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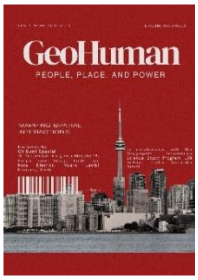

Analysis of Flood Vulnerability Maps Based on Proximity to Rivers and Land Use (Dynamic Pressure) Using the Pressure and Release (PAR) Model in Medan City

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ABSTRACT

Flooding is the most frequent disaster in Medan City and has a significant impact on urban communities. This phenomenon is influenced not only by physical factors in the region, but also by dynamic pressures arising from changes in land use and residential development. This study aims to analyze flood vulnerability levels based on river distance and land use using the Pressure and Release (PAR) Model approach. The analysis was conducted spatially using a Geographic Information System (GIS) through the creation of river buffers, land use classification, vulnerability assessment, and the combination of these two variables to produce a flood vulnerability map of Medan City. The results show that areas within 0–100 meters of rivers and high-risk land uses such as dense settlements, rice fields, and fish ponds have the highest vulnerability levels. The most vulnerable areas include the banks of the Deli and Babura Rivers, the northern coastal zone, and dense settlements in the city center. Within the PAR Model framework, this vulnerability is an accumulation of major causes such as rapid urbanization and weak spatial control, dynamic pressures in the form of land use changes and loss of riverbank vegetation, and unsafe conditions such as dense settlements in low-lying areas. Socially, these conditions have an impact on increasing the vulnerability of urban communities, especially low-income groups who depend on river and coastal areas for shelter and livelihoods, thus potentially experiencing economic losses, disruption of daily activities, and limited capacity to adapt to flooding. The resulting vulnerability map is expected to serve as a basis for more inclusive flood mitigation and risk-based spatial planning, while also supporting efforts to raise

awareness and social resilience among communities in reducing the impact of flooding in the city of Medan.

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Introduction

Hydrometeorological disasters, particularly flooding, are one of the main threats to the sustainability of urban areas, especially in low-lying areas and cities with high levels of urbanization. Globally, urban flooding is becoming an increasingly complex problem due to a combination of natural factors and human activities, such as high-intensity rainfall, land use changes, and limited drainage system capacity. (Ashfaq et al., 2025). In Indonesia, this condition also occurs in the city of Medan, which is one of the metropolitan cities with rapid physical growth and population density. (Silitonga, 2019). This phenomenon indicates an imbalance between regional development and environmental carrying capacity, which requires a more comprehensive risk assessment.

In the context of disaster risk management, risk assessment cannot focus solely on hazards, but must also include the dimension of vulnerability, which determines the level of impact. Flood vulnerability is influenced by a combination of physical and spatial factors, such as topography, distance from rivers, drainage systems, and land use characteristics that affect runoff patterns and water absorption capacity (Fetam watershed study; (Ashfaq et al., 2025) A number of studies show that areas located close to river channels and dominated by built-up land use have a higher level of vulnerability to flooding than areas with better vegetation cover.

To understand the relationship between hazards and vulnerability, this study uses the Pressure and Release (PAR) Model framework proposed by (Wisner & Nivaran, n.d.) The PAR Model views disasters as the result of the intersection between natural hazards and vulnerability processes that develop from root causes, dynamic pressures, to unsafe conditions. This approach allows for the analysis of disasters not only as natural phenomena, but also as consequences of social, economic, and spatial processes occurring within a region (Kappes et al., 2012a). Thus, the PAR model provides a strong conceptual basis for identifying structural factors that increase a region's vulnerability to flooding.

This study specifically focuses on one of the main components in the PAR Model, namely Dynamic Pressure. Dynamic Pressure refers to the processes that transform the root causes of vulnerability, such as development policies and spatial utilization patterns, into unsafe physical conditions (Wisner & Nivaran, n.d.) In the context of Medan City, this dynamic pressure is manifested physically through two key parameters, namely proximity to rivers and land use. Proximity to rivers increases exposure to flooding, while changes in land use towards the dominance of built-up areas reduce infiltration capacity and increase surface runoff, thereby increasing flood vulnerability (Blöschl, 2022); (Permatasari et al., 2017)

The Geographic Information System (GIS)-based approach has been widely used in flood vulnerability research to systematically and objectively integrate various spatial parameters. Spatial analysis allows the combination of river distance, land use, and other physical factors through scoring and overlay techniques to produce well-classified vulnerability maps (Fetam watershed study; Swat river catchment study). Methods such as Weighted Overlay Analysis or weighted averaging are considered effective in describing spatial variations in vulnerability and providing relevant information for disaster mitigation planning and spatial planning.

