TECHNICAL COMMUNICATION,
ISSN / eISSN 0049-3155,
Publisher : SOC TECHNICAL COMMUNICATION,
9401 LEE HIGHWAY, STE 300,
FAIRFAX, USA, VA, 22031
Volume 25-Issue 1-(2025)
http://doi.org/10.65281/660899

Analytical Framework for Social Vulnerability Indicators in Flood Risk Mapping by GIS: A Case Study of Tebessa City, Algeria.

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Sumbit in: January 2025
Accepted: Mars 2025
Publication: ..... December 2025

1. Abstract:

This study develops a GIS-based analytical framework to analyze social vulnerability to flooding in Tebessa, northeastern Algeria. Three categories of indicators—social, economic, and physical—were analyzed using recent spatial and statistical datasets. The results show that the highest levels of vulnerability are concentrated in the historic city center and surrounding informal settlements, where population density, poverty rates, and building density are significantly elevated. These areas also contain aging infrastructure and intense commercial activity, which together amplify exposure and reduce the capacity to cope with flood hazards. In contrast, peripheral districts exhibit lower vulnerability due to newer construction, improved planning, and lower demographic pressure. The integrated mapping of these indicators allowed the identification of vulnerability hotspots and provided a spatially explicit understanding of risk patterns across the city. The study highlights the need for targeted interventions aimed at infrastructure improvement, drainage enhancement, and social support to strengthen flood resilience in Tebessa.

Key words: Social vulnerability, indicators, flood risk, GIS, Tebessa city.

2. INTRODUCTION

Floods remain one of the most frequent and damaging natural hazards worldwide, and their impacts have grown increasingly severe due to intensifying climate variability and rapid urban expansion (Lenderink & van Meijgaard 2008; Balica et al. 2012). Extreme precipitation events—primary drivers of flood occurrences—have become more variable and intense in recent decades, increasing hydrological uncertainty and exposing urban populations to greater risk (Costa & Soares 2009). Climate model projections consistently indicate that warming atmospheric conditions will further amplify precipitation intensity, particularly in semi-arid and Mediterranean regions (Emori & Brown 2005; Groisman et al. 2005; Pall et al. 2007). As a result, flood-prone cities must reassess hazard patterns and vulnerability dynamics in order to develop effective risk management strategies.

Tebessa City, located in northeastern Algeria, is no exception. The city has experienced recurrent flooding driven by a combination of intense rainfall events, geomorphological constraints, and unregulated urban expansion into natural drainage pathways. Similar to other urban centers in North Africa, rapid demographic growth and informal land development have increased exposure to hydrometeorological hazards, amplifying the socio-economic impacts of flood events (Douglas et al. 2008; Liao 2012). These trends underscore the necessity of addressing not only the physical drivers of flooding but also the social dimensions that shape how communities experience and respond to hazard events.

Within contemporary flood risk research, risk is conceptualized as the interaction between **hazard** and **vulnerability**, where vulnerability refers to the conditions that influence a population's capacity to anticipate, cope with, and recover from hazardous events (Alexander 2000; Wisner et al. 2004). Vulnerability itself is multidimensional and shaped by a combination of social, economic, demographic, and environmental factors (Westen & Kingma 2009). It encompasses three major analytical components: exposure, sensitivity, and adaptive capacity (Adger 2006; Fekete 2009b; Tate 2011). Social vulnerability—focusing on the socio-economic characteristics of individuals or groups—is particularly critical in flood-prone urban contexts, as marginalized populations often face disproportionately higher levels of risk (Cutter et al. 2003; Wisner et al. 2004).

Geographic Information Systems (GIS) have emerged as essential tools for mapping and analyzing these complex dimensions of vulnerability. By integrating socio-economic indicators with spatial flood hazard data, GIS enables detailed visualization of risk patterns and supports more informed decision-making for disaster preparedness and urban planning (Gouldby & Samuels 2005). Developing a GIS-based analytical framework for identifying social vulnerability indicators is therefore crucial for cities such as Tebessa city, where spatial inequalities and rapid urbanization intensify the consequences of extreme hydrological events.

