

urgency of integrated and adaptive flood mitigation strategies, particularly in vulnerable regions such as North Luwu Regency in South Sulawesi.

Flood disasters frequently occur in North Luwu Regency due to its topographic characteristics, land use changes, and increasing rainfall intensity. These factors significantly influence the hydrological response of the watershed and generate complex spatial flood patterns. Therefore, spatial analysis tools are essential for effective flood hazard assessment and management.

North Luwu Regency has experienced recurrent flood events, including the devastating flash flood that struck Masamba in July 2020. The disaster caused significant loss of life, extensive infrastructure damage, and long-term socio-economic disruption. The event highlighted the vulnerability of low-lying riverine settlements and underscored the need for improved spatial risk assessment and land-use planning. Despite the magnitude of the 2020 disaster, spatially explicit flood hazard mapping at the regional scale remains limited. Therefore, developing a systematic GIS-based hazard assessment framework is essential to support mitigation strategies and strengthen disaster preparedness in the region.

North Luwu gained national attention after the catastrophic flash flood in Masamba in 2020, which caused extensive casualties, infrastructure destruction, and long-term disruption to livelihoods [7-9]. The event exposed major weaknesses in regional flood management and emphasized the need for mitigation strategies tailored to geomorphological and ecological conditions [10-12]. High sedimentation, steep catchment gradients, and rapid land conversion have intensified flood vulnerability, making conventional structural solutions insufficient [13-15].

Structural measures such as levees, retention basins, and drainage improvements remain dominant approaches [16-19]. However, their long-term efficacy is limited due to sedimentation, maintenance issues, and ecological degradation [20,21]. For North Luwu, this situation demands complementing structural solutions with broader strategies rooted in ecological restoration and community participation.

Non-structural measures—including land-use regulation, community capacity building, early warning systems, and ecosystem rehabilitation—have proven effective in reducing flood risk globally [22-24]. Wetland restoration and riparian vegetation help slow runoff and increase infiltration, reducing peak flow [25,26], while community-based preparedness improves local resilience [27,28]. These examples demonstrate the necessity of balancing structural and non-structural solutions for sustainable mitigation.

The Integrated Flood Management (IFM) framework emphasizes synergy between physical engineering, ecological restoration, and institutional coordination [29,30]. IFM promotes integration across water resources planning, land-use management, and community

engagement [31,32]. Applying IFM in North Luwu offers an opportunity to address both the physical causes of flooding and the socio-ecological dimensions of vulnerability.

Advances in Geographic Information Systems (GIS) and remote sensing have transformed flood risk analysis and spatial planning [33,34]. GIS enables the integration of hydrological, topographic, and land-use datasets for spatially explicit decision-making [35,36], and has been successfully implemented in Indonesian flood research using GIS and AHP [37,38]. However, most studies focus only on hazard mapping or community action without integrating structural and non-structural solutions within IFM [39-41]. This research addresses this gap by using four spatial datasets—Digital Elevation Model (DEM), Flow Direction, Flow Accumulation, and Flood Hazard Map—to comprehensively analyse flood risk in North Luwu and evaluate both forms of mitigation.

The capacity of GIS to provide spatial specificity in risk identification also makes it a powerful decision-support tool for allocating resources, prioritizing mitigation measures, and optimizing land-use regulations in hazard-prone regions.

Therefore, the aim of this study is to formulate integrated flood mitigation strategies by bridging structural measures (levees, retention basins, drainage systems) and non-structural approaches (land-use regulation, ecosystem restoration, community-based early warnings) through GIS-based spatial analysis to support sustainable disaster management and enhance regional resilience.

This study aims to address this gap by providing a structured and reproducible flood hazard mapping framework tailored to the geomorphological characteristics of North Luwu Regency.

This study focuses primarily on morphometric (terrain-based) parameters derived from DEM data to assess flood susceptibility at the regional scale. Terrain characteristics, such as elevation, slope, and flow accumulation, represent fundamental controls on surface runoff convergence and water retention. In data-limited environments, morphometric analysis provides a practical and reproducible framework for preliminary flood hazard assessment. While dynamic hydrological variables such as rainfall intensity, soil permeability, and land-use change significantly influence flood occurrence, these factors were not incorporated in the present model due to data constraints and scope limitations.

2. Materials and Methods

2.1. Study Area and Climate

North Luwu Regency is located in the northern part of South Sulawesi Province, Indonesia (2.8700°S, 120.3200°E) with an area of approximately 7,502 km² and elevation ranging from 10 to 1,500 meters above sea level. The

region features diverse topography, including lowland river valleys, rolling hills, and steep uplands, which significantly influence hydrological flow patterns. Masamba District is the most flood-prone area due to its location along major rivers and low-lying zones, compounded by land-use changes such as the conversion of forests into agricultural and built-up areas that reduce natural retention capacity and increase surface runoff. The regency has an estimated population of around 350,000, with dense settlements concentrated along rivers and coastal areas. Land use primarily consists of 42% agricultural land, 30% forest areas, 18% built-up zones, and 10% water bodies and wetlands, contributing to varied levels of exposure and vulnerability.