Although several studies related to flooding in Medan City have been conducted (Silitonga, 2019); (Tobing et al., n.d.), studies that specifically integrate river proximity and land use parameters as representations of Dynamic Pressure within the conceptual framework of the PAR Model at the scale of the entire Medan City area are still relatively limited. In fact, this approach is important for understanding how development and spatial utilization processes contribute to the formation of spatial flood vulnerability.

Therefore, this study aims to: (1) compile a flood vulnerability map of Medan City based on river proximity and land use parameters using a GIS approach, and (2) analyze the resulting flood vulnerability level in the context of the PAR Dynamic Pressure Model. The results of this study are expected to provide valid and reliable geospatial information as a basis for formulating disaster mitigation policies and spatial planning that are more adaptive to flood risks in the city of Medan.

Methodology

This study uses a quantitative approach with a Geographic Information System (GIS)-based spatial analysis method to measure and map the level of flood vulnerability throughout the administrative area of Medan City. The research focuses on the Dynamic Pressure component in the Pressure and Release (PAR) Model, which is represented by two main variables, namely river proximity and land use.

The data used is secondary geospatial data, including river network maps and the latest land cover/land use maps of Medan City. All data is processed in a GIS environment using the UTM WGS 84 projection system to maintain spatial consistency and accuracy of analysis.

The analysis begins with the process of scoring each variable separately. The river proximity variable is analyzed through buffer operations on the river network to produce several distance zones that reflect the level of physical exposure to the threat of river flooding. Each distance zone is scored from 1 to 5, with the zone closest to the river receiving the highest score because it has the greatest exposure to flooding. The classification of river proximity zones and the scoring system used are presented in Table 1.

Table 1. River Proximity Zone

Zone (Distance from the River)	*Score*
0-50 meter	*5*
50-100 meter	*4*
100-250 meter	*3*
250-500 meter	*2*
500-1000 meter	*1*
1000-2000 meter	*1*

Next, land use variables were analyzed by classifying each type of land cover based on its physical characteristics, impermeability level, and function in relation to surface runoff processes. Each land use class was assigned a score of 1–5, with land with a high risk of flooding and a high proportion of impervious surfaces receiving a higher score. The land use classification and scoring used are shown in Table 2.

Table 2. Land Cover

Land Cover	*Score*
Plantations	*2*
Settlements	*4*
Secondary Mangrove Forests	*1*
Swamp Scrub	*2*
Dry Land Agriculture	*3*

Rice Fields	*4*
Fish Ponds	*5*
Airports/Ports	*4*

After the river proximity score map and land use score map were generated, the two maps were combined through an overlay process. The total flood vulnerability score was calculated using a simple average method with the following formula:

$$\text{Total Score} = \frac{\text{Zone Score} + \text{Land Score}}{2}$$

The total scores obtained were then reclassified into five categories of flood vulnerability, namely not vulnerable (1), less vulnerable (2), moderately vulnerable (3), moderately vulnerable (4), and highly vulnerable (5). The final result of this stage was a map of flood vulnerability in Medan City, which was used to answer the research objectives.

