Flood Risk Mapping Based on Geographic Information System Analysis

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Abstract: *Flood events are increasing in frequency and severity worldwide due to climate change, rapid urbanization, and land-use transformation. Flood risk mapping has therefore become a critical tool for disaster risk reduction and spatial planning. This study aims to develop and analyze a flood risk mapping framework based on Geographic Information System (GIS) and multi-criteria decision analysis techniques. The research integrates physical, environmental, and socio-economic factors including rainfall intensity, slope, elevation, land use, soil type, drainage density, and population exposure. Analytical Hierarchy Process (AHP) and weighted overlay analysis were applied to derive flood risk indices and spatial risk zoning. The results classify the study area into very low, low, moderate, high, and very high flood risk zones. High-risk zones are primarily located in low-lying floodplains with dense settlements and poor drainage conditions. The findings are consistent with previous studies in Asia, Africa, and Europe, demonstrating the robustness of GIS-based multi-criteria approaches for flood risk assessment. This research contributes to the growing body of evidence that GIS-based flood risk mapping is an effective and scalable tool for supporting disaster mitigation, land-use planning, and policy formulation. The study recommends integrating GIS-based flood risk maps into regional planning frameworks to improve flood preparedness and resilience.*

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INTRODUCTION

Flooding represents one of the most frequent and destructive natural hazards globally, causing severe social, economic, and environmental impacts. Its increasing intensity and spatial extent are closely associated with climate change, which has altered precipitation patterns and increased the frequency of extreme rainfall events (Ibanga & Idehen, 2020; Cai et al., 2021). At the same time, rapid urbanization and land-use change have reduced infiltration capacity, increased surface runoff, and intensified exposure in flood-prone areas. These interacting processes have transformed flooding from a primarily hydrological phenomenon into a complex socio-environmental risk. Consequently, flood risk assessment has become a central concern for disaster risk reduction, sustainable development, and spatial planning.

Flood risk is commonly defined as the interaction between hazard, exposure, and vulnerability. Hazard refers to the physical probability and magnitude of flood events, exposure denotes the presence of people, infrastructure, and assets in flood-prone areas, and vulnerability reflects the susceptibility of those elements to damage. Traditional flood studies focused mainly on hazard modeling using hydrological and hydraulic approaches. However, such approaches alone are insufficient for understanding and managing flood impacts because they do not capture the spatial

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distribution of human exposure and socio-economic vulnerability. This limitation has driven the development of integrative frameworks that combine physical and social dimensions of flood risk.

Geographic Information System has emerged as a key platform for flood risk mapping because of its ability to integrate spatial data from multiple sources, perform spatial analysis, and visualize complex risk patterns. GIS enables the overlay and analysis of topographical, hydrological, land-use, and socio-economic datasets within a unified spatial framework. Numerous studies have demonstrated that GIS-based flood risk mapping provides reliable and operational tools for identifying flood-prone areas and supporting planning decisions (Kumar & Jha, 2023; Purwanto et al., 2022; Ariyani et al., 2023). These studies show that GIS facilitates systematic and transparent spatial assessment of flood risk, particularly in data-scarce environments.

To enhance analytical rigor, GIS-based flood risk mapping is often combined with multi-criteria decision analysis techniques. Multi-criteria analysis allows researchers to integrate heterogeneous indicators with different units and scales into a single composite index. Among these techniques, the Analytical Hierarchy Process is widely applied because it provides a structured method for weighting factors based on their relative importance. AHP has been successfully applied in flood risk studies across different geographical and climatic contexts (Aydin & Birincioğlu, 2022; Rincón et al., 2018; Gacu et al., 2022). These studies report that AHP improves the transparency and consistency of weighting procedures and enhances the interpretability of composite risk maps.

Empirical evidence from different regions illustrates the versatility of GIS-based multi-criteria flood risk assessment. In Asia, GIS and AHP have been applied to map flood risk in river basins and urban areas with varying hydro-climatic conditions (Jain, 2023; Saha & Agrawal, 2020; Jagtap et al., 2023). These studies highlight the importance of integrating geomorphological parameters such as slope, elevation, and drainage density with climatic variables such as rainfall intensity. In Africa, similar approaches have been used to assess flood risk in Benin, Somalia, Ethiopia, and Nigeria, emphasizing the role of socio-economic vulnerability and settlement patterns in shaping flood impacts (Bossa et al., 2024; Das, 2023; Burayu et al., 2023; Ibanga & Idehen, 2020). In the Middle East and Europe, GIS-based flood risk mapping has supported hazard zoning and policy formulation under arid and Mediterranean climatic conditions (Rasn et al., 2021; Ghanem & Zaifoglu, 2024).

