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# Assessing Flood Vulnerability Using GIS Spatial Analytics to Inform Infrastructure Planning, Emergency Response and Community Resilience Strategies

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## Abstract

Flood risk poses a persistent and escalating threat to lives, infrastructure, and economic stability, particularly in the United States where climate variability, urban expansion, and aging drainage systems amplify exposure. This study assesses flood vulnerability using Geographic Information System (GIS)-based spatial analytics to support evidence-driven infrastructure planning, emergency response, and community resilience strategies. A U.S.-based case study integrates hydrological data, digital elevation models, land-use patterns, soil characteristics, population density, and critical infrastructure layers to construct a composite Flood Vulnerability Index. Spatial multi-criteria analysis and hotspot mapping are applied to identify high-risk zones, vulnerable populations, and infrastructure bottlenecks under historical and extreme rainfall scenarios. Results demonstrate clear spatial disparities in flood exposure and adaptive capacity, with low-lying urban neighborhoods and transport corridors exhibiting disproportionate vulnerability. Scenario-based analyses further show how targeted interventions such as green infrastructure placement, drainage upgrades, and prioritized emergency routing can substantially reduce risk concentrations. The findings highlight the value of GIS spatial analytics in translating complex environmental and socio-economic data into actionable insights for planners and emergency managers. By grounding resilience strategies in spatially explicit evidence, this approach supports proactive flood risk mitigation, equitable resource allocation, and improved preparedness across U.S. communities facing intensifying flood hazards nationwide planning contexts.

**Keywords:** Flood vulnerability; GIS spatial analytics; Infrastructure planning; Emergency response; Community resilience

## 1. Introduction

### 1.1. Background and Motivation

Flooding has become one of the most recurrent and economically damaging natural hazards in the United States, affecting both inland and coastal regions with increasing regularity [1]. Empirical evidence indicates that the frequency, severity, and spatial reach of flood events have intensified over recent decades, driven by changes in precipitation extremes, storm dynamics, and sea-level rise [2]. These evolving patterns have translated into escalating direct and indirect losses, including damage to housing, transportation networks, utilities, and public services, reinforcing flood risk as a national policy priority [3].

Climate variability significantly amplifies flood risk through shifts in rainfall intensity, storm duration, and seasonal hydrological cycles, particularly in regions already prone to flooding [4]. Concurrently, rapid urbanisation has altered

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natural landscapes, increasing impervious surface coverage and accelerating surface runoff during heavy rainfall events [5]. Land-use change, including development within floodplains and wetlands, has further reduced natural water retention capacity, exacerbating flood exposure in many metropolitan and peri-urban areas [6].

Infrastructure stress represents a critical dimension of contemporary flood vulnerability. Much of the United States' stormwater, transportation, and utility infrastructure was designed based on historical hydrological assumptions that no longer reflect current or projected conditions [3]. As flood events exceed design thresholds, infrastructure failure can trigger cascading socio-economic impacts, including prolonged service disruptions, economic losses, and public health risks [7]. These impacts are not evenly distributed, as communities with limited resources often face greater exposure and slower recovery [8]. Consequently, there is a growing need for analytical frameworks that integrate physical flood hazards with socio-economic vulnerability to support more adaptive and equitable flood risk management strategies [9].

### **1.2. Flood Risk Management Challenges in the United States**

Flood risk management in the United States faces persistent challenges despite advances in hydrological modeling and hazard assessment technologies [6]. Traditional floodplain mapping approaches, which rely heavily on historical flood records and fixed return periods, often fail to account for dynamic drivers such as climate change, land-use transitions, and infrastructure expansion [1]. As a result, flood risk is frequently underestimated, particularly in areas outside officially designated high-risk zones [2].

Institutional fragmentation further complicates effective flood management. Infrastructure planning, land-use regulation, and emergency response are commonly managed by separate agencies operating under different mandates and time horizons [7]. This lack of integration can delay preparedness measures, limit data sharing, and reduce the effectiveness of coordinated response during flood emergencies [3]. Post-disaster recovery efforts may also be hindered when long-term resilience planning is disconnected from immediate response strategies [8].

Equity concerns are central to these challenges. Numerous studies show that low-income communities and marginalized populations are disproportionately exposed to flood hazards due to historical zoning practices, housing affordability constraints, and limited access to protective infrastructure [4]. These groups often experience higher losses and slower recovery, underscoring the need for flood risk assessment tools that explicitly incorporate social vulnerability alongside physical exposure [9].

### **1.3. Role of GIS Spatial Analytics in Flood Vulnerability Assessment**

GIS spatial analytics provides a robust methodological foundation for addressing the complex and interconnected drivers of flood vulnerability [5]. By enabling the integration of topographic, hydrological, land-use, demographic, and infrastructure datasets within a unified spatial environment, GIS supports comprehensive assessments of flood risk across multiple dimensions [6]. This spatial integration allows analysts to examine how physical flood hazards intersect with population distribution, critical facilities, and socio-economic conditions [8].

Compared to single-factor hazard models that focus solely on inundation extent or flood depth, GIS-based approaches facilitate multi-criteria decision analysis and vulnerability indexing [9]. Techniques such as weighted overlay, spatial clustering, and hotspot analysis allow for the identification of areas where exposure, sensitivity, and limited adaptive capacity converge [7]. These capabilities make GIS spatial analytics particularly valuable for informing infrastructure prioritization, emergency response planning, and resilience-oriented policy interventions [3].

### **1.4. Research Objectives and Contributions**

This study aims to assess flood vulnerability using GIS spatial analytics to support infrastructure planning, emergency response, and community resilience strategies in the United States [1]. The research develops a composite Flood Vulnerability Index (FVI) that integrates hydrological, physical, and socio-economic indicators within a spatial multi-criteria framework [9]. Using a U.S.-based case study, the study demonstrates how GIS-driven vulnerability mapping can identify high-risk communities and infrastructure bottlenecks [6]. The findings provide spatially explicit, policy-relevant decision-support outputs to guide equitable flood mitigation, preparedness, and long-term resilience planning [8].

## 2. Conceptual framework and theoretical foundations

### 2.1. Flood Vulnerability as a Multidimensional Construct

Flood vulnerability is widely recognized as a multidimensional concept that extends beyond physical flood hazard to encompass social, economic, and institutional characteristics that influence potential damage and recovery capacity [7]. Contemporary vulnerability frameworks conceptualize flood risk as a function of exposure, sensitivity, and adaptive capacity, each representing a distinct but interrelated dimension of impact [8].

Exposure refers to the presence of people, infrastructure, and economic assets located within flood-prone areas [9]. In the U.S. context, exposure is shaped by settlement patterns, land-use decisions, and infrastructure siting, particularly in low-lying urban and peri-urban regions [10]. High exposure does not necessarily imply high vulnerability, but it establishes the spatial precondition for potential flood impacts.

Sensitivity describes the degree to which exposed elements are affected when a flood event occurs [11]. Sensitivity is influenced by factors such as building quality, infrastructure age, population demographics, and dependence on flood-sensitive livelihoods or services [12]. For example, transportation corridors, healthcare facilities, and low-income housing often exhibit high sensitivity due to limited redundancy and structural resilience [8].