Result and Discussion

Result

1. **Characteristics of the Research Area in Medan City**

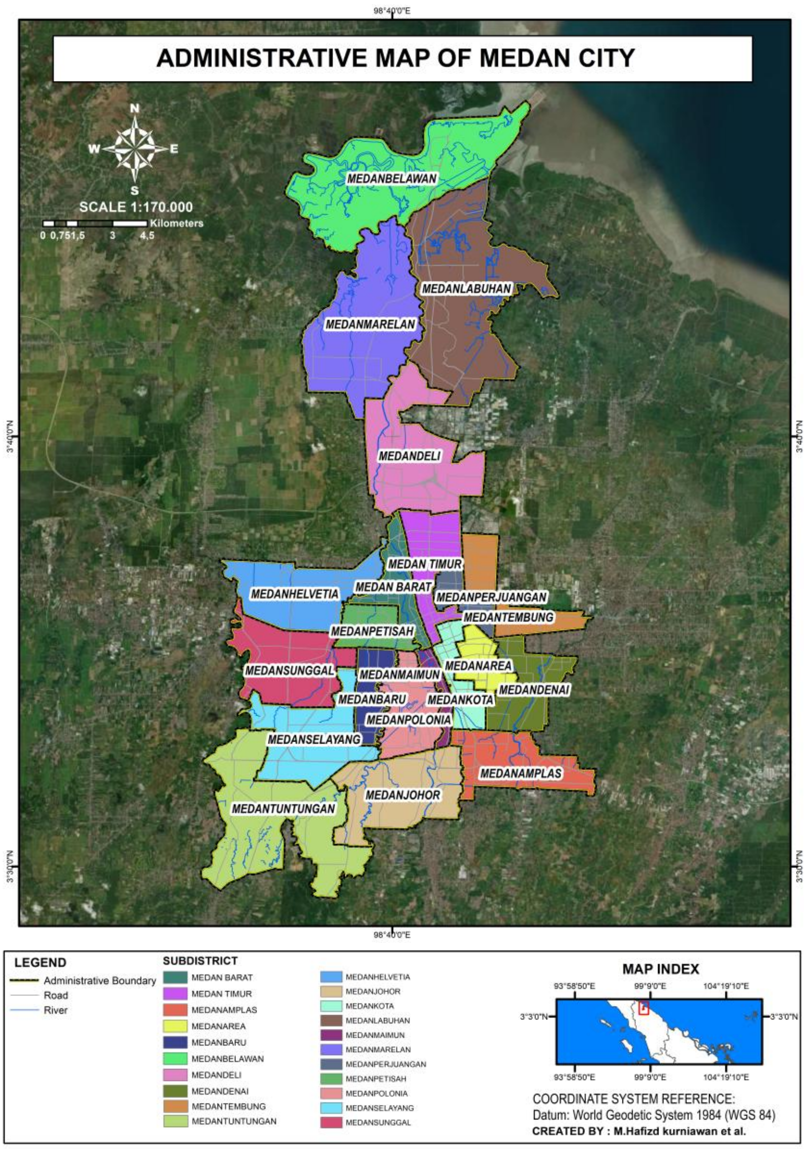

Figure 1. Administrative Map of Medan City

The city of Medan is an urban area with a high level of spatial complexity in terms of physical conditions, population density, and land use variation. Administratively, the study area covers all subdistricts in the city of Medan, which have relatively flat to low topography, especially in the central and northern parts of the city. These conditions make the city of Medan vulnerable to surface runoff accumulation, especially during the high-intensity rainy season.

In addition to topographical characteristics, the existence of river systems that cross urban areas is an important factor in flood vulnerability analysis. The Deli, Babura, and Belawan rivers flow from the southern region to the central and northern coastal areas of Medan City, crossing densely populated settlements and economic activity centers. Subdistrict administrative boundaries were used as spatial analysis units to facilitate the identification of flood vulnerability distribution between regions. The administrative map of Medan City, which formed the basis for spatial analysis, is presented in Figure 1.