The climate of North Luwu is classified as tropical rainforest (Af) under the Köppen-Geiger system, with annual rainfall ranging from 2,000 to 3,500 mm, peak precipitation occurring between November and March, temperatures between 23 °C and 32 °C, and humidity exceeding 75%. These climatic conditions, combined with steep upstream catchments, increase rapid runoff and intensify flash flood risks in downstream settlements. Figure 1 presents the administrative boundaries and hydrological network of North Luwu, while Figure 2 illustrates population density distribution, highlighting vulnerable high-density areas such as Baebunta, Sukamaju, and coastal zones. The maps provide essential spatial context for flood mitigation planning and support the integration of structural and non-structural strategies.

2.2. Data and Data Collection

This study utilized both qualitative and quantitative data that complement each other in analysing flood risk in Masamba District, North Luwu Regency. Qualitative data were obtained through field observations to document real conditions, including flood events, infrastructure conditions, and vulnerability indicators. Quantitative data consist of spatial and numerical datasets such as topography, slope gradient, soil type, geology, rainfall, land use, and flood hazard and vulnerability indices, which were processed using GIS-based spatial analysis to generate thematic maps. The integration of these data types enables a comprehensive understanding of the physical characteristics and socio-environmental dimensions influencing flood risk.

Primary data were collected directly through field surveys and on-site observations focusing on flood-prone areas, land use patterns, and infrastructure. Secondary data were sourced from institutional reports and official documents, including the Regional Spatial Plan (RTRW) of North Luwu Regency 2024–2043, data from BPS, BAPPEDA, PUPR, Inarisk BNPB, and previous research publications. Spatial datasets, such as DEM, geology, slope, rainfall, and land use maps, were obtained from governmental sources and processed to support hydrological modelling and flood hazard mapping. The combination of primary field information and reliable

secondary datasets ensures valid, updated, and contextually grounded analysis to support comprehensive flood mitigation planning.

2.3. Data Sources and Technical Specifications

The Digital Elevation Model (DEM) used in this study was obtained from the Shuttle Radar Topography Mission (SRTM) dataset with a spatial resolution of 30 meters and a vertical accuracy of approximately ± 16 meters. The dataset was downloaded from the United States Geological Survey (USGS) Earth Explorer platform. All spatial analyses were conducted using ArcGIS Desktop version 10.8 (ESRI Inc., USA). Hydrological modelling was performed using the Spatial Analyst toolbox, including the Fill, Flow Direction (D8 algorithm), and Flow Accumulation tools. The spatial reference system applied in this study was the Universal Transverse Mercator (UTM) projection, Zone 50 South, using the World Geodetic System 1984 (WGS 84) datum to ensure spatial accuracy and consistency.

The detailed specification of data sources, spatial resolution, projection systems, classification thresholds, and GIS workflow enhances methodological transparency and ensures reproducibility of the analytical framework.

2.4. Flood Hazard Map

Flood hazard mapping plays a critical role in disaster risk reduction and spatial planning by identifying areas that are likely to be inundated during flood events. The development of flood hazard maps relies on the integration of geospatial datasets and hydrological modelling, particularly the Digital Elevation Model (DEM), flow direction, and flow accumulation maps. These datasets allow researchers to analyze surface topography, water flow behavior, and potential flood-prone zones, forming an evidence-based foundation for mitigation and preparedness strategies.

The Digital Elevation Model (DEM) was used as the primary dataset to derive hydrological parameters relevant to flood hazard mapping. DEM preprocessing included sink filling to remove artificial depressions and ensure accurate surface flow modeling. Based on the corrected DEM, flow direction was calculated using the D8 algorithm to determine the direction of surface runoff from each grid cell to its steepest downslope neighbor. Subsequently, flow accumulation was generated to quantify the number of upstream cells contributing runoff to each location, thereby identifying potential drainage paths and areas susceptible to water concentration. These hydrological derivatives were then integrated into the flood hazard classification framework to delineate zones with varying levels of flood susceptibility. The DEM data were processed using hydrological tools in ArcGIS to generate flow direction and flow accumulation layers. These layers were subsequently used to identify potential flood-prone areas through spatial overlay analysis.

indicates a high degree of alignment between modelled flow paths and real drainage networks. This validation suggests that the DEM preprocessing and hydrological conditioning were effective in reducing errors such as artificial depressions. Consequently, the flow direction map (Figure 5) serves as a robust foundation for subsequent flow accumulation analysis and flood hazard zoning. It highlights not only where water flows but also how local communities and land-use systems are positioned relative to these hydrological pathways, thereby providing a critical evidence base for planning and adaptation efforts in flood-prone areas of North Luwu Regency.

3.3. Flow Accumulation Map

The flow accumulation map, as shown in Figure 6, illustrates the spatial distribution of water flow concentration across the drainage basin in North Luwu Regency. Flow accumulation map generated using the D8 algorithm. High accumulation zones indicate potential drainage convergence areas and increased flood risk. High flow accumulation values are prominently aligned with river channels, valleys, and natural drainage lines, indicating the pathways where surface runoff is most likely to concentrate. These areas function as the backbone of the hydrological network, and their delineation provides crucial insights into flood hazard mapping and water resource management. In contrast, areas with low flow accumulation values are typically found on ridges, slopes, and higher elevations, where water disperses rather than accumulates.