In this context, this study proposes an analytical framework for analyzing social vulnerability in flood-prone areas of Tebessa City using GIS. By systematically integrating demographic, socio-economic, and urban indicators, this approach offers a comprehensive understanding and accurate analysis of the vulnerability of local communities to flood risks, ultimately supporting more targeted and equitable flood risk management strategies.

2. MATERIALS AND METHODS

2.1 Study Area

Tebessa city, as a border city, faces a series of structural challenges that constrain its economic development and hinder progress toward sustainable urban growth. To contextualize these issues, it is first necessary to situate the city geographically, particularly in relation to its exposure to flood risk.

Situated in the extreme eastern region of Algeria, Tebessa occupies a strategically significant position between the Tellian zones and the southern highland areas extending toward the pre-Saharan regions. The city lies approximately 16 km from the Algerian–

Tunisian border in a straight line, or 45 km via National Road No. 10. It is located 130 km south of Souk Ahras along National Road No. 16, 233 km from Annaba, 200 km from Constantine, and 634 km southeast of Algiers (URBA-BA, 2018).

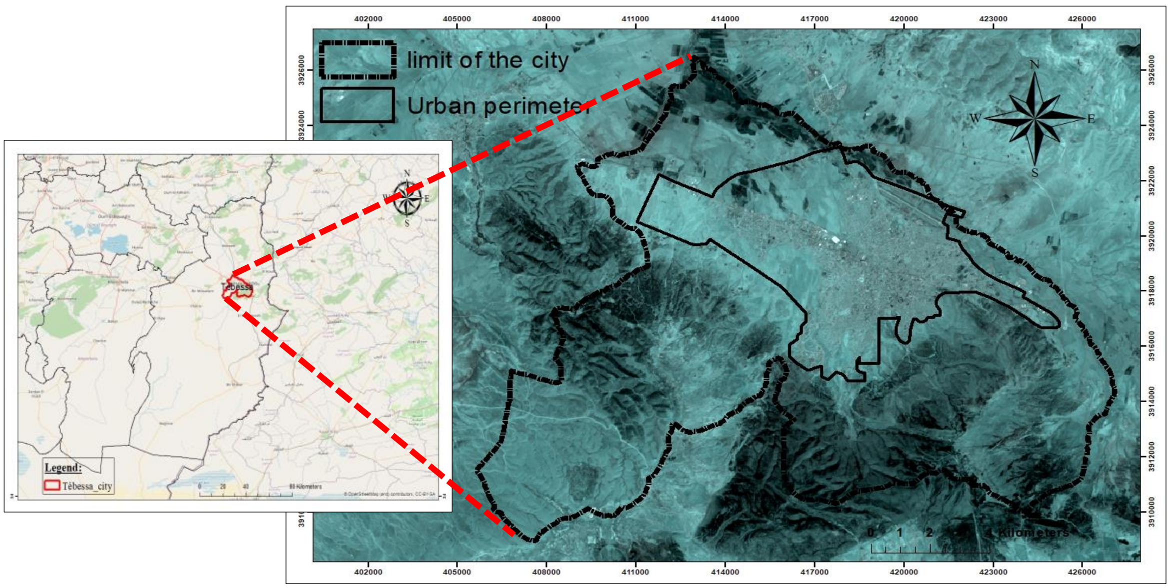


Fig.01: Location of study area.

2.2 Methodological Framework

The social vulnerability model to flood risk was applied to the municipality of Tebessa city (figure 1), where several flood events have occurred in the recent past (protection civil as a source). The following data were used in this study: geographic information from the Algerian Population Census and Statistics issued by the Directorate of Planning and Programming (DPAT), and land use data issued by the Directorate of Urban Planning, Architecture, and Construction of the Wilaya of Tebessa (DUAC).

The 2025 census data is geographic reference information based on small territorial units called land use plans. Which is the territorial unit that defines the smallest homogeneous area, dividing the urban perimeter of the city of Tebessa into 36 sections and representing a block within the urban area. Furthermore, the highly detailed master plan for development and urban planning regulates the population concentration within the city (PDAU source urba-batna 2018).