2. Results of River Proximity Analysis

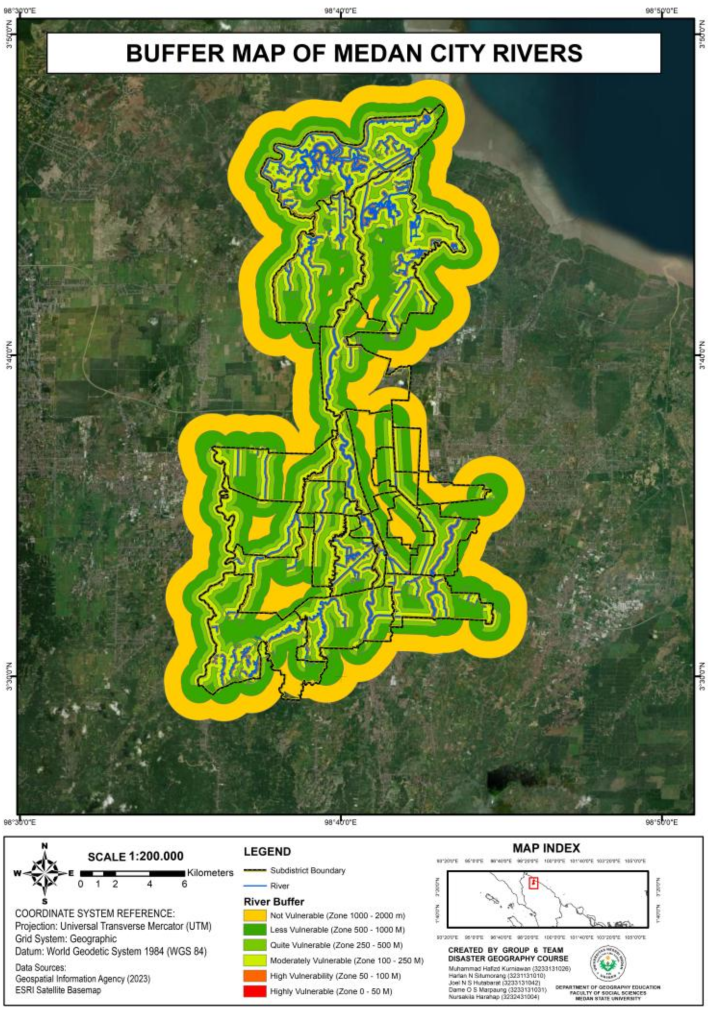

Figure 2. Buffer Map of Medan City Rivers

The results of the river proximity analysis show that the level of exposure of the Medan City area to flooding varies spatially based on the distance from the main river channel. Zones closest to the river have a higher potential for flood exposure because they are located in areas that naturally function as floodplains. Riverbank areas, particularly along the Deli and Babura Rivers, show a concentration of zones with high exposure levels due to the limited capacity of the rivers to accommodate water discharge when rainfall increases.

Conversely, areas located further away from the main river network show a relatively lower level of exposure. However, some areas that are spatially distant from rivers still have the potential to experience flooding due to urban drainage conditions and surface runoff accumulation. The distribution of river proximity zones illustrating variations in flood exposure levels across the city of Medan is shown in Figure 2, which is one of the main parameters in the creation of flood vulnerability maps.