Adaptive capacity represents the ability of individuals, communities, and institutions to anticipate, cope with, and recover from flood impacts [13]. This dimension encompasses access to emergency services, financial resources, governance effectiveness, and social networks [7]. Communities with strong adaptive capacity may experience lower overall vulnerability despite high exposure, highlighting the importance of integrating social and institutional indicators into flood vulnerability assessments [14]. Recognizing flood vulnerability as a composite of these three dimensions provides a robust conceptual foundation for spatially explicit risk analysis [15].

### 2.2. GIS-Based Vulnerability Modeling Framework

GIS-based vulnerability modeling provides a systematic framework for operationalizing the multidimensional nature of flood vulnerability through spatial data integration and analysis [9]. GIS enables the combination of raster data, such as digital elevation models and rainfall surfaces, with vector data, including land-use polygons, infrastructure networks, and administrative boundaries [10]. This integration allows diverse physical and socio-economic indicators to be analyzed within a consistent spatial reference system [11].

Raster-based analysis is particularly effective for representing continuous flood-related variables such as elevation, slope, flow accumulation, and inundation probability [12]. Vector datasets, by contrast, are well suited for representing discrete features such as roads, buildings, utilities, and emergency facilities [13]. The joint use of raster and vector data enhances analytical precision and supports multi-scale vulnerability assessment.

Spatial Multi-Criteria Decision Analysis (SMCDA) forms the analytical core of many GIS-based vulnerability frameworks [14]. SMCDA enables the evaluation of multiple indicators with differing units and relative importance through normalization, weighting, and aggregation [15]. By embedding expert judgment and policy priorities into spatial analysis, SMCDA supports transparent and reproducible vulnerability mapping. This approach is especially valuable for flood risk management, where trade-offs between physical hazard, social vulnerability, and infrastructure resilience must be explicitly considered [8].

### 2.3. Mathematical Formulation of Flood Vulnerability Index

To quantify spatial variations in flood vulnerability, this study employs a composite Flood Vulnerability Index (FVI) constructed using a weighted linear combination of standardized indicators [7]. The FVI is calculated at each spatial unit  $i$  according to the following formulation:

$$FVI_i = \sum_{j=1}^n w_j \cdot X_{ij}$$

where:

$FVI_i$  represents the flood vulnerability score at spatial unit  $i$ ;

$X_{ij}$  denotes the normalized value of indicator  $j$  at spatial unit  $i$ ;

$w_j$  is the weight assigned to indicator  $j$ ;

$n$  is the total number of indicators;

$$\sum_{j=1}^n w_j = 1.$$

This additive structure assumes that individual vulnerability components contribute independently and cumulatively to overall flood vulnerability [9]. The formulation is widely adopted in spatial vulnerability and risk assessment studies due to its conceptual clarity and computational efficiency [10]. By applying the index at fine spatial resolution, localized vulnerability patterns can be identified that may be obscured in aggregate analyses [11].

The FVI framework supports scenario analysis by allowing indicator weights or values to be modified to reflect alternative planning assumptions or intervention strategies [12]. Moreover, the index structure facilitates sensitivity testing, enabling the evaluation of how changes in specific indicators influence overall vulnerability outcomes [13]. This mathematical formulation thus provides a flexible and transparent mechanism for translating complex, multidimensional flood risk factors into actionable spatial information for planners and emergency managers [14,15].

#### 2.4. Weighting Techniques and Normalization

Indicator normalization is a critical step in composite index construction, ensuring comparability across variables with different units and scales [8]. This study applies min–max normalization, expressed as:

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

where  $X'$  is the normalized indicator value [9]. Weight assignment is guided by the Analytical Hierarchy Process (AHP), which systematically incorporates expert judgment through pairwise comparisons [14]. AHP enhances transparency and consistency in weighting decisions, reducing subjectivity while aligning indicator importance with flood risk management priorities [15].

### 3. study area and data sources (U.S. CASE STUDY)

#### 3.1. Geographic and Climatic Characteristics of the Study Area

The study area is located within the United States and represents a flood-prone region characterized by complex interactions between hydrology, climate, and human settlement patterns [13]. The regional hydrological system is shaped by a combination of riverine networks, surface runoff pathways, and low-lying floodplains that are highly sensitive to extreme precipitation events [14]. Major watersheds within the area exhibit variable flow regimes, with seasonal fluctuations that influence flood magnitude and duration [15].

Rainfall patterns across the study area are marked by increasing variability, with a documented rise in short-duration, high-intensity precipitation events linked to climate change [16]. These rainfall extremes exceed the absorptive capacity of both natural landscapes and engineered drainage systems, increasing the likelihood of pluvial and fluvial flooding [17]. Spatial heterogeneity in rainfall distribution further contributes to localized flood hotspots, particularly in urbanized sub-catchments [18].

Historically, the study area has experienced recurrent flood events resulting in substantial economic losses, infrastructure damage, and community displacement [19]. Flood records indicate that both riverine flooding and surface-water flooding have intensified over recent decades, reflecting the combined influence of climatic drivers and land-use transformation [14]. Past flood events have disproportionately affected low-income neighborhoods and critical transportation corridors, underscoring the need for spatially explicit vulnerability assessment [20]. These geographic and climatic characteristics make the study area suitable for examining flood vulnerability through integrated GIS spatial analytics.

#### 3.2. Data Collection and Preprocessing

Flood vulnerability assessment requires the integration of multiple spatial datasets capturing physical, environmental, and socio-economic dimensions of risk [13]. In this study, data collection focused on acquiring high-resolution, publicly available geospatial datasets relevant to flood processes and human exposure within the study area [15].

A Digital Elevation Model (DEM) was used to derive elevation, slope, and flow accumulation layers essential for modeling surface runoff and flood propagation [16]. The DEM data were preprocessed to remove sinks and ensure hydrological consistency, which is critical for accurate flood hazard representation [17]. Land-use/land-cover (LULC) data were incorporated to capture surface permeability, urban expansion, and floodplain encroachment patterns [18].

Soil permeability data were obtained to represent infiltration capacity and runoff potential, reflecting spatial variability in soil texture and drainage properties [14]. Drainage networks, including rivers, streams, and stormwater infrastructure, were mapped to analyze flow connectivity and flood transmission pathways [19]. These datasets enable the identification of areas where drainage capacity may be exceeded during extreme rainfall events.

Socio-economic exposure was represented using population density data, allowing the identification of densely populated areas with heightened flood risk [20]. Critical infrastructure layers including hospitals, emergency facilities, roads, utilities, and public service buildings were included to assess functional vulnerability and emergency response constraints [15]. All datasets underwent preprocessing steps including format conversion, attribute cleaning, and spatial clipping to the study boundary.