According to previous studies, there are three important indicators were extracted in the process of analyzing societal vulnerability, such are:

a. *Demographic indicator:*

The demographic indicator encompasses the population characteristics and social attributes that shape a community's exposure and sensitivity to flood hazards. It includes classic demographic variables such as age structure, dependency ratio, gender distribution, and household size, but also integrates broader social factors that critically influence vulnerability. **Population density** plays a major role, as densely populated areas typically face higher exposure, greater pressure on emergency services, and increased difficulty during evacuation or response operations. Similarly, the **poverty rate** is a key determinant of demographic vulnerability, as economically disadvantaged populations often lack the resources required to adequately prepare for, cope with, or recover from flood impacts. Collectively, these demographic and social characteristics determine how effectively different population groups can anticipate, withstand, and recover from flood events. **(Cutter et al., 2003; Wisner et al., 2004; Adger, 2006; Blaikie et al., 1994; Balica et al., 2012)**

b. *Economic indicator:*

The economic indicator reflects the financial capacity and material conditions that influence a community's ability to resist, absorb, and recover from flood hazards. It incorporates variables such as household income, employment levels, property ownership, housing quality, and overall access to economic resources. A crucial component of this indicator is the structure and distribution of **economic activities**, as areas dependent on fragile or informal economic sectors are generally more vulnerable to disruption during flood events. Communities that rely on stable, diversified, or resilient economic activities tend to recover more quickly, whereas those dependent on daily-wage labor, small-scale commerce, or climate-sensitive sectors face heightened socio-economic impacts. Therefore, the economic indicator captures not only the financial assets of a population but also the robustness and vulnerability of the local economic system. **(Blaikie et al., 1994; Tate, 2012; Balica et al., 2012; Wisner et al., 2004)**

c. *Facilities indicator:*

The facilities indicator refers to the availability, accessibility, and spatial distribution of essential services and critical infrastructure that support community resilience during flood events. This includes access to health care centers, educational institutions, emergency shelters, transportation networks, and basic utilities such as water, sanitation, and electricity. In addition to service-related variables, this indicator incorporates **physical and urban characteristics** that significantly influence vulnerability. **Building density** is an important factor, as highly compacted urban areas often face elevated exposure levels, limited evacuation routes, and increased pressure on emergency response systems. Similarly, **building age** is a key determinant of structural vulnerability; older structures are frequently constructed with outdated materials or techniques that may not withstand intense hydrometeorological events. Together, these infrastructural and urban factors determine the degree to which the built environment supports or undermines a community's capacity to prepare for, respond to, and recover from flooding.

(Gouldby & Samuels, 2005; Westen & Kingma, 2009; Fekete, 2009a; Douglas et al., 2008)