3. **Land Use Analysis Results**

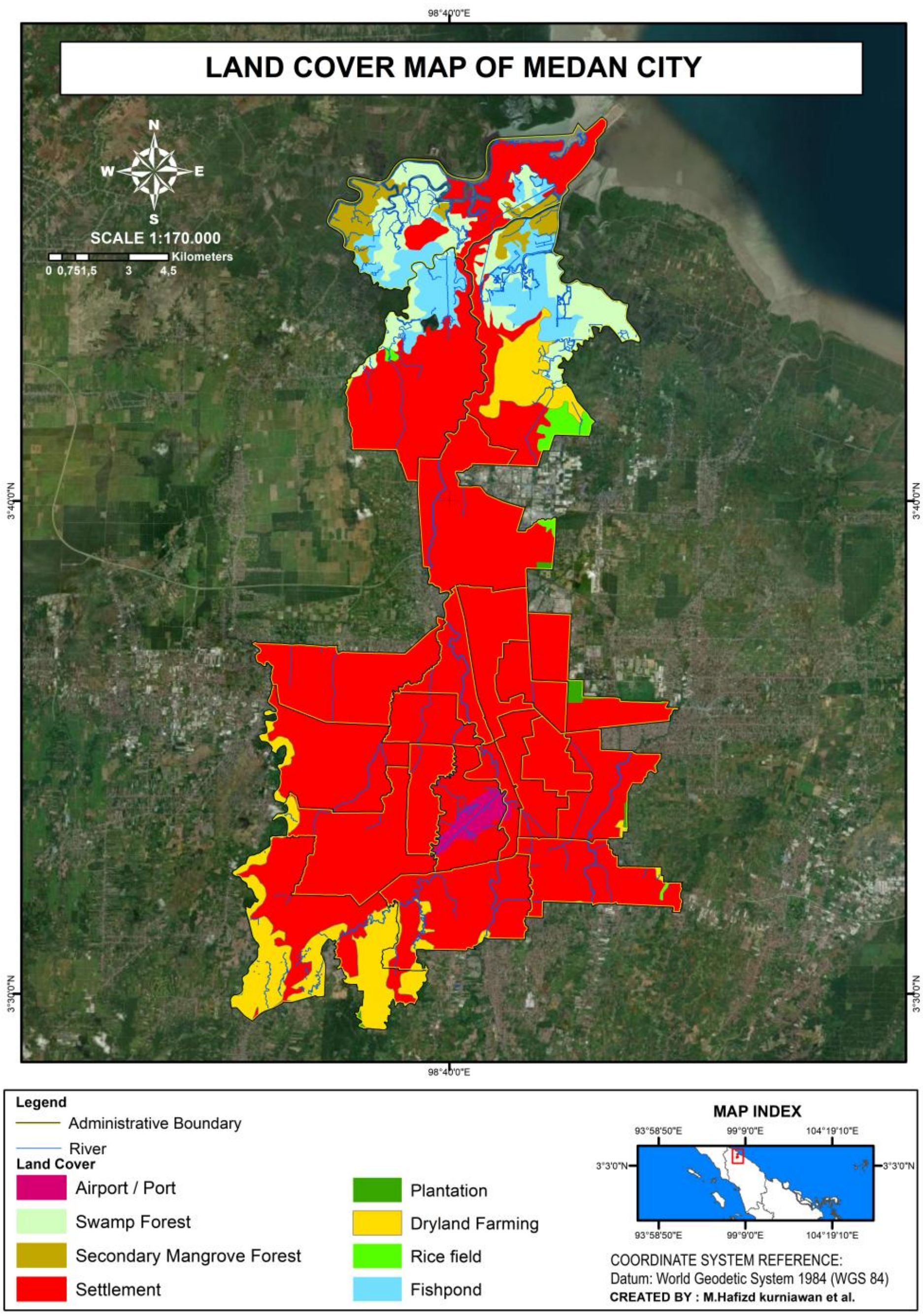

Figure 3. Land Cover Map of Medan City

Land use analysis shows that Medan City is dominated by developed land, especially dense settlements spread across the city center and surrounding areas. In addition to residential areas, land use with a high risk of flooding, such as rice fields, fish ponds, and airport and port infrastructure areas, was also found to be significant, especially in the northern coastal region. These types of land use have physical characteristics that tend to increase surface runoff and reduce water infiltration capacity.

On the other hand, areas with vegetation cover such as plantations, swamp scrub, and secondary mangrove forests are still found, especially in the southern part and some coastal areas. This vegetation cover plays a role in reducing the sensitivity of the area to flooding because it has an ecological function as a catchment area and surface runoff barrier. The spatial distribution of land use in Medan City, which is used as a sensitivity parameter in flood vulnerability analysis, is shown in Figure 3.