**Table 1** Data sources, spatial resolution, and thematic relevance

Data Layer	Data Source	Spatial Resolution / Scale	Thematic Relevance to Flood Vulnerability
Digital Elevation Model (DEM)	U.S. Geological Survey (USGS) National Elevation Dataset	10–30 m raster	Derivation of elevation, slope, and flow accumulation; identification of low-lying flood-prone areas
Land-Use / Land-Cover (LULC)	National Land Cover Database (NLCD)	30 m raster	Representation of impervious surfaces, urban expansion, and surface runoff potential
Soil Permeability / Hydrologic Soil Groups	USDA Natural Resources Conservation Service (NRCS) SSURGO	Polygon (variable scale)	Assessment of infiltration capacity and runoff generation characteristics
Drainage Networks (Rivers & Streams)	National Hydrography Dataset (NHD)	Vector (1:24,000)	Modeling of hydrological connectivity, flow paths, and flood transmission zones
Stormwater & Drainage Infrastructure	Local/State GIS Portals	Vector (asset-level)	Identification of drainage bottlenecks and infrastructure exposure to flooding
Population Density	U.S. Census Bureau (Decennial Census / ACS)	Census block or tract	Measurement of human exposure and identification of high-risk population concentrations
Socio-Economic Indicators	American Community Survey (ACS)	Census tract	Representation of social sensitivity and adaptive capacity (income, age, housing conditions)
Transportation Networks	U.S. Department of Transportation / TIGER	Vector (road centerlines)	Assessment of evacuation route exposure and transportation system vulnerability
Critical Infrastructure (Hospitals, Schools, Utilities)	Homeland Infrastructure Foundation-Level Data (HIFLD)	Point/Polygon	Evaluation of functional vulnerability and emergency response constraints

### 3.3. Spatial Resolution, Projection, and Data Harmonization

To ensure analytical consistency, all spatial datasets were harmonized to a common coordinate reference system and spatial resolution prior to analysis [16]. Projection selection was guided by minimizing spatial distortion across the

study area while maintaining compatibility with national geospatial standards [17]. Raster datasets were resampled to a uniform cell size to enable accurate overlay and index computation [18].

Data harmonization involved aligning raster and vector layers through spatial snapping, edge matching, and topology validation [14]. Attribute normalization and reclassification were applied to ensure consistency in indicator representation across datasets [19]. These steps reduced spatial misalignment errors and ensured that vulnerability calculations accurately reflected spatial relationships among hazard, exposure, and adaptive capacity indicators [20]. Harmonization is particularly critical in multi-criteria GIS analysis, where inconsistencies can propagate uncertainty into composite indices.

### 3.4. Assumptions and Limitations of the Dataset

Several assumptions underpin the dataset used in this study. First, static representations of land use, population, and infrastructure are assumed to approximate current conditions, despite temporal variability [13]. Second, publicly available datasets may contain classification errors or spatial generalizations that introduce uncertainty [15]. Additionally, the analysis assumes uniform data quality across the study area, which may not fully capture localized conditions [18]. These limitations highlight the need for cautious interpretation of results and support future integration of dynamic, real-time, and higher-resolution data sources to enhance flood vulnerability assessment [20].

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## 4. Methodology: gis spatial analytics workflow

### 4.1. Flood Hazard Layer Generation

Flood hazard layer generation constitutes the foundation of the GIS-based flood vulnerability assessment, as it characterizes the physical processes governing flood occurrence and propagation [18]. In this study, flood hazard modeling is derived primarily from topographic and hydrological indicators, with elevation and slope serving as critical determinants of surface runoff behavior and inundation potential [19].

Elevation data extracted from the Digital Elevation Model (DEM) were used to identify low-lying areas susceptible to water accumulation during extreme rainfall events [20]. Slope was computed to assess terrain steepness, which directly influences runoff velocity and infiltration capacity. The slope gradient was calculated using the following expression:

$$\text{Slope} = \tan^{-1} \left( \frac{\Delta z}{\Delta d} \right)$$

where  $\Delta z$  represents the change in elevation and  $\Delta d$  denotes horizontal distance between adjacent cells [21]. Areas with gentle slopes were assigned higher flood susceptibility scores due to slower runoff and increased likelihood of water stagnation [18].

Flow accumulation modeling was subsequently performed to identify drainage convergence zones and potential flood pathways [22]. Using hydrologically corrected DEMs, flow direction and accumulation grids were generated to represent upstream contributing areas [23]. High flow accumulation values indicate locations where runoff concentrates, increasing flood hazard under intense precipitation [24]. These layers collectively form the flood hazard component of the vulnerability framework, capturing both terrain-controlled exposure and hydrological connectivity across the landscape [25].