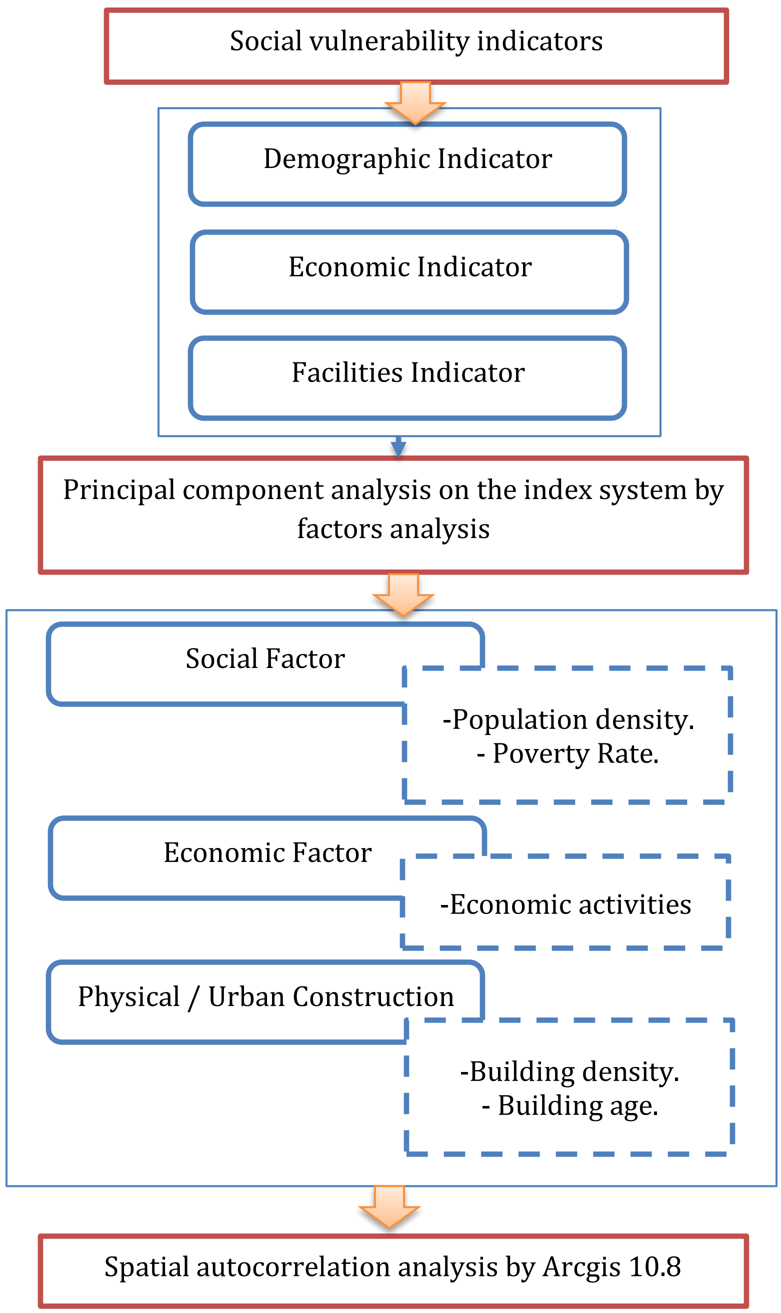


Fig.02: Methodological flowchart of spatial autocorrelation analysis.

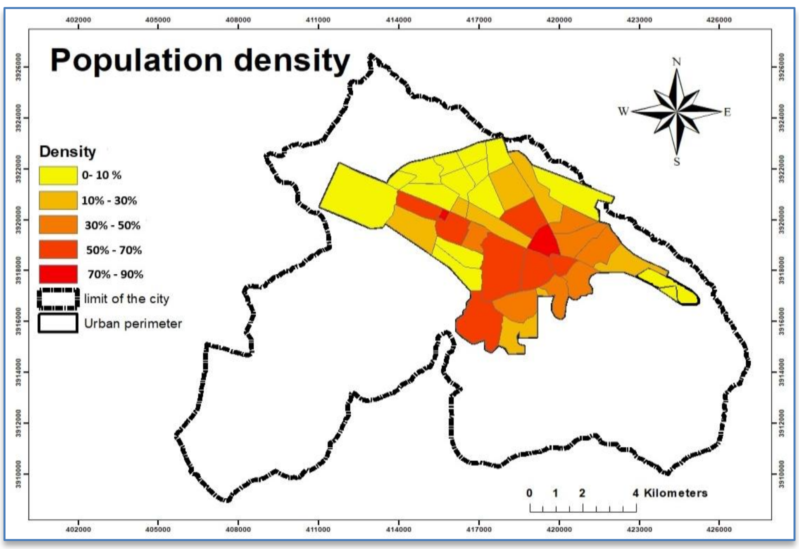
3. RESULTS

3.1 Social Vulnerability Index Results

The results show a set of maps that were extracted using Geographic Information Systems, particularly the ArcGIS software, and which were divided into three groups as presented in the research methodology of the paper.

Social Factor:

The two maps presented below illustrate the spatial distribution of population density and poverty rates within the city of Tebessa (Figure N°03), based on the most recent data provided by the Directorate of Planning and Programming of the Wilaya of Tebessa. The analysis reveals a clear concentration of high population density in the central urban core, particularly within the historic city center. This area, characterized by narrow streets and compact urban morphology, extends along National Route N° 16, which functions as the primary structural axis of the city and facilitates connectivity between its major districts.