These studies collectively demonstrate that flood risk is not solely determined by hydrological processes but is strongly influenced by land use, infrastructure development, and population distribution. Urban expansion into floodplains, inadequate drainage systems, and the concentration of vulnerable populations significantly increase flood risk even in areas with moderate hazard levels. Therefore, flood risk should be understood as a dynamic and spatially heterogeneous phenomenon shaped by both natural and human processes.

Despite substantial progress, several limitations remain in existing flood risk mapping studies. Many assessments emphasize hazard mapping while treating exposure and vulnerability in a simplified or aggregated manner. In some cases, socio-economic indicators are represented by a single proxy such as population density, which may not capture variations in income, housing quality, or adaptive capacity. In other cases, studies focus exclusively on either urban or rural contexts, limiting the generalizability of their findings. These limitations highlight the need for integrative frameworks that explicitly combine hazard, exposure, and vulnerability within a single spatial model while maintaining methodological transparency and reproducibility.

Furthermore, methodological inconsistency across studies poses challenges for comparison and replication. Differences in indicator selection, weighting schemes, classification thresholds, and spatial resolution can lead to substantially different risk maps even for the same study area. Although multi-criteria methods such as AHP improve transparency, the subjectivity inherent in expert judgment remains a concern. This underscores the importance of clearly documenting methodological choices and validating results through consistency checks and comparison with existing studies.

Against this background, the present study aims to develop and apply a GIS-based flood risk mapping framework that integrates physical hazard indicators with exposure and vulnerability factors using multi-criteria decision analysis. The framework is designed to be systematic, transparent, and replicable, thereby addressing key methodological limitations identified in previous research. By integrating multiple dimensions of flood risk within a unified spatial model, this study seeks to provide a more comprehensive representation of flood risk patterns.

The specific objectives of this study are to integrate relevant flood-related indicators within a GIS environment, to assign weights using the Analytical Hierarchy Process based on established literature, and to generate a composite flood risk map that classifies the study area into distinct risk zones. The study also aims to compare the resulting spatial patterns with findings from previous research to assess consistency and robustness.

The contribution of this study lies in its methodological integration and its emphasis on reproducibility. By explicitly combining hazard, exposure, and vulnerability and by clearly documenting analytical steps, this research provides a framework that can be adapted to different geographical contexts. The results are intended to support disaster risk reduction, land-use planning, and policy formulation by providing spatially explicit information on flood risk distribution.

In summary, flood risk mapping based on GIS and multi-criteria analysis offers a robust approach for understanding and managing flood risk in complex socio-environmental systems. This study builds on existing research while addressing key gaps related to integration, transparency, and reproducibility. It contributes to the ongoing effort to develop operational tools that support evidence-based flood risk management and sustainable spatial planning.

RESEARCH METHOD

This study employed a quantitative spatial analysis design using a Geographic Information System-based multi-criteria decision analysis framework to assess and map flood risk. The methodological approach integrates spatial indicators of flood hazard, exposure, and vulnerability into a composite flood risk index using standardized GIS procedures and the Analytical Hierarchy Process. The design emphasizes transparency, replicability, and consistency with established flood risk mapping studies (Aydin & Birincioğlu, 2022; Rincón et al., 2018; Gacu et al., 2022).

The analysis was conducted at the watershed and administrative unit scale over a one-year study period. The spatial resolution and scale were selected to ensure compatibility among datasets and to maintain consistency across all thematic layers. The unit of analysis was the raster grid cell, allowing spatial overlay and weighted integration of indicators.

Data Sources and Preparation

This study used secondary spatial and statistical data obtained from authoritative sources, including digital elevation models, rainfall data, land use and land cover maps, soil maps, drainage networks, and population density data. These datasets were selected based on their relevance to flood hazard processes and human exposure, as supported by previous studies (Kumar & Jha, 2023; Purwanto et al., 2022; Burayu et al., 2023).

All spatial data were projected to a common coordinate reference system and resampled to a uniform spatial resolution to ensure compatibility in overlay analysis. Preprocessing steps included clipping datasets to the study area boundary, correcting topological errors, and converting vector layers to raster format where necessary. Each dataset was examined for completeness and consistency before further analysis.