Areas with high flow accumulation values can be considered critical in flood risk assessment since they represent potential zones for waterlogging and overflow during heavy rainfall events. Particularly in the southern part of the basin, the map highlights zones where drainage lines converge, forming larger channels that eventually feed into the main river systems. Such convergence zones often become hotspots for flash floods and inundation hazards, especially in areas where land use has altered natural infiltration capacity. This is consistent with the findings of Jenson and Domingue (1988), who emphasized the importance of flow accumulation in predicting stream networks and flood-prone areas.

Moreover, the map indicates that flow accumulation values reach up to 6,507,839, which signifies significant volumes of contributing upstream runoff converging into specific points. Such extreme values are typical for primary river channels, where the integration of upstream drainage networks results in maximum water discharge potential. Studies by Tarboton [45] and O'Callaghan and Mark [46] similarly noted that high flow accumulation values are directly associated with river channel initiation and downstream flood susceptibility. This supports the interpretation that the identified channels in the North Luwu basin represent natural flood corridors.

Critical areas highlighted by this map also overlap with low-lying regions within the basin that are vulnerable to prolonged inundation. This corresponds with earlier works by Jahangir et al. [47], who demonstrated that flow accumulation models, when coupled with flood records, are effective for identifying inundation-prone areas. In the case of North Luwu, these regions may coincide with historical flood occurrences, suggesting the reliability of this map as a predictive tool. Field validation or the integration of past flood event data would further strengthen this observation.

The flood hazard map was qualitatively compared with documented historical flood reports from local authorities in North Luwu Regency. Although comprehensive field-based flood inventory data were not available, the spatial distribution of high-hazard zones aligns with areas historically reported as flood-prone, and the high-flow accumulation zones show strong spatial correlation with recorded inundation sites. For example, lowland settlements and agricultural zones within the basin are located along these major flow lines, increasing their susceptibility to flood impacts. This pattern echoes findings by Debnath et al. [48], who highlighted that overlaying flow accumulation outputs with land use and flood history improves flood hazard assessments significantly. Therefore, the North Luwu basin map not only identifies hydrologically significant pathways but also provides a practical framework for risk reduction planning.

In summary, the flow accumulation map provides valuable evidence of potential flood-prone corridors in North Luwu Regency. It highlights how hydrological modelling using DEM data can reveal critical drainage pathways and water concentration zones. When compared with prior studies, the results align with established hydrological principles and empirical flood mapping practices, further validating the approach. Thus, Figure 6 serves as an essential basis for developing integrated flood hazard management strategies in the region.

3.4. Flood Hazard Map

The flood hazard map of North Luwu Regency, as shown in Figure 7, presents the spatial classification of flood-prone zones into three categories: high, moderate, and low hazard levels. Reclassified flood hazard parameters integrating elevation, slope, and flow accumulation prior to weighted overlay analysis. The distribution of hazard zones reveals that high-risk areas are concentrated predominantly in the southern and southeastern parts of the regency, particularly along the coastal plains bordering the Gulf of Bone. These low-lying areas, characterized by flat topography and dense drainage networks, are highly susceptible to recurrent inundation. Moderate hazard zones extend across transitional landscapes between coastal plains and upland regions, whereas low hazard zones dominate the higher elevations and mountainous areas in the northern and central parts of the basin.

Figure 7. Flood hazard classification map of North Luwu Regency, generated through spatial overlay analysis integrating elevation, flow direction, and flow accumulation parameters

Nevertheless, the presented hazard map provides a critical tool for decision-makers in North Luwu Regency. It identifies priority areas where flood mitigation and adaptation strategies must be strengthened, such as through improved drainage systems, flood-resilient infrastructure, and community-based disaster preparedness programs. Integrating this spatial hazard assessment with climate projections and socio-economic data could significantly enhance resilience planning. Comparable studies, such as those by Tehrani et al. [51], demonstrated that multi-criteria flood hazard mapping—combining hydrological, topographical, and socio-economic indicators—yields more robust predictions and better supports local planning.

In conclusion, the flood hazard map (Figure 7) highlights the spatial heterogeneity of flood risk in North Luwu Regency, with high-risk zones concentrated in the southern lowlands, directly threatening settlements, agriculture, and infrastructure. While the results align with hydrological expectations and previous research findings, further integration of dynamic rainfall, LULC, and vulnerability data would enhance the reliability of the model. Thus, the map serves as both a practical foundation for local disaster management and a guide for future research to strengthen flood hazard assessment in the region.

3.5. Model Validation Using Historical Flood Events

This discussion interprets the spatial patterns identified in the Results section and situates them within the broader context of flood hazard research. The findings derived from this study are first summarized, followed by a comparison with relevant literature and implications for local planning and policy development.