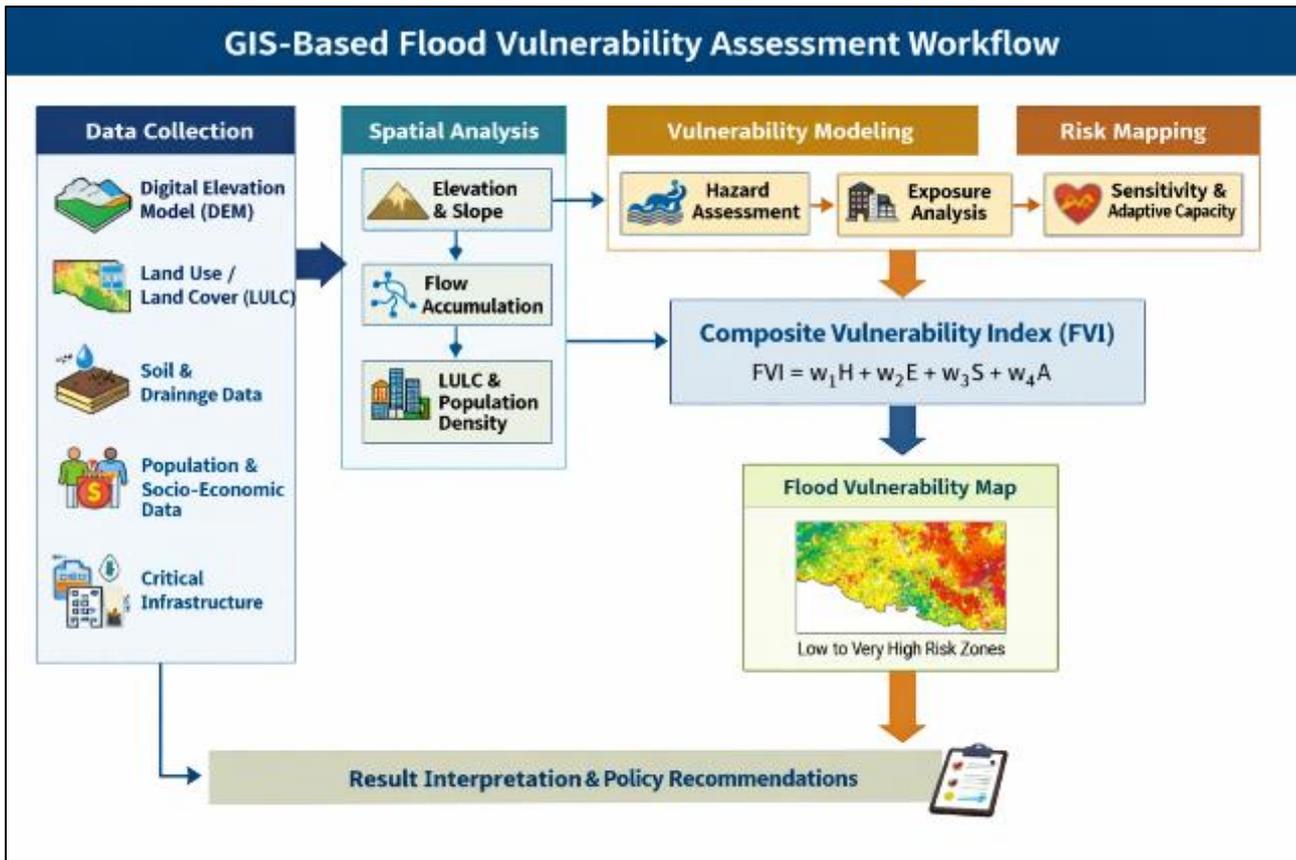


Figure 1 GIS-based flood vulnerability assessment workflow

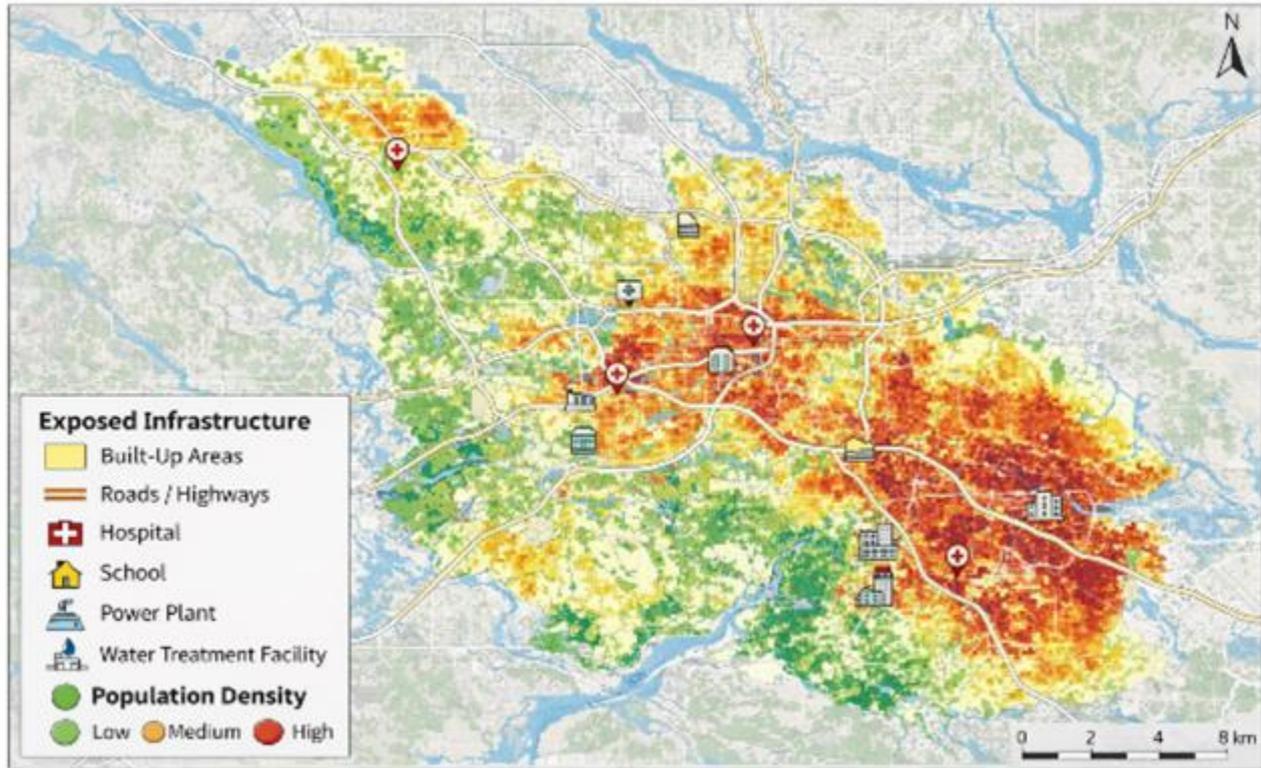
#### 4.2. Exposure Analysis

Exposure analysis evaluates the spatial distribution of people, assets, and infrastructure located within flood-prone areas, representing the elements potentially affected by flood hazards [18]. In this study, exposure was assessed through the integration of built-up areas, transportation networks, utilities, and public facilities within the GIS environment [19].

Built-up areas were extracted from land-use and land-cover (LULC) datasets to identify residential, commercial, and industrial zones vulnerable to flooding [20]. Urban areas were assigned higher exposure values due to dense asset concentration and higher potential for economic loss [21]. Transportation corridors, including major roads and bridges, were mapped to assess network exposure and the risk of mobility disruption during flood events [22].

Utilities and public facilities such as power substations, water treatment plants, schools, and emergency service buildings were incorporated to evaluate functional exposure [23]. These facilities are critical for maintaining essential services during and after flood events, and their disruption can produce cascading impacts beyond the immediate flood zone [24]. Population density data were overlaid with exposed infrastructure to identify areas where high human exposure coincides with critical asset vulnerability [25].

By spatially intersecting flood hazard layers with exposed elements, the analysis identifies zones where physical flooding is most likely to intersect with human and infrastructural systems. This spatial representation of exposure supports targeted mitigation and emergency planning decisions [19].



**Figure 2** Spatial distribution of exposed infrastructure and population [22]

#### 4.3. Sensitivity and Adaptive Capacity Modeling

Sensitivity and adaptive capacity modeling captures the differential impacts of flooding across communities and infrastructure systems, recognizing that not all exposed elements experience flood impacts equally [18]. Sensitivity reflects the degree to which exposed populations and assets are affected, while adaptive capacity represents the ability to anticipate, cope with, and recover from flood events [19].

Socio-economic indicators were used to represent population sensitivity, including income levels, age distribution, housing conditions, and social vulnerability metrics [20]. Populations with limited financial resources, higher dependency ratios, or substandard housing were assigned higher sensitivity scores due to reduced coping capacity during flood events [21]. These indicators were spatially normalized and incorporated into the vulnerability framework to reflect heterogeneous social impacts [22].

Emergency accessibility was modeled using proximity analysis to emergency services, evacuation routes, and response facilities [23]. Areas with longer travel times to emergency services were considered more vulnerable due to delayed response and evacuation challenges [24]. Healthcare and shelter proximity were also evaluated, with greater distances indicating lower adaptive capacity and increased post-flood risk [25].

The integration of sensitivity and adaptive capacity indicators allows the framework to move beyond hazard-centric analysis and capture social and institutional dimensions of flood vulnerability. This approach ensures that vulnerability mapping reflects both physical exposure and the uneven capacity of communities to respond to and recover from flood impacts [18].

**Table 2** Flood vulnerability indicators and assigned weights

Vulnerability Dimension	Indicator	Description / Rationale	Weight ( $w_i$ )
Flood Hazard	Elevation	Low-lying areas have higher flood susceptibility	0.12
	Slope	Gentle slopes promote water accumulation and inundation	0.08
	Flow Accumulation	High upstream contributing area increases flood potential	0.10
Exposure	Land-Use / Built-Up Density	Dense urban development increases asset exposure	0.12
	Population Density	Higher population concentration increases potential impacts	0.10
	Transportation Infrastructure Density	Exposure of critical mobility and evacuation routes	0.08
Sensitivity	Housing Condition	Poor-quality housing increases flood damage severity	0.07
	Age Dependency Ratio	Elderly and children are more vulnerable during floods	0.06
	Economic Status (Income Proxy)	Lower income reduces coping and recovery capacity	0.07
Adaptive Capacity	Distance to Emergency Services	Longer distances increase response time and risk	0.06
	Healthcare Facility Accessibility	Limited access reduces post-flood recovery capacity	0.06
	Shelter Availability	Fewer shelters reduce evacuation effectiveness	0.04
—	Total		1.00

#### 4.4. Composite Vulnerability Index Construction

The composite Flood Vulnerability Index (FVI) was constructed through raster overlay and weighted summation of hazard, exposure, sensitivity, and adaptive capacity layers [19]. Each indicator layer was first normalized to a common scale to ensure comparability across datasets with different units and ranges [20]. Normalized layers were then combined using a weighted linear aggregation approach consistent with spatial multi-criteria decision analysis principles [21].