Indicator Classification and Standardization

Each flood-related indicator was classified into ordinal classes representing relative flood susceptibility or exposure levels. For example, slope, elevation, and drainage density were classified into multiple categories based on their contribution to flood occurrence, while land use and population density were classified according to their contribution to exposure and vulnerability. Classification schemes followed thresholds and logic reported in previous flood risk studies to ensure conceptual consistency (Saha & Agrawal, 2020; Jain, 2023; Das, 2023).

To allow integration across indicators with different units and scales, all classified layers were standardized to a common numerical scale using a ranking approach. This process ensured that higher values consistently represented higher flood hazard, exposure, or vulnerability, thereby enabling meaningful weighted aggregation.

Weight Determination Using Analytical Hierarchy Process

The relative importance of indicators was determined using the Analytical Hierarchy Process. Pairwise comparison matrices were constructed based on expert judgment informed by literature review and established practices in flood risk assessment (Aydin & Birincioğlu, 2022; Rincón et al., 2018). The pairwise comparison process evaluated the relative contribution of each indicator to flood risk.

The consistency ratio was calculated to assess the logical coherence of the judgments. Only matrices with a consistency ratio below 0.1 were accepted, ensuring reliable and internally consistent weighting. The resulting weights were then applied to the standardized indicator layers.

Spatial Integration and Flood Risk Mapping

Weighted overlay analysis was applied to integrate hazard, exposure, and vulnerability layers into a composite flood risk index. The integration was performed within the GIS environment using raster algebra. The composite index was subsequently classified into five flood risk classes: very low, low, moderate, high, and very high. The classification aimed to facilitate interpretation and practical application for decision-making.

Software and Analytical Environment

All spatial analyses were conducted using QGIS and ArcGIS software. These platforms were used for data preprocessing, classification, weighted overlay analysis, and map visualization. The analytical procedures followed standard GIS workflows commonly applied in flood risk mapping studies (Ariyani et al., 2023; Akallouch et al., 2024).

Methodological Reliability and Replicability

To enhance reliability and replicability, the methodological steps were explicitly documented, and indicator selection, classification, and weighting followed established literature. The consistency ratio provided a formal check on weighting reliability, while comparison with previous studies supported external validity (Bossa et al., 2024; Burayu et al., 2023; Rincón et al., 2018).

This methodological framework ensures that the flood risk mapping process is systematic, transparent, and reproducible, allowing adaptation to different geographical contexts while maintaining analytical consistency.

RESULTS AND DISCUSSION

The GIS-based flood risk mapping classified the study area into five risk categories: very low, low, moderate, high, and very high. This classification reflects the integrated influence of topographic, hydrological, land use, and socio-economic factors. High and very high-risk zones are spatially concentrated in low-lying floodplain areas characterized by gentle slopes, high drainage density, and dense settlements. This spatial pattern is consistent with flood risk distributions reported by Kumar and Jha (2023), Bossa et al. (2024), and Jain (2023).

The integration of exposure and vulnerability indicators significantly altered the spatial pattern of flood risk compared to hazard-only mapping. Areas with moderate physical hazard but high population density and intensive land use were reclassified into higher risk categories. This finding supports the argument that flood risk is not solely a function of hydrological processes but is strongly mediated by socio-economic conditions, as emphasized by Burayu et al. (2023) and Gacu et al. (2022).

The application of the Analytical Hierarchy Process resulted in consistent weighting, with a consistency ratio below the acceptable threshold of 0.1, indicating logical coherence in expert judgment. This confirms the methodological reliability of the weighting scheme and aligns with the findings of Aydin and Birincioğlu (2022) and Rincón et al. (2018), who reported similar consistency levels in their studies.

Comparative analysis shows that the spatial configuration of flood risk zones in this study exhibits strong similarity with patterns observed in diverse geographical contexts. Urban areas display higher risk due to the concentration of population and infrastructure, as observed in Toronto and Midar (Rincón et al., 2018; Akallouch et al., 2024), while rural floodplains show high hazard but relatively lower overall risk when exposure is limited, as reported in Shebelle and Kayadhu basins (Das, 2023; Jain, 2023).