To assess the reliability of the flood hazard model, the resulting hazard map was qualitatively compared with documented historical flood events in North Luwu Regency. Secondary data from local government reports and disaster management agencies indicate that recurrent flooding has primarily occurred along major river corridors and low-lying floodplains. These documented flood locations spatially correspond with areas classified as high and very high hazard zones in the present analysis.

This spatial agreement suggests that topographic controls derived from DEM-based hydrological modelling effectively capture areas prone to surface runoff concentration and inundation. Although quantitative validation using hydrodynamic modelling or extensive field measurements was beyond the scope of this study, the consistency between historical flood distribution and modelled hazard zones provides reasonable confidence in the analytical framework. Future research may incorporate time-series flood inventory data and field verification surveys to further strengthen model validation. For example, major flood events recorded in 2020 and 2021 were concentrated in districts located within the high

accumulation and low elevation zones identified in this study.

To evaluate the predictive reliability of the Flood Hazard Index (FHI), 150 historical flood occurrence points were overlaid onto the final hazard map. The spatial agreement between observed flood locations and predicted hazard zones was assessed using a confusion matrix approach.

Out of the total 150 flood points analysed, 70 points (46.67%) were located within the High-Hazard zone, 53 points (35.33%) within the Moderate-Hazard zone, and 27 points (18.00%) within the Low-Hazard zone. Notably, 82.00% of historical flood events fall within the combined Moderate-to-High hazard categories, indicating strong spatial agreement between observed flood occurrences and the model's predicted susceptible zones. These results demonstrate that the terrain-based Flood Hazard Index provides a reasonably reliable representation of regional flood susceptibility patterns. Table 3 shows the confusion matrix for flood hazard classification.

Table 3. Confusion matrix for flood hazard classification

| Observed / Predicted | High Hazard | Moderate Hazard | Low Hazard |
|----------------------|-------------|-----------------|------------|
| Flood Occurrence | 70 | 53 | 27 |

Since only flood occurrence points were available, a full binary classification accuracy assessment (including true negatives) could not be computed. However, spatial agreement analysis indicates that the majority of observed flood events correspond to moderate-to-high susceptibility zones.

3.6. Validation and Reliability Assessment

The spatial distribution of high flood hazard zones identified in this study has direct implications for regional spatial planning in North Luwu Regency. Areas classified as high hazard are predominantly located along low-elevation river corridors and floodplains, suggesting the need for stricter land-use regulations and development controls in these zones.

The hazard map can support local authorities in prioritizing flood mitigation infrastructure, such as drainage improvement, retention basins, and riverbank reinforcement. Furthermore, integration of the flood hazard map into the Regional Spatial Plan (RTRW) would enhance risk-sensitive land-use allocation and disaster preparedness strategies. By providing spatially explicit hazard information, this study contributes a practical decision-support tool for local government agencies and disaster management institutions.

The reliability of the flood hazard map was assessed through qualitative comparison with documented historical flood reports from local government agencies in North Luwu Regency. These reports indicate that recurrent flood events primarily occurred along major river corridors and low-lying floodplain areas. The spatial distribution of high

and very high hazard zones identified in this study corresponds with these historically affected locations, providing reasonable confidence in the modelling results.

However, high-resolution flood extent datasets derived from satellite imagery or systematic field surveys were not available for comprehensive quantitative validation. Therefore, the validation process remains primarily qualitative. While this approach supports the general reliability of the hazard classification, it limits the ability to statistically quantify model accuracy.

3.7. Uncertainty and Modelling Limitations

Several sources of uncertainty should be acknowledged in this study. First, the DEM used has a spatial resolution of 30 meters, which may not fully capture fine-scale micro-topographic variations influencing localized flood dynamics. Vertical accuracy limitations may also affect slope derivation and flow accumulation estimates.

Second, the modelling approach is based on static terrain parameters and does not incorporate dynamic hydrological variables such as rainfall intensity, river discharge, land-use change dynamics, or soil infiltration capacity. Consequently, the resulting flood hazard map represents potential susceptibility rather than real-time flood prediction.

Despite these limitations, the integration of topographic and hydrological parameters provides a reliable preliminary assessment framework suitable for regional-scale flood risk planning. Future studies should incorporate time-series hydrological data and higher-resolution elevation models to enhance predictive accuracy.

The present analysis relies exclusively on terrain-derived morphometric parameters. Although elevation, slope, and flow accumulation represent key structural controls of flood susceptibility, flood generation is inherently influenced by additional factors such as rainfall intensity, soil infiltration capacity, and land-use dynamics.

The exclusion of rainfall, soil, and land-use variables limits the model to representing potential topographic susceptibility rather than dynamic flood hazard prediction. Consequently, the results should be interpreted as a preliminary regional-scale susceptibility framework.

Future research should integrate time-series rainfall data, soil hydrological groups, and land-use change analysis to develop a more comprehensive multi-factor flood hazard model. Combining morphometric and hydrometeorological parameters would significantly enhance predictive reliability and scientific depth. Terrain-based modeling provides a structurally stable foundation, upon which dynamic hydrological variables can be integrated in subsequent research phases.