Raster overlay techniques were applied to integrate individual indicators at the cell level, producing a continuous vulnerability surface across the study area [22]. Weights assigned to each indicator reflected their relative importance in influencing flood vulnerability, as determined through expert judgment and Analytical Hierarchy Process (AHP) procedures [23]. The weighted summation approach allows transparent interpretation of how individual factors contribute to overall vulnerability [24].

The resulting FVI map provides a spatially explicit representation of flood vulnerability, enabling comparison across locations and supporting scenario-based analysis [25]. This composite approach balances methodological rigor with computational efficiency, making it suitable for practical planning and decision-support applications.

## 5. Hotspot and Risk Classification

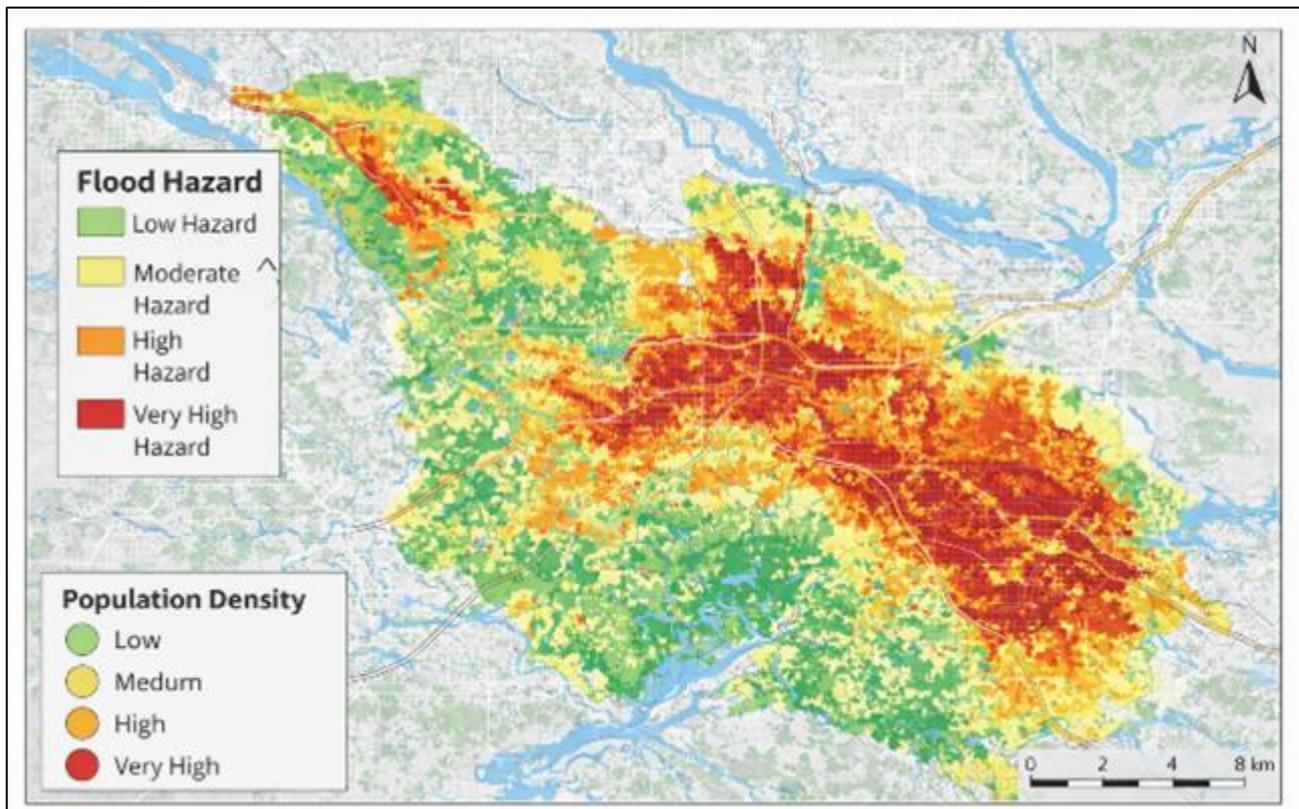
To enhance interpretability, the continuous FVI values were classified into discrete vulnerability categories using established spatial classification techniques [18]. The Natural Breaks (Jenks) method was employed to identify statistically meaningful groupings by minimizing intra-class variance and maximizing inter-class differences [22]. This approach is well suited for spatial vulnerability mapping where values are unevenly distributed [23].

In parallel, quantile classification was applied to ensure equal representation of spatial units within each vulnerability class [24]. Comparing both methods enabled robustness checks and facilitated sensitivity analysis of classification effects [25]. Hotspot analysis was subsequently conducted to identify clusters of high vulnerability, supporting targeted intervention and resource allocation. These classification outputs translate complex vulnerability metrics into actionable spatial insights for planners and emergency managers [19].

### 5.1. Flood Hazard Zonation Results

The flood hazard zonation results reveal pronounced spatial variability in flood susceptibility across the study area, reflecting the combined influence of topography, hydrological connectivity, and drainage characteristics [23]. Areas characterized by low elevation and gentle slopes exhibit significantly higher flood hazard scores due to reduced runoff velocity and increased water accumulation potential [24]. These zones are predominantly concentrated along river corridors, floodplains, and poorly drained urban sub-catchments [25].

Flow accumulation analysis further refines hazard delineation by identifying drainage convergence zones where upstream runoff is likely to concentrate during extreme precipitation events [26]. Cells with high flow accumulation values consistently align with historically flood-affected locations, validating the effectiveness of the hazard modeling approach [27]. In contrast, upland areas with steeper slopes and lower contributing catchment areas demonstrate comparatively lower flood hazard, although localized risks persist near artificial drainage bottlenecks [23].



**Figure 3** Flood hazard zonation map of the study area

The resulting flood hazard zonation map categorizes the study area into low, moderate, high, and very high hazard classes, providing a clear spatial representation of flood-prone zones [28]. High and very high hazard areas occupy a relatively small proportion of total land area but account for a disproportionate share of historical flood impacts [29].

