fire safety.

4.7 Comparison with Incident-Based Fire Risk Models

From this above comparison with the proposed fire vulnerability index based on AHP with respect to classical incident-based hotspot maps, some similarities and contradictions with respect to the above-mentioned areas have also been found, particularly since there has been a significant overlap with respect to the historic area, validating assumptions related to structurally vulnerable areas and existing phenomena of fire-related incidents within this area. The results have differed with respect to transitional peri-urban areas.

In the incident-based models, it has been identified that some of the regions in these rapidly densifying areas of the periphery are identified to be in the low-risk group simply because of the lack of major incidents of fire in these regions. But these have been identified in the AHP-based framework as being moderately and even highly vulnerable due to the increase in densities of buildings, lack of widths of the roads, and even due to the lack of time available in response. This would thus present us with a better illustration of the upmost predictive efficiency of deductive vulnerability modeling.

4.8 Implications for Urban Fire Governance

The spatial differentiation of the vulnerability to fires would need anchoring support through a governing scheme for these issues in urban planning. Furthermore, the non-structural widening of the road in the specific region under question, being part of the historic core, makes the technological interventions for these regions absolutely necessary and the justification needed for these interventions with regards to the particular concern in question. The provision of quick vehicle technology, the provision of motorcycle-based mist technologies, and the provision for storing water could help remedy the problem of inaccessibility in the areas that are vulnerable to fires, away from the fire stations.

In the case where there are moderate risk zones of transition, any action with respect to a regulative measure can be a necessity. The installation of minimum road widths, side yards, land use programs for a developing zone may be a necessity. These actions may be essential for avoiding risk pattern quality as it existed in reference to the historic core. The fire vulnerability index not only has diagnosing qualities but also has a predictive quality.

5. CONCLUSION

This study contributes to developing urban fire risk research by conceptualizing the idea of fire vulnerability as a latent characteristic, but not one constructed post-hoc based only on past fire accidents. The current research incorporates the Analytical Hierarchy Process technique and Geographic Information Systems methodology in developing a deductive conceptual paradigm for creating the Fire Vulnerability Index that could detect the underlying susceptibility within the urban built environment of Nagpur City. This introduced methodology changes the paradigm in urban fire risk research and encourages the use of proactive research rather than reactive research.

The findings show that morphology and accessibility are the constraints that strongly influence the level of fire vulnerability in Nagpur city. The high-risk fire prone areas, including the historic nature of neighborhoods such as Gandhibagh, Mahal, and Itwari, are identified not just for the recurrence of fires, but also for the poor efficacy of emergency services. This is supported through the weighting factors obtained through the AHP method, where the factor influencing fire vulnerability the most is the accessibility of the road network. This challenges conventional approaches to fire planning and the applicability of distance-based service area solutions in the urban core area.

Possibly the most important single achievement that the research discussed in the paper can contribute is that it addresses the role of land surface temperatures as an environmental multiplier for assessing risks. Undoubtedly, the spatial relationship between urban heat island zones and fire vulnerability zones creates the critical nexus where the enhancement of the climatic conditions intensifies the risks of ignitions within the congested neighborhood zones. Such a state demonstrates the expanded dimensions involved in fire risk assessment, which now incorporates climate-sensitive urban design as part of the fire mitigation process.

The notable difference between the proposed fire vulnerability index and the models developed in relation to the occurrence of fires should give further credence to the utilization of the deductive methodology, keeping in mind that, while it does show marked correspondence in line with the hotspots of fire occurrence in the historic zone, which in itself is a zone of structural vulnerability, there are increasing zones of vulnerability concern in the areas of increasing density in the urban periphery, still outside the realms of fire occurrence, and already sprouting into zones of concern prior to the occurrence of fire events.

From the governance standpoint, the results highlight the significance of context-specific fire-related interventions. For structurally constrained historic areas, improving infrastructure by widening roads is not feasible; hence, interventions could be focused on technological solutions, including compact fire-fighting vehicles, local storage facilities, etc. On the other hand, for the transitional and peripheral regions, regulatory interventions in the context of road wideness, setbacks, and land-use regulation could limit the reproduction of high fire-risk morphologies identified within the urban core. The ward-level vulnerability results developed within the current study could be useful in prioritizing such fire-related interventions.

Although the study contributed to the aforementioned advancements, the paper also has some limitations. In the vulnerability study, the activities of the system are based on static data and are not taking into consideration the dynamics of the system, which include the risks of congestions that might occur in the near future, the seasonal wind, and the continuously changing number of people. Although the judgement has been validated based on the consistency judgement, there is an element of subjective weighting in the judgement itself.

Therefore, in essence, one is able to clearly ascertain the implications and results derived from this exposition is that the immediate contribution of the present research is to offer the promise of developing a structure pertaining to the fire vulnerability assessment in the context of the urbanization process in the countries constituting the Global South. Thus, by establishing a clear linkage between the fire risks and the quantified structural and environmental variables, the methodological framework ensures a scientifically proper basis is developed to promote a shift in the management of the urban fire risk in a forward direction appropriate for the types of resilience.

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