3.8. Synthesis and Implications

The integration of the four maps—Digital Elevation

Model (DEM), flow direction, flow accumulation, and flood hazard—provides a comprehensive understanding of flood dynamics in North Luwu Regency. The DEM highlights variations in elevation that form the basis of hydrological processes, showing how topography governs water movement. Flow direction analysis illustrates the natural drainage pathways, while flow accumulation identifies areas where runoff converges into streams, rivers, and potential flood channels. The flood hazard map synthesizes these hydrological inputs with additional environmental factors to classify risk zones. Together, these datasets provide a coherent framework for identifying where floods are most likely to occur and how they may impact communities and landscapes.

The relationship between topography and hydrology is evident across the analysis. Steeper upland areas direct runoff quickly downslope, contributing to high flow accumulation in the low-lying floodplains. Flow direction analysis reveals a dominant water movement from the north and central uplands toward the southern coastal plain, where accumulation peaks. These conditions coincide with the high hazard zones on the flood hazard map, which are clustered along river valleys and the coastal fringe. This spatial linkage demonstrates how elevation gradients and drainage patterns interact to amplify flood risks in downstream settlements, particularly during periods of intense rainfall.

From a planning perspective, the findings have significant implications for spatial development and disaster mitigation. High hazard zones should be prioritized for non-residential land use, such as green buffer zones, flood retention areas, or agriculture with adaptive practices, while settlements and critical infrastructure should be directed to moderate or low hazard zones. Infrastructure resilience measures, such as elevated roads and flood-resistant housing, should be implemented in at-risk areas. The results can also support zoning regulations, early warning systems, and targeted flood management interventions by local authorities. This aligns with international best practices where hazard mapping is integrated into land-use planning to minimize exposure and vulnerability [52,53].

At the policy level, the flood hazard map provides a scientific basis for strengthening disaster risk reduction strategies in North Luwu Regency. Policymakers can use the hazard zones to prioritize investments in drainage systems, flood defenses, and community-based adaptation programs. Furthermore, the integration of hydrological modelling with socio-economic vulnerability assessments could enhance the alignment of disaster risk management with local development goals. Embedding these findings into local planning documents, such as spatial plans (RTRW) and disaster management blueprints, would ensure that flood hazards are systematically considered in future development.

Despite its utility, this study has several limitations that should be acknowledged. The reliance on DEM resolution

influences the precision of flow direction and accumulation modelling, potentially overlooking micro-scale flood risks in small catchments. The flood hazard map was generated using static topographic and hydrological data without incorporating dynamic rainfall records, land use change trajectories, or field-based flood validation, which may affect accuracy. Future research should integrate high-resolution satellite data, rainfall-runoff modelling, and community-based flood history surveys to refine hazard predictions. By addressing these limitations, future studies can deliver more accurate and actionable flood risk assessments, enhancing their value for both scientific and policy applications.

Beyond the visual representation of hazard zones, the spatial analysis reveals important geomorphological relationships influencing flood susceptibility in North Luwu Regency. High hazard zones are spatially clustered along low-gradient floodplains with concentrated flow accumulation, indicating strong terrain-controlled hydrological convergence.

This pattern suggests that topographic controls play a dominant role in shaping flood exposure in the region, particularly in areas undergoing land-use expansion near river corridors. The spatial configuration of hazard zones also reflects potential amplification effects where low elevation coincides with limited drainage capacity.

These findings highlight the need for terrain-sensitive planning policies and emphasize that flood mitigation strategies should prioritize hydrologically connected lowland systems rather than isolated administrative boundaries. While the modeling framework relies on terrain-based parameters, the spatial relationships identified provide insight into underlying flood-generating mechanisms at the regional scale. The integration of multiple terrain derivatives moves beyond simple elevation mapping and offers a more systematic susceptibility assessment. This analytical approach contributes to a more robust understanding of spatial flood dynamics in data-limited environments.

3.9. Spatially Specific Intervention Strategies

The spatial specificity of the flood hazard map enables targeted intervention strategies tailored to the unique risk profile of each zone. High-Hazard zones, particularly in the central and southern corridors where flow accumulation values are highest, should be prioritized for structural measures such as levee construction, channel deepening, and improved drainage infrastructure. These high-risk areas coincide with densely populated floodplains and areas with limited natural buffer capacity.

Moderate-Hazard zones, often located on transitional slopes and secondary catchment branches, may benefit from nature-based solutions such as riparian reforestation to enhance soil stability and reduce rapid runoff. Reforestation and vegetative buffer strips can increase infiltration capacity, mitigate surface runoff, and reduce

sediment transport into stream networks. Low-Hazard zones, while less susceptible, should be incorporated into strategic land-use planning to prevent future vulnerability under changing climate conditions.

Recent applications of GIS in hazard mitigation emphasize the importance of integrating spatial risk maps with intervention planning. For example, L. Wang et al. [11] used GIS-based susceptibility maps to allocate watershed restoration projects, while M. Tumpu et al. [52] applied multi-criteria GIS models to optimize the placement of green infrastructure in flood-prone basins. These studies demonstrate how GIS can translate hazard assessments into actionable policy recommendations, reinforcing the value of spatially explicit outputs in regional planning.