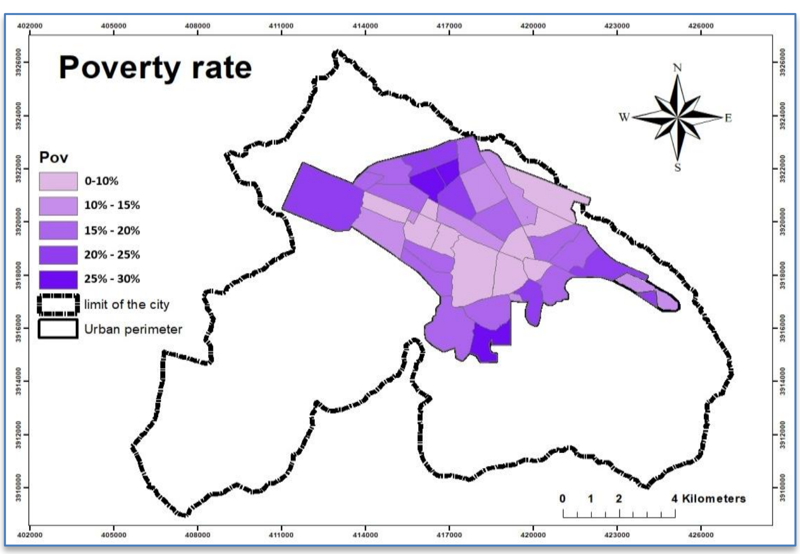


Fig.03: Maps of population density and poverty rate in Tebessa city.

In contrast, the spatial pattern of poverty displays a different yet overlapping distribution. The poverty rate map indicates that socio-economically vulnerable populations are predominantly located in older, densely built urban zones, with a marked presence in informal and under-serviced settlements. Neighborhoods such as Zawiya, Bouhaba, and El Merdja show particularly elevated poverty levels. These areas are typified by aging housing stock, limited access to infrastructure, and inadequate urban services, conditions that exacerbate social vulnerability and heighten susceptibility to flood-related impacts.

The combined interpretation of these two indicators—population density and poverty rate—highlights the existence of socially vulnerable clusters within Tebessa. These findings are of particular importance for flood risk assessment, as densely populated and economically disadvantaged districts tend to have reduced adaptive capacity and face greater challenges in preparedness, emergency response, and post-disaster recovery.

Economic Factor:

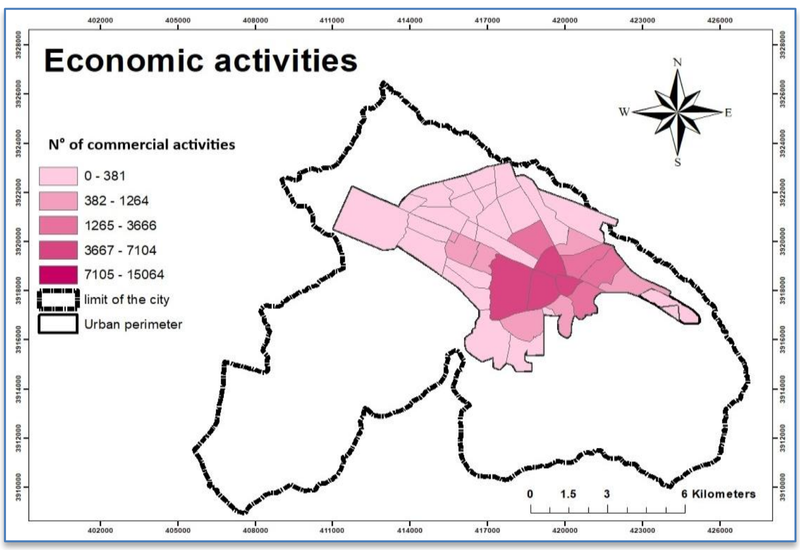
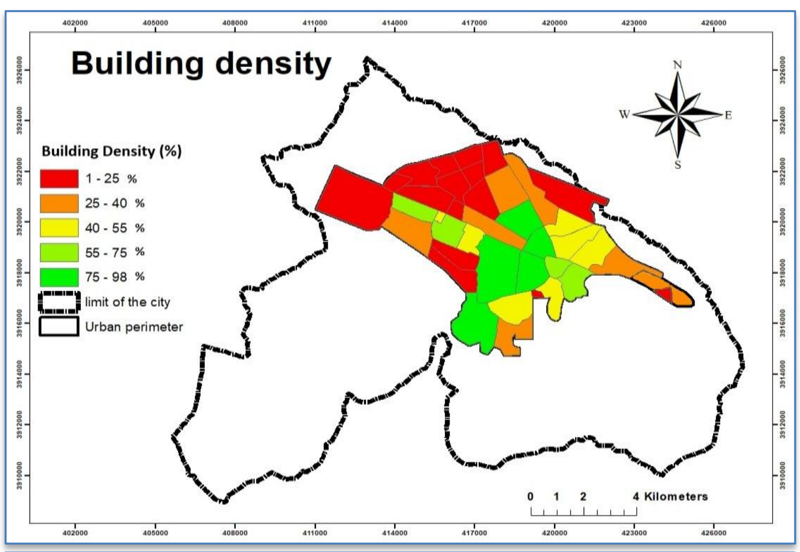