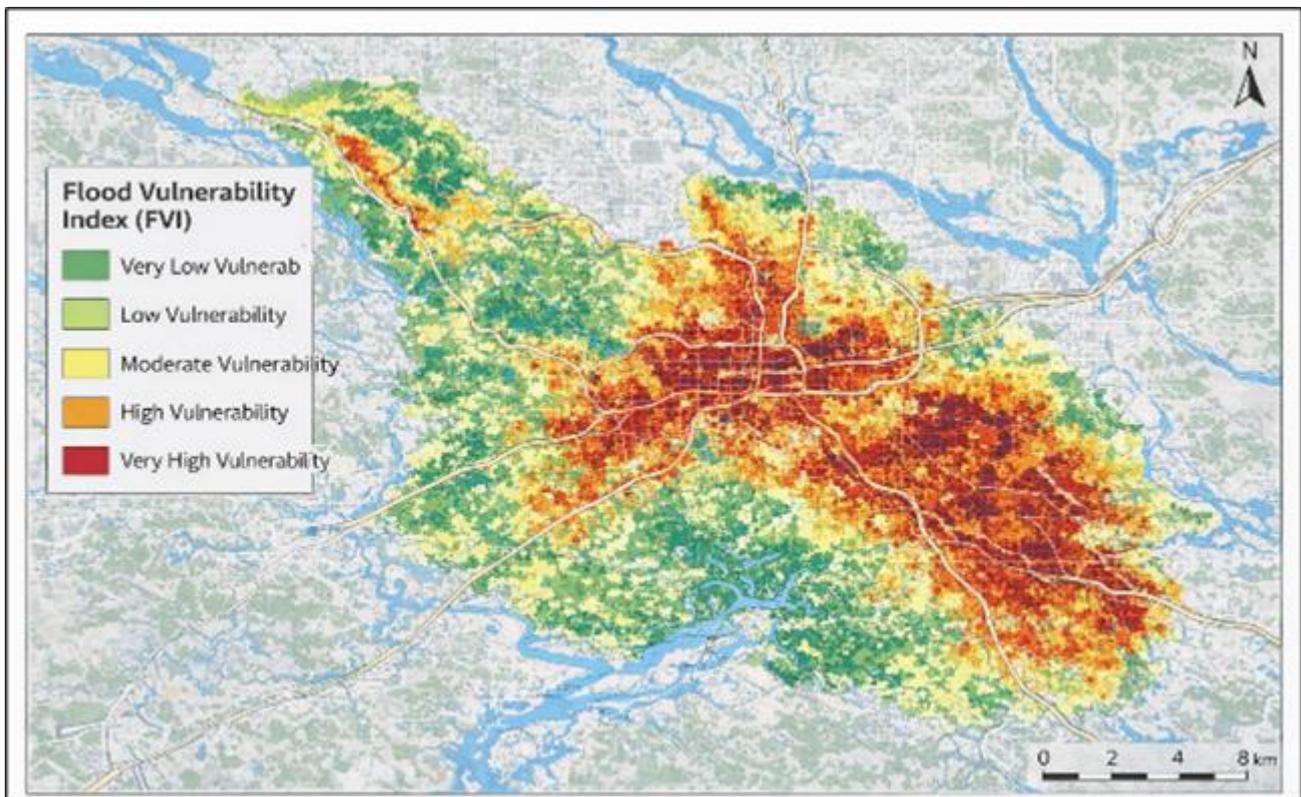
These results underscore the importance of spatially explicit hazard assessment in identifying priority zones for flood mitigation and emergency preparedness planning.

## 5.2. Flood Vulnerability Index Mapping

The composite Flood Vulnerability Index (FVI) map integrates flood hazard, exposure, sensitivity, and adaptive capacity indicators to provide a comprehensive spatial depiction of flood vulnerability [23]. Unlike hazard maps that reflect only physical flood potential, the FVI reveals how social and infrastructural characteristics modulate flood impacts across the study area [24]. As a result, areas with moderate hazard levels may still exhibit high vulnerability due to dense populations, sensitive infrastructure, or limited adaptive capacity [25].

Spatial analysis of the FVI map shows that high and very high vulnerability zones are clustered primarily within urban and peri-urban areas, where intense development coincides with constrained drainage systems and high population density [26]. These clusters are particularly evident in neighborhoods with aging infrastructure and limited access to emergency services, amplifying overall vulnerability [27]. Conversely, some high-hazard rural areas display lower composite vulnerability due to sparse population and greater adaptive capacity, highlighting the value of multidimensional assessment [28].

The FVI map also reveals transitional zones of moderate vulnerability, where targeted interventions could significantly reduce flood risk [29]. These areas often represent rapidly urbanizing fringes with increasing exposure but still-developing adaptive capacity [23]. The spatial continuity of vulnerability patterns suggests that flood risk is not randomly distributed but structured by underlying socio-environmental processes [24]. Overall, the FVI mapping provides actionable insights for prioritizing infrastructure investment, land-use regulation, and resilience-building initiatives.



**Figure 4** Composite Flood Vulnerability Index (FVI) map

## 5.3. Identification of High-Risk Communities and Infrastructure

The identification of high-risk communities and infrastructure highlights significant disparities in flood vulnerability across the study area [25]. High-vulnerability zones are disproportionately associated with communities characterized by lower income levels, higher population density, and limited access to emergency resources [26]. These findings align with broader evidence that socio-economic disadvantage amplifies flood impacts and slows recovery processes [27].

Disproportionate impacts are particularly evident in neighborhoods located within historical floodplains that have undergone extensive urban development [28]. In these areas, residential housing, transportation corridors, and public utilities are frequently co-located within high-hazard zones, increasing the likelihood of cascading failures during flood events [29]. Transportation infrastructure, including arterial roads and bridges, emerges as a critical vulnerability hotspot due to its role in evacuation, emergency response, and economic continuity [23].

Comparative analysis reveals notable differences between urban and peri-urban vulnerability patterns [24]. Urban cores exhibit high vulnerability driven by dense exposure and infrastructure sensitivity, even where flood hazard levels are moderate [25]. Peri-urban areas, by contrast, often display rapidly increasing vulnerability as land-use change outpaces infrastructure adaptation [26]. These transitional zones face compounded risk due to expanding development, limited drainage capacity, and insufficient emergency service coverage [27]. Identifying these spatial patterns supports more equitable flood risk management by directing attention to communities and assets facing the greatest cumulative risk [28].

## 6. Statistical Summary of Vulnerability Classes

Statistical analysis of flood vulnerability classes provides quantitative insight into the distribution of vulnerability across land-use types within the study area [23]. Classification results indicate that a substantial proportion of built-up and mixed-use areas fall within the high and very high vulnerability categories, reflecting the convergence of hazard exposure, population density, and infrastructure sensitivity [24]. In contrast, agricultural and open land areas are more frequently associated with low to moderate vulnerability classes, despite occasional high hazard levels [25].

The distribution of vulnerability classes varies systematically across land-use categories, underscoring the influence of human activity on flood risk outcomes [26]. Residential and commercial zones account for the majority of high-vulnerability areas, while transportation and utility corridors contribute disproportionately to very high vulnerability due to their critical functional roles [27]. These findings highlight the importance of protecting infrastructure assets whose failure can generate cascading impacts beyond their immediate footprint [28].

Statistical summaries also reveal spatial clustering of high-vulnerability classes, suggesting that flood risk management interventions may benefit from area-based rather than asset-specific strategies [29]. By quantifying vulnerability distribution across land-use types, the analysis supports evidence-based prioritization of mitigation measures and resource allocation.