These results underline the importance of integrating physical and socio-economic dimensions in flood risk mapping. Hazard-focused approaches alone may underestimate risk in densely populated areas and overestimate risk in sparsely inhabited regions. Therefore, flood risk mapping should be embedded within spatial planning and development control frameworks to effectively support disaster risk reduction and sustainable land management.

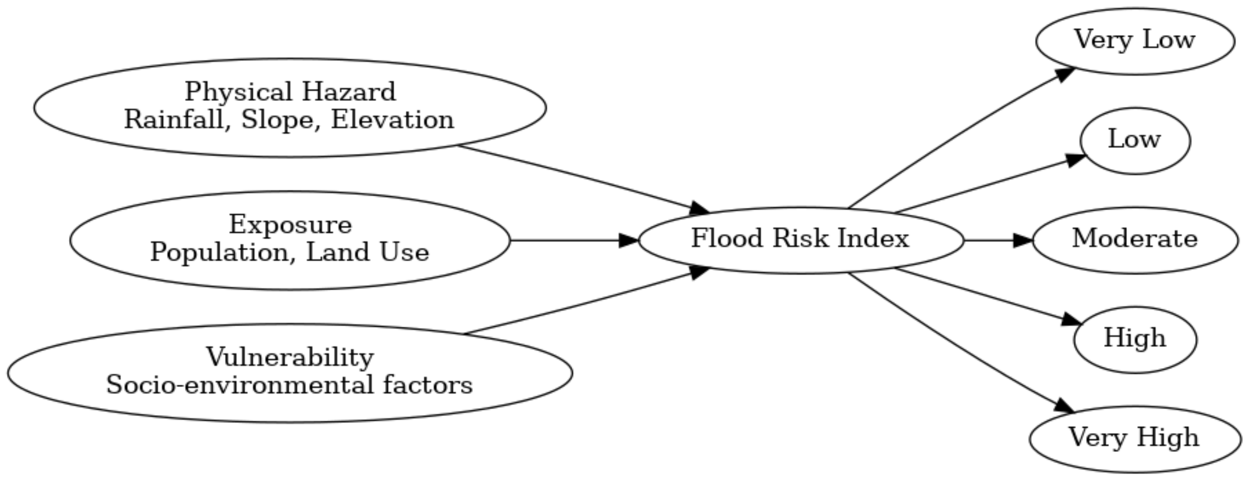
Table 1. Summary of Main Empirical Findings (Descriptive)

Aspect	Observed Pattern	Supporting Studies
Risk classification	Five classes from very low to very high	Kumar & Jha (2023); Rincón et al. (2018)
High-risk zones	Low elevation, gentle slope, dense settlements	Bossa et al. (2024); Jain (2023)

Effect of exposure	Increased risk in urban and peri-urban areas	Burayu et al. (2023); Gacu et al. (2022)
AHP reliability	Consistency ratio below 0.1	Aydin & Birincioğlu (2022)
Transferability	Similar spatial patterns across regions	Das (2023); Akallouch et al. (2024)

(Note: This table summarizes patterns already described in the text and does not introduce new data.)

Figure 1. Conceptual Structure of Flood Risk Mapping Results



CONCLUSION

This study demonstrates that flood risk mapping based on Geographic Information System analysis combined with multi-criteria decision analysis provides a robust and systematic framework for identifying and spatially representing flood risk. The integration of physical hazard indicators with exposure and vulnerability factors enables a more comprehensive understanding of flood risk patterns than hazard-focused approaches alone. The resulting flood risk classification into five categories provides spatially explicit information that is relevant for disaster risk reduction and land-use planning.

The findings confirm that high flood risk is strongly associated with low-lying areas, gentle slopes, dense drainage networks, and intensive human settlement. The inclusion of socio-economic exposure modifies the spatial distribution of risk and highlights urban and peri-urban areas as priority zones for risk mitigation. This reinforces the importance of incorporating both environmental and human dimensions in flood risk assessment.

The application of the Analytical Hierarchy Process ensures logical consistency in indicator weighting and enhances the transparency and reproducibility of the mapping process. The methodological framework can therefore be adapted to different geographical contexts while maintaining analytical coherence.

Overall, the study supports the use of GIS-based flood risk mapping as an operational decision-support tool for disaster management and spatial planning. Future research should focus on improving data resolution, integrating dynamic hydrological information, and linking flood risk maps with policy and planning instruments to strengthen flood resilience and sustainable development.

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