4. Conclusions

This study provides a spatially explicit flood hazard assessment for North Luwu Regency using an integrated GIS-based terrain analysis approach. The findings demonstrate that low-elevation areas with gentle slopes and high flow accumulation values are predominantly associated with high flood hazard zones. These spatial patterns confirm the strong influence of topographic and hydrological parameters in determining flood susceptibility at the regional scale.

From a scientific perspective, this study contributes a structured and transparent GIS workflow that integrates elevation, slope, and flow accumulation into a coherent flood hazard classification framework. The study also strengthens methodological transparency by explicitly describing data sources, classification thresholds, and uncertainty considerations.

Practically, the resulting flood hazard map offers a decision-support tool for local governments in spatial planning and disaster risk reduction. The identification of high-risk zones provides a basis for zoning regulation, infrastructure prioritization, and risk-sensitive land-use planning. Integration of these findings into regional spatial plans can enhance long-term resilience against flood hazards.

Future research should incorporate higher-resolution DEM data, dynamic hydrological modelling, rainfall-runoff simulations, and time-series flood extent validation using satellite imagery. Combining terrain-based susceptibility modelling with climate change projections would further improve predictive reliability and policy relevance.

Acknowledgements

The authors would like to express their gratitude to the local government of Luwu Utara for providing access to regional data and relevant information. Special thanks are extended to the research team and academic colleagues whose insights and feedback greatly enriched this study.

Finally, appreciation is given to the community members who shared their local knowledge, which added valuable perspectives to the analysis.

REFERENCES

- [1] R. Rahmawati, M. Tumpu, and A. Yuniarta, "Hydrodynamic and sedimentological impacts of intake gate opening adjustments for flood mitigation in water systems," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 1–10, 2025. DOI: 10.48084/etasr.10729.
- [2] A. F. M. Aldardasawi and B. Eren, "Floods and their impact on the environment," *Academic Perspective Procedia*, vol. 4, no. 2, pp. 42–49, 2021. DOI: 10.33793/acperpro.
- [3] C. C. R. Gan *et al.*, "A scoping review of climate-related disasters in China, Indonesia and Vietnam: Disasters, health impacts, vulnerable populations and adaptation measures," *International Journal of Disaster Risk Reduction*, vol. 66, p. 102608, 2021. DOI: 10.1016/j.ijdr.2021.102608.
- [4] R. Latief, T. Budu, M. Tumpu, M. P. Hatta, and E. Aprianti, "Quality of life analysis with WHOQOL-BREF in disaster preparedness for flood-prone areas in Makassar City, Indonesia," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 1–12, 2025. DOI: 10.48084/etasr.10450.
- [5] J. Xiong and Y. Yang, "Climate change and hydrological extremes," *Current Climate Change Reports*, vol. 11, no. 1, pp. 1–12, 2025. DOI: 10.1007/s40641-024-00198-4.
- [6] F. Granata, S. Zhu, and F. Di Nunno, "Hydrological extremes in the Mediterranean basin: Interactions, impacts, and adaptation in the face of climate change," *Regional Environmental Change*, vol. 25, p. 100, 2025. DOI: 10.1007/s10113-025-02432-7.
- [7] A. Maulana, M. Tumpu, I. P. Indriani, and I. Utama, "Flood sedimentology for future floods mitigation in North Luwu, Sulawesi, Indonesia," *Civil Engineering Journal*, vol. 9, no. 4, pp. 906–918, 2023. DOI: 10.28991/CEJ-2023-09-04-011.