**Table 3** Distribution of flood vulnerability classes across land-use types

Land-Use Type	Low Vulnerability (%)	Moderate Vulnerability (%)	High Vulnerability (%)	Very High Vulnerability (%)
Residential	18.4	32.7	31.5	17.4
Commercial / Industrial	21.6	29.3	30.2	18.9
Transportation Corridors	12.1	26.8	34.6	26.5
Public & Critical Infrastructure	14.7	28.4	33.1	23.8
Mixed-Use Urban Areas	16.9	31.2	32.4	19.5
Agricultural Land	42.3	34.8	16.1	6.8
Open / Green Spaces	48.6	33.5	12.4	5.5

### 6.1. Infrastructure Planning and Investment Prioritization

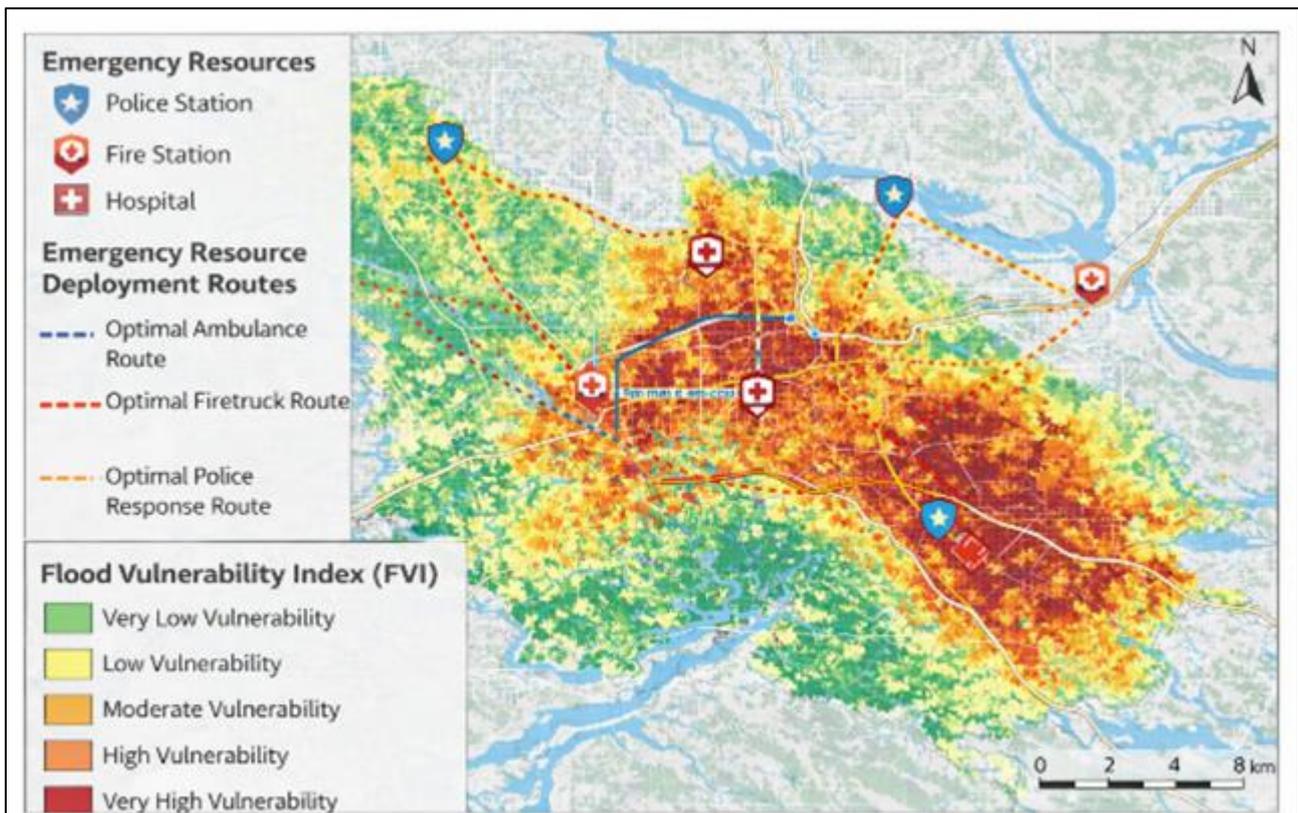
The spatial patterns revealed by the Flood Vulnerability Index (FVI) have direct implications for infrastructure planning and investment prioritization within flood-prone regions of the United States [27]. By identifying zones where high hazard intersects with concentrated exposure and limited adaptive capacity, GIS-based vulnerability mapping enables planners to move from reactive repairs toward proactive, risk-informed infrastructure investment [28].

Drainage upgrades emerge as a critical priority in high-vulnerability urban and peri-urban areas. Results indicate that many flood hotspots coincide with undersized or aging stormwater systems unable to accommodate intensified rainfall events [29]. Targeted drainage improvements such as increasing conveyance capacity, retrofitting culverts, and separating combined sewer systems can significantly reduce surface flooding and downstream impacts when aligned with spatial vulnerability patterns [30].

Transportation resilience is another key planning implication. Major roadways, bridges, and transit corridors frequently overlap with high-vulnerability zones, amplifying economic losses and emergency response challenges during flood events [27]. Integrating flood vulnerability maps into transportation asset management allows agencies to prioritize elevation, reinforcement, or rerouting of critical corridors that serve evacuation and emergency access functions [31].

The results also support strategic green infrastructure siting as a complementary flood mitigation approach. Vulnerability mapping highlights areas where nature-based solutions such as bioswales, retention basins, permeable pavements, and restored wetlands can reduce runoff while providing co-benefits for urban cooling and environmental quality [32]. By spatially targeting green infrastructure investments to high-vulnerability zones, planners can maximize flood risk reduction while enhancing long-term system resilience [33].

## 6.2. Emergency Response Optimization



**Figure 5** Emergency response optimization using flood vulnerability maps

Flood vulnerability mapping provides actionable intelligence for optimizing emergency response planning and operations [28]. By overlaying hazard intensity, population exposure, and infrastructure sensitivity, emergency managers can identify locations where response delays or access constraints are most likely during flood events [29].

Evacuation route planning benefits significantly from this spatial insight. Results show that several high-vulnerability communities rely on transportation corridors that are themselves exposed to flooding, increasing the risk of isolation during emergencies [30]. Incorporating vulnerability maps into evacuation modeling enables the identification of alternative routes, priority clearance corridors, and staging areas that remain accessible under flood conditions [31]. This approach supports more reliable evacuation strategies, particularly for populations with limited mobility or access to private transportation [32].

Emergency facility placement is similarly informed by vulnerability analysis. Facilities such as shelters, emergency operations centers, and medical response units must be accessible to high-risk populations while remaining operational during flood events [33]. The spatial results indicate that some existing facilities are located within moderate to high vulnerability zones, potentially compromising response effectiveness [27]. Vulnerability-informed site selection can guide the relocation, reinforcement, or redundancy of emergency facilities to ensure continuity of operations under extreme flood scenarios [28].

### 6.3. Community Resilience and Equity Considerations

The findings underscore the central role of equity in flood resilience planning, as vulnerability is unevenly distributed across socio-economic and demographic groups [29]. High-vulnerability zones are disproportionately associated with low-income households, elderly populations, and communities with limited access to insurance, healthcare, and emergency resources [30]. These groups often experience greater losses and longer recovery periods following flood events [31].