Fig.04: Map of Economic activities in Tebessa city.

According to the map of (Figure N°04) shows the spatial distribution of residential and public facilities, the city of Tebessa exhibits a clearly defined commercial core. The spatial analysis of economic activities shows a strong concentration of commercial functions in the heart of the city, which operates as its economic **"beating heart."** This central zone hosts an estimated **3,667 to 15,064** commercial establishments, representing the full spectrum of legally registered commercial activities within the urban perimeter. This dense commercial clustering not only shapes the socio-economic dynamics of the city but also influences patterns of land use, mobility, and exposure to urban risks—particularly in areas where commercial expansion intersects with vulnerable flood-prone zones.

Physical / Urban Construction:

The spatial analysis of the physical and urban indicators, represented through the building density and building age maps, reveals clear patterns that significantly influence flood vulnerability in the city of Tebessa. The highest building densities—reaching 75–98%—are concentrated in the historic urban core and along major circulation axes, reflecting compact, highly urbanized tissues with minimal open space and therefore limited infiltration capacity. Surrounding these zones, medium-density districts form a transitional belt characterized by mixed residential development and mid-twentieth-century urban expansion. In contrast, the peripheral neighborhoods exhibit low building density and more available open space, corresponding largely to recent planned developments. The building age map reinforces this spatial gradient, showing that the oldest structures are clustered in the central core, where aging infrastructure and traditional urban forms further amplify exposure to flood hazards. Mid-aged districts extend outward from this nucleus, while the newest constructions are located on the urban fringe, generally benefiting from modern planning regulations and improved drainage systems. Together, these patterns highlight that the combination of **high density and older building stock** in the central areas constitutes the most critical physical vulnerability zone, whereas newer, lower-density peripheries exhibit comparatively reduced levels of risk.



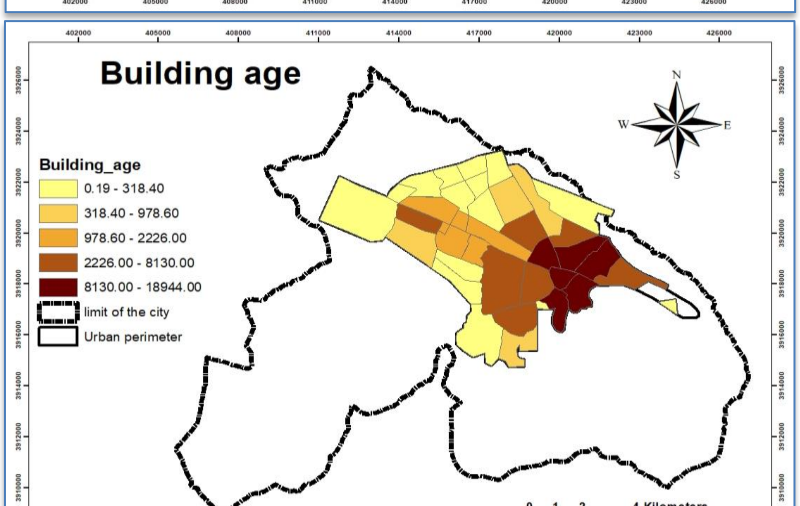


Fig.05: Maps of building density and building age in Tebessa city.