- [8] D. Ruslanjari *et al.*, "Humanitarian aid distribution in the context of human rights-based approach among vulnerable communities," in *Climate-related Human Mobility in Asia and the Pacific*, Springer, 2024, pp. 141–160. DOI: 10.1007/978-981-97-3234-0_9.
- [9] S. N. Hasan *et al.*, "The role of three rivers crossing the urban area on the Masamba 2020 flash floods," *Journal of Applied Geoscience*, vol. 4, no. 1, pp. 1–12, 2025. DOI: 10.36777/jag2025.4.1.1.
- [10] A. K. Katyal and I. G. Petrisor, "Flood management strategies for a holistic sustainable development," *Environmental Forensics*, vol. 12, no. 3, pp. 206–218, 2011. DOI: 10.1080/15275922.2011.595051.
- [11] L. Wang *et al.*, "A review of flood management: From flood control to flood resilience," *Heliyon*, vol. 8, no. 11, p. e11763, 2022. DOI: 10.1016/j.heliyon.2022.e11763.
- [12] S. M. Khan *et al.*, "A systematic review of disaster management systems: Approaches, challenges, and future directions," *Land*, vol. 12, no. 8, p. 1514, 2023. DOI: 10.3390/land12081514.
- [13] G. Barrocu and S. Eslamian, "Geomorphology and flooding," in *Flood Handbook*, 1st ed., CRC Press, 2022, pp. 1–32.
- [14] J. D. E. Mendoza *et al.*, "Alteration of catchments and rivers and the effect on floods," *Water*, vol. 17, no. 8, p. 1177, 2025. DOI: 10.3390/w17081177.
- [15] P. L. M. Tolentino, R. D. Williams, and M. D. Hurst, "Natural flood risk management in tropical Southeast Asia," *Wiley Interdisciplinary Reviews: Water*, 2025. DOI: 10.1002/wat2.70000.
- [16] C. Wenger, "Better use and management of levees: Reducing flood risk in a changing climate," *Environmental Reviews*, vol. 23, no. 3, pp. 240–255, 2015. DOI: 10.1139/er-2014-0060.
- [17] U. Hansamali *et al.*, "Leaky dams as nature-based solutions in flood management," *Hydrology*, vol. 12, no. 4, p. 95, 2025. DOI: 10.3390/hydrology12040095.
- [18] W.Y. Leong, "Virtual Reality-Driven Training for Environmental Resilience and Disaster Preparedness," in *Sustainable Development of Water and Environment*, J. Han-Yong, Ed., Environmental Science and Engineering, Cham: Springer, 2026. DOI: 10.1007/978-3-032-08652-5_24.
- [19] M. H. Assiddiqi, M. Lanuru, and M. Tumpu, "Analysis of the availability of residential locations based on flood mitigation in Momunu District," *Engineering, Technology & Applied Science Research*, vol. 15, no. 1, pp. 1–10, 2025. DOI: 10.48084/etasr.10811.
- [20] S. Mondal and P. P. Patel, "Examining the utility of river restoration approaches for flood mitigation," *Environmental Earth Sciences*, vol. 77, p. 195, 2018. DOI: 10.1007/s12665-018-7381-y.
- [21] O. Iacob, J. S. Rowan, I. Brown, and C. Ellis, "Evaluating wider benefits of natural flood management strategies: An ecosystem-based adaptation perspective," *Hydrology Research*, vol. 45, no. 6, pp. 774–787, 2014. DOI: 10.2166/nh.2014.184.
- [22] Z. W. Kundzewicz, "Non-structural flood protection and sustainability," *Water International*, vol. 27, no. 1, pp. 3–13, 2002. DOI: 10.1080/02508060208686972.
- [23] A. S. Kamara, "Assessing the effectiveness of structural and non-structural flood mitigation measures of Bushrod Island's unplanned settlements," Master's Thesis, Department of Architecture, Brac University, Liberia, 2023. Available: <http://hdl.handle.net/10361/22117>.
- [24] H. Raza, "Flood prevention strategies in China: A review of policies, technologies, and practices," *Prevention and Treatment of Natural Disasters*, vol. 2, no. 2, pp. 14–23, 2023. DOI: 10.54963/ptnd.v2i2.1089.
- [25] T. A. Russo, A. T. Fisher, and J. W. Roche, "Improving riparian wetland conditions based on infiltration and drainage behavior during and after controlled flooding," *Journal of Hydrology*, vols. 432–433, pp. 98–111, 2012. DOI: 10.1016/j.jhydrol.2012.02.022.
- [26] M. Acreman and J. Holden, "How wetlands affect floods,"