Integrating vulnerability mapping into resilience planning enables more inclusive and just decision-making by explicitly identifying communities that face compounded risk [32]. Rather than allocating resources solely based on hazard exposure, planners can prioritize interventions that reduce social vulnerability and enhance adaptive capacity in underserved areas [27]. Examples include targeted infrastructure upgrades, improved emergency communication, and expanded access to shelters and recovery assistance [28].

Resource allocation fairness is a critical policy implication of this approach. Spatially explicit vulnerability metrics provide a transparent basis for directing public investment toward communities with the greatest need, reducing the risk of politically driven or inequitable distribution of resources [33]. By aligning infrastructure planning and emergency preparedness with vulnerability evidence, decision-makers can strengthen community resilience while advancing broader goals of social equity and environmental justice [29].

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## 7. Discussion

### 7.1. Comparison with Existing Flood Risk Assessment Approaches

Conventional flood risk assessment approaches in the United States have historically emphasized hydrological modeling and floodplain delineation based on probabilistic return periods, such as the 100-year flood standard [30]. While these methods provide valuable insight into flood extent and inundation probability, they often focus narrowly on physical hazard characteristics and underrepresent socio-economic vulnerability and infrastructure sensitivity [31]. As a result, traditional assessments may underestimate risk in areas where moderate flood hazards intersect with high population density or limited adaptive capacity [32].

In contrast, the GIS-based vulnerability framework adopted in this study aligns with emerging risk assessment paradigms that conceptualize flood risk as a product of hazard, exposure, and vulnerability [33]. Unlike static floodplain maps, spatial vulnerability indices capture spatial heterogeneity in social conditions, infrastructure resilience, and emergency accessibility, providing a more nuanced representation of real-world flood impacts [34]. Furthermore, conventional approaches often rely on aggregated administrative units, which can obscure localized risk patterns [30]. The cell-based GIS methodology used here allows fine-scale analysis, supporting more targeted mitigation and response strategies [35]. This comparison highlights the limitations of hazard-only assessments and reinforces the value of integrated, vulnerability-focused spatial analysis for contemporary flood risk management.

### 7.2. Strengths of GIS-Driven Spatial Vulnerability Modeling

GIS-driven spatial vulnerability modeling offers several methodological and practical advantages over traditional flood risk assessment techniques [36]. One of its primary strengths lies in its ability to integrate diverse datasets ranging from topographic and hydrological variables to socio-economic indicators and infrastructure networks within a unified analytical framework [37]. This integration enables comprehensive assessment of flood vulnerability that reflects both physical and social dimensions of risk [38].

Another key strength is spatial explicitness. GIS-based models reveal localized vulnerability patterns that are often masked in regional or administrative-scale analyses [39]. This spatial granularity supports precision planning, allowing decision-makers to prioritize interventions at the neighborhood or asset level [40]. The use of spatial multi-criteria decision analysis further enhances transparency by explicitly documenting indicator selection, weighting, and aggregation processes [41].

GIS-based vulnerability modeling also supports scenario analysis and adaptability. Indicator weights and inputs can be modified to reflect alternative planning assumptions, climate projections, or policy priorities [31]. This flexibility makes GIS frameworks particularly well suited for dynamic flood risk environments, where uncertainty and change are inherent [32]. Collectively, these strengths position GIS-driven vulnerability modeling as a robust tool for advancing evidence-based flood resilience planning.

### **7.3. Policy Relevance and Scalability Across U.S. Regions**

The findings of this study have direct policy relevance for flood risk management across diverse U.S. regions [33]. By translating complex spatial data into interpretable vulnerability maps, the GIS-based framework supports risk-informed decision-making in infrastructure investment, land-use regulation, and emergency preparedness [34]. Such evidence is increasingly critical as federal, state, and local agencies seek to allocate limited resources under intensifying climate-related pressures [35].

A key advantage of the proposed framework is its scalability. The methodology relies primarily on publicly available geospatial datasets and standardized GIS techniques, enabling replication across urban, suburban, and rural contexts [30]. This adaptability allows policymakers to tailor vulnerability assessments to regional hydrological conditions, development patterns, and socio-economic characteristics [31]. Moreover, the framework can be integrated into existing planning instruments, including hazard mitigation plans and capital improvement programs [32].

Importantly, the explicit incorporation of social vulnerability enhances alignment with equity and environmental justice objectives [33]. By identifying communities facing compounded flood risk, the approach supports fairer distribution of mitigation funding and resilience investments [34]. As climate-driven flood risk continues to evolve, scalable GIS-based vulnerability modeling offers a practical pathway for strengthening flood resilience across the United States [35].

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## **8. Conclusions and future research directions**

### **8.1. Key Findings**

This study demonstrates that flood vulnerability in the United States is shaped by the interaction of physical flood hazards, infrastructure exposure, and socio-economic conditions rather than by hazard intensity alone. The GIS-based spatial analytics framework developed in this research reveals pronounced spatial heterogeneity in flood vulnerability, with high-risk zones often occurring where moderate flood hazards intersect with dense populations, sensitive infrastructure, and limited adaptive capacity. The composite Flood Vulnerability Index (FVI) successfully captures these multidimensional dynamics, enabling the identification of communities and assets facing compounded flood risk.

The results show that urban and peri-urban areas exhibit the highest vulnerability due to extensive impervious surfaces, constrained drainage capacity, and high dependence on interconnected infrastructure systems. At the same time, the analysis highlights disparities in vulnerability across socio-economic groups, indicating that flood impacts are not evenly distributed. By moving beyond hazard-only mapping, the study provides a more realistic representation of flood risk that aligns with observed flood impacts and recovery challenges. Overall, the findings confirm that spatially integrated vulnerability assessment is essential for understanding flood risk in complex, human-dominated landscapes.

### **8.2. Practical Contributions to Flood Risk Management**

The study makes several practical contributions to flood risk management and resilience planning. First, it provides a transferable GIS-based methodology that can be applied by planners and emergency managers using commonly available spatial data. Second, the vulnerability maps generated through the FVI offer a clear basis for prioritizing infrastructure investments, such as drainage upgrades and transportation resilience measures, in areas of greatest need. Third, the framework supports more effective emergency response planning by identifying communities likely to face evacuation constraints or delayed access to critical services during flood events.

Importantly, the approach facilitates more equitable flood risk management by explicitly incorporating social vulnerability into decision-making. By linking technical flood analysis with community-level impacts, the study bridges the gap between engineering assessments and policy-oriented resilience planning, supporting more targeted and just allocation of flood mitigation resources.

### 8.3. Limitations and Future Research Opportunities

Despite its contributions, the study has several limitations that suggest avenues for future research. The analysis relies on static spatial datasets, which may not fully capture temporal variations in land use, population distribution, or infrastructure conditions. Incorporating dynamic flood modeling could improve representation of time-varying flood processes and event-specific impacts. Future studies may also benefit from the integration of real-time sensors, such as rainfall gauges, stream monitors, and Internet-of-Things devices, to enhance situational awareness and near-real-time vulnerability assessment.

Additionally, AI-enhanced spatial prediction offers promising opportunities to improve flood vulnerability modeling by identifying non-linear relationships among indicators and enhancing predictive accuracy under changing climate conditions. Combining GIS-based frameworks with machine learning and real-time data streams could support more adaptive, forward-looking flood risk management strategies.

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### Compliance with ethical standards

#### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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