4. DISCUSSION

The integrated analysis of social, economic, and physical indicators provides a comprehensive understanding of the spatial dynamics of vulnerability to flooding in Tebessa. The social factor analysis demonstrates that population density and poverty are unevenly distributed across the city, forming identifiable clusters of heightened vulnerability. High population densities are concentrated in the historic center, where compact urban morphology and constrained street networks characterize the built environment. These conditions pose significant challenges during flood events, including limited evacuation capacity and increased exposure of dense residential blocks to runoff accumulation. Simultaneously, the spatial pattern of poverty reveals that economically disadvantaged populations are disproportionately located in older urban fabrics and informal settlements such as Zawiya, Bouhaba, and El Merdja. These areas not only lack adequate services and infrastructure but also exhibit socio-economic fragility that reduces their ability to anticipate, withstand, and recover from flood impacts. The overlap between high density and poverty intensifies social vulnerability, indicating that the central districts of Tebessa are at elevated risk due to both demographic pressures and socio-economic deprivation.

The analysis of economic factors reinforces this conclusion by highlighting the strong centralization of commercial activities within the urban core. Serving as the economic backbone of the city, this area hosts a high concentration of legal commercial establishments, forming the primary hub of economic exchange. While this commercial clustering contributes to urban vitality and economic growth, it also introduces additional layers of vulnerability. High concentrations of commercial activities attract large daily population flows, increase impervious surfaces, and place additional stress on mobility networks. Moreover, flood events in such economically dense zones would likely result in substantial disruption to businesses, supply chains, and livelihoods, further amplifying the social and economic consequences for the local population. Thus, the city’s economic core represents a zone of dual importance: a focal point for development but also a critical node of potential flood-related disruption.

Physical and urban construction factors further explain the spatial differentiation of vulnerability within Tebessa. The highest building densities coincide with the oldest parts of the city, where the urban fabric is compact and infrastructure aging. These characteristics severely limit water infiltration, accelerate surface runoff, and increase the risk of local flooding. Older buildings and drainage systems in these districts may be structurally ill-equipped to cope with intense rainfall events, thereby compounding physical exposure. In contrast, peripheral areas characterized by lower building densities and newer construction benefit from improved land-use planning, greater availability of open spaces, and modern infrastructure. These features collectively reduce both exposure and sensitivity to flooding, positioning the urban peripheries as comparatively resilient zones.

When analyzed collectively, the three dimensions—social, economic, and physical—converge to reveal a consistent spatial pattern: Tebessa's central districts exhibit the highest concentration of vulnerability due to the combined effects of dense population, poverty, aging infrastructure, and intense commercial activity, whereas the peripheral zones demonstrate lower vulnerability due to more recent development, improved infrastructure, and reduced demographic pressures. These findings underscore the need for targeted flood risk mitigation strategies that prioritize the historic urban core and vulnerable informal settlements, focusing on infrastructure rehabilitation, social support programs, and land-use regulation reforms. Only through an integrated, multi-dimensional approach can the city enhance its resilience and reduce the disproportionate risk borne by its most vulnerable populations.

5. CONCLUSION

This study provides a multidimensional assessment of social, economic, and physical vulnerability to flooding in the city of Tebessa, demonstrating that flood risk is the outcome of complex interactions between demographic pressures, socio-economic conditions, and urban form. The results highlight a clear spatial polarization of vulnerability, with the historic urban core and adjacent informal settlements emerging as the most at-risk areas. These districts are characterized by high population density, elevated poverty rates, concentrated commercial activity, and aging infrastructure—factors that collectively heighten exposure and reduce the capacity of local communities to cope with and recover from flood events.

In contrast, the peripheral zones of the city exhibit lower levels of vulnerability due to their newer construction, lower building density, and improved urban planning frameworks. This spatial disparity underscores the uneven distribution of risk across Tebessa and emphasizes the urgent need for targeted interventions. Strengthening resilience in the highly vulnerable central districts should therefore be a priority, with strategies focusing on infrastructure rehabilitation, enhancement of drainage systems, regulation of informal urban expansion, and social programs aimed at supporting economically fragile households.

Overall, the integrated analytical approach employed in this research demonstrates its effectiveness for identifying vulnerability hotspots and guiding risk-informed urban planning. By combining social, economic, and physical indicators through GIS-based mapping, the study provides a robust foundation for the development of evidence-based flood risk management policies in Tebessa. Future efforts should aim to integrate hydrological modeling, climate projections, and participatory community assessments to further refine flood risk mitigation strategies and support the long-term sustainability and resilience of the city.

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