- Wetlands*, vol. 33, no. 5, pp. 773–786, 2013. DOI: 10.1007/s13157-013-0473-2.
- [27] V. Tarchiani *et al.*, “Community and impact based early warning system for flood risk preparedness: The experience of the Sirba River in Niger,” *Sustainability*, vol. 12, no. 5, p. 1802, 2020. DOI: 10.3390/su12051802.
- [28] P. J. Smith, S. Brown, and S. Dugar, “Community-based early warning systems for flood risk mitigation in Nepal,” *Natural Hazards and Earth System Sciences*, vol. 17, pp. 423–440, 2017. DOI: 10.5194/nhess-17-423-2017.
- [29] R. Kotharkar, A. Ghosh, and R. Keskar, “Fine-scale mapping of heat-hazard risk and vulnerability using geo-spatial techniques,” *International Scientific Journal Geographica Annonica*, vol. 29, no. 2, pp. 84–107, 2025. DOI: 10.5937/gp29-56164.
- [30] R. Nordbeck, W. Seher, H. Grüneis, *et al.*, “Conflicting and complementary policy goals as sectoral integration challenge,” *Policy Sciences*, vol. 56, pp. 595–612, 2023. DOI: 10.1007/s11077-023-09503-8.
- [31] N. S. Grigg, “Two decades of integrated flood management: Status, barriers, and strategies,” *Climate*, vol. 12, no. 5, p. 67, 2024. DOI: 10.3390/cli12050067.
- [32] A. M. Juarez Lucas and K. M. Kibler, “Integrated flood management in developing countries,” *International Journal of River Basin Management*, vol. 14, no. 1, pp. 19–31, 2015. DOI: 10.1080/15715124.2015.1068180.
- [33] A. A. Al-Omari *et al.*, “Utilizing remote sensing and GIS techniques for flood hazard mapping and risk assessment,” *Civil Engineering Journal*, vol. 10, no. 5, pp. 1423–1442, 2024. DOI: 10.28991/CEJ-2024-010-05-05.
- [34] X. Wang and H. Xie, “A review on applications of remote sensing and GIS in water resources and flood risk management,” *Water*, vol. 10, no. 5, p. 608, 2018. DOI: 10.3390/w10050608.
- [35] E. Efraimidou and M. Spiliotis, “A GIS-based flood risk assessment using the DEMATEL approach,” *Environmental Processes*, vol. 11, p. 9, 2024. DOI: 10.1007/s40710-024-00683-w.
- [36] H. A. O. Karary, A. Elhag, and A. Hassan, “GIS applications in land management,” *Journal of Khartoum University Engineering Studies*, vol. 3, no. 2, p. 259, 2023. DOI: 10.54388/jkues.v3i2.259.
- [37] A. A. Kurniawan, H. Sunardi, and I. Ridwansyah, “Flood management using GIS-based multicriteria evaluation,” *Preprints*, 2024, pp. 1–28. DOI: 10.20944/preprints202405.1163.v1.
- [38] D. N. Sari *et al.*, “Detection of flood hazard potential zones using analytical hierarchy process,” *Geographia Technica*, vol. 19, no. 1, pp. 61–78, 2024. DOI: 10.21163/GT_2024.191.05.
- [39] K. A. Sullivan-Wiley, A. G. Short Gianotti, and J. P. Casellas Connors, “Mapping vulnerability: Opportunities and limitations of participatory community mapping,” *Applied Geography*, vol. 105, pp. 47–57, 2019. DOI: 10.1016/j.apgeog.2019.02.008.
- [40] A. Maskrey, *Disaster Mitigation: A Community-Based Approach*, Oxfam GB, Oxford, UK, 1989. Available: <https://policy-practice.oxfam.org.uk/publications/disaster-mitigation-a-community-based-approach-121119>.
- [41] M. M. Sarabia *et al.*, “The challenges of impact evaluation,” *International Journal of Disaster Risk Reduction*, vol. 49, p. 101732, 2020. DOI: 10.1016/j.ijdr.2020.101732.
- [42] N. M. Iskandar, “Opportunities of low impact development for water infrastructure in Jakarta,” Master’s Thesis, Universitas Terbuka, Indonesia, 2021. Available: <https://hdl.handle.net/2152/89508>.
- [43] P. Aprijanto *et al.*, “Innovative strategies for tidal flood protection,” *Marine Systems & Ocean Technology*, vol. 20, p. 9, 2025. DOI: 10.1007/s40868-024-00158-5.
- [44] I. Chowdhoree, “External interventions for enhancing community resilience,” in *External Interventions for Disaster Risk Reduction*, Springer, 2020. DOI: 10.1007/978-981-15-4948-9_1.
- [45] D. G. Tarboton, “A new method for the determination of flow directions and upslope areas in grid digital elevation models,” *Water Resources Research*, vol. 33, no. 2, pp. 309–319, 1997. DOI: 10.1029/96WR03137.
- [46] J. F. O’Callaghan and D. M. Mark, “The extraction of drainage networks from digital elevation data,” *Computer Vision, Graphics, and Image Processing*, vol. 28, pp. 323–344, 1984.
- [47] M. H. Jahangir, S. M. M. Reineh, and M. Abolghasemi, “Spatial prediction of flood zonation mapping using artificial neural networks,” *Weather and Climate Extremes*, vol. 25, p. 100215, 2019. DOI: 10.1016/j.wace.2019.100215.
- [48] J. Debnath *et al.*, “Flood susceptibility assessment using machine learning,” *Environmental Monitoring and Assessment*, vol. 196, p. 110, 2024. DOI: 10.1007/s10661-023-12240-3.
- [49] Y. Chen, J. Yu, and S. Khan, “Spatial sensitivity analysis of multi-criteria weights,” *Environmental Modelling & Software*, vol. 25, no. 12, pp. 1582–1591, 2010. DOI: 10.1016/j.envsoft.2010.06.001.
- [50] T. Tingsanchali, “Urban flood disaster management,” *Procedia Engineering*, vol. 32, pp. 25–37, 2012. DOI: 10.1016/j.proeng.2012.01.1233.
- [51] M. S. Tehrany, B. Pradhan, and M. N. Jebur, “Flood susceptibility mapping using ensemble models,” *Journal of Hydrology*, vol. 512, pp. 332–343, 2014. DOI: 10.1016/j.jhydrol.2014.03.008.
- [52] M. Tumpu *et al.*, “Index-based spatial assessment of flood hazard and multi-sectoral vulnerability in flood-prone areas,” *Civil Engineering and Architecture*, vol. 14, no. 1, pp. 176–199, 2026. DOI: 10.13189/cea.2026.140112.
- [53] R. Varatharajan, S. Y. D. Ng, K. Shavarebi, F. M. Zaini, and A. E. Oke, “Flood disaster in the construction industry: How do Malaysians cope?,” *International Journal of Disaster Resilience in the Built Environment*, vol. 16, no. 5, pp. 638–653, 2025. DOI: 10.1108/IJDRBE-12-2024-0144.