4. Medan City Flood Vulnerability Map

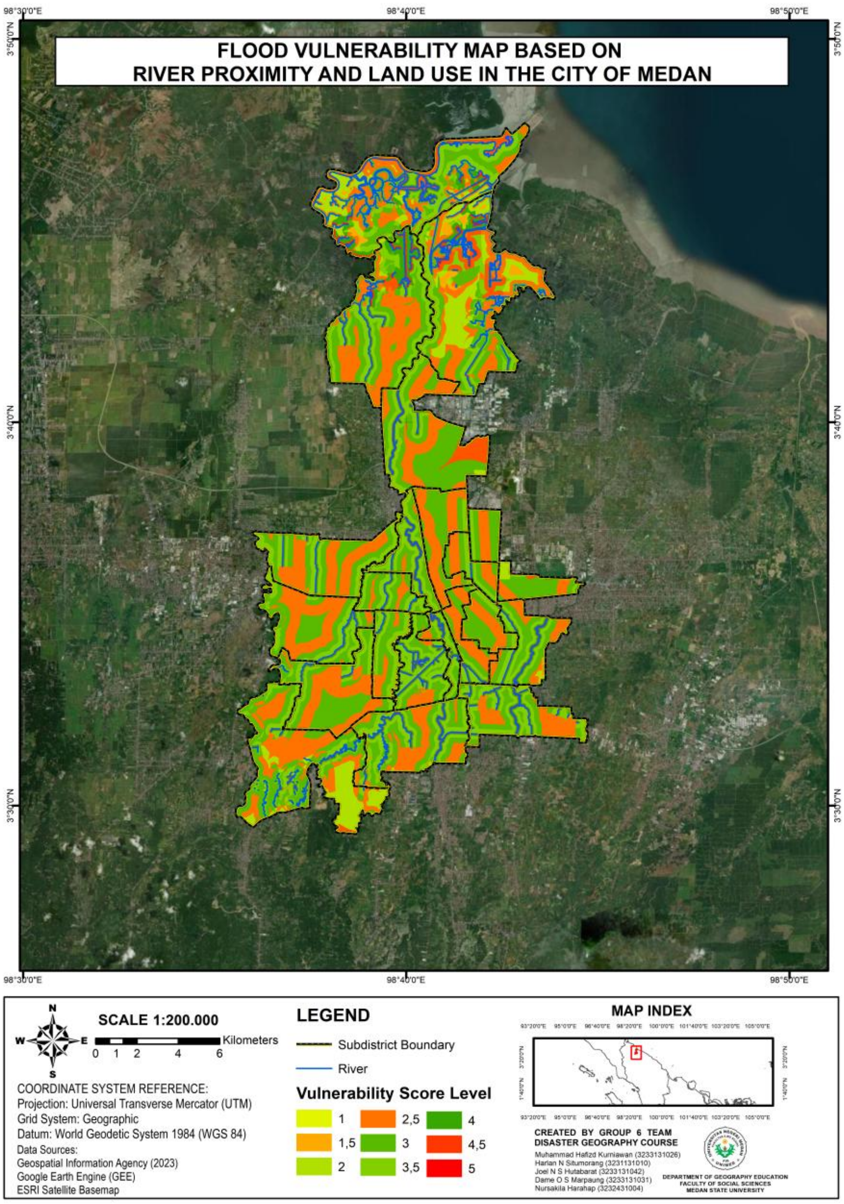

Figure 4. Flood Vulnerability Map of Medan City

The combination of river proximity parameters as exposure factors and land use as sensitivity factors was carried out through overlay analysis to produce a flood vulnerability map of Medan City. The spatial processing results show that the level of flood vulnerability is not evenly distributed, but rather forms a clear spatial pattern following the physical characteristics and spatial utilization of the area. The level of flood vulnerability is classified into five categories, namely not vulnerable, less vulnerable, moderately vulnerable, moderately vulnerable, and highly vulnerable.

Areas with high vulnerability are mainly concentrated along the banks of major rivers, the northern coastal areas, and densely populated settlements in the center of Medan City. Meanwhile, areas with low to no vulnerability are generally located relatively far from river channels and still have dominant vegetation cover. The final analysis of the flood vulnerability map of Medan City is presented in Figure 4, which will be used as the basis for discussion in the framework of the Pressure and Release (PAR) Dynamic Pressure Model.

Discussion

Flood vulnerability patterns in Medan City show a non-random spatial configuration and are strongly influenced by the interaction between proximity to rivers and land use characteristics. The concentration of high vulnerability zones along the banks of the Deli and Babura Rivers confirms that the riverine areas still function as natural floodplains that are vulnerable to flooding, especially when the rivers are unable to accommodate peak discharge. Various studies state that urbanization in floodplain areas significantly increases exposure and potential losses due to flooding because of the accumulation of population, buildings, and economic activities in vulnerable zones (Kim et al., 2025); (Fatmawaty, 2025) . In the context of Medan City, this condition is exacerbated by limited spatial control in riverbank areas.

Land use changes towards built-up areas play an important role in increasing the sensitivity of an area to flooding. Dense settlements, road infrastructure, and commercial buildings dominated by impervious surfaces reduce soil infiltration capacity and accelerate surface runoff. GIS-based studies and multi-criteria analyses show that the conversion of green areas into built-up areas is strongly correlated with increased flood vulnerability, particularly in rapidly developing urban areas (Putra et al., 2024); (Sholeh et al., 2024). These findings are consistent with the results of this study, where areas with better vegetation cover show relatively low vulnerability levels.

Within the framework of the Pressure and Release (PAR) Model, this phenomenon reflects the existence of dynamic pressures arising from development processes and spatial changes. These dynamic pressures act as a link between the main causes—such as population growth, space requirements, and economic development orientation—and the creation of unsafe conditions at the local level. A number of studies confirm that weak control over spatial use and development policies that are insensitive to environmental risks accelerate the transformation of natural hazards into disasters (Kappes et al., 2012b); (Efraimidou & Spiliotis, 2024). Thus, flood vulnerability in Medan cannot be understood solely as a result of physical factors, but rather as the result of an accumulation of social and spatial processes.

The northern coastal area of Medan City shows a high level of flood vulnerability due to a combination of low-lying topography and changes in coastal land use. The conversion of coastal areas into fish ponds and other aquaculture activities has reduced their natural ecological function as a buffer zone for water flow, thereby increasing sensitivity to tidal flooding and runoff from upstream areas. Research in various coastal areas shows that changes in coastal land use significantly increase flood vulnerability, especially for communities living and working in the land-sea transition zone (Anisa Yudita et al., 2025).

From a socio-economic perspective, these conditions have a direct impact on coastal communities whose livelihoods depend on fisheries, wetland agriculture, and informal activities. Recurring floods have the potential to damage production facilities, cause loss of income, and increase household economic uncertainty. Studies on social vulnerability confirm that communities with high dependence on local resources and limited access to infrastructure tend to have lower adaptive capacity to flood disasters(Paloma & Mutiara, 2025). Within the PAR framework, these conditions demonstrate how dynamic pressures contribute to the formation of socially insecure conditions.

Conversely, the southern part of Medan City, which is relatively far from the main river channel and still dominated by vegetation cover, shows a lower level of vulnerability. The presence of vegetation plays a role in slowing surface runoff, increasing infiltration, and reducing runoff volume. Various studies show that areas with good vegetation cover have a natural ability to reduce the impact of flooding(Tascón-González et al., 2020);(Kim et al., 2025). Socially, this condition provides benefits in the form of stable economic activity, low potential for material losses, and relatively better community adaptation capacity.

The Geographic Information System (GIS) approach used in this study allows for the systematic integration of spatial variables to identify variations in vulnerability between regions. Previous studies have confirmed that GIS-based vulnerability mapping and multi-criteria approaches are effective tools for revealing spatial risk inequalities and supporting risk-based mitigation planning (Ikhsan & Santosa, 2025).In the context of GeoHuman, vulnerability maps serve not only as technical representations, but also as a medium for understanding the relationship between people, space, and risk.

Overall, the results of this study confirm that flood vulnerability in Medan City is a socio-spatial construct shaped by land use dynamics, development pressures, and community social capacity. Flood risk is unevenly distributed and tends to be greater for communities with limited access to safe spaces and flood control infrastructure. Therefore, flood mitigation efforts need to be directed not only at technical approaches, but also at strengthening spatial planning policies, protecting vulnerable groups, and increasing the social resilience of urban communities.

Conclusion

The results of the study show that flood vulnerability in Medan City forms a clear spatial pattern as a result of the interaction between river proximity and land use. Zones with the highest levels of vulnerability are concentrated along the banks of the Deli and Babura Rivers and the northern coastal areas, which are characterized by high exposure to river flow and the dominance of risky land uses such as dense settlements and fish ponds. From the perspective of the Pressure and Release (PAR) Model, particularly the Dynamic Pressure component, this pattern reflects the impact of land use changes and intensified development in flood-prone areas. Socio-economically, areas with high vulnerability are generally inhabited by communities that depend on river and coastal areas for shelter and livelihoods, so the risk of flooding has the potential to increase economic losses and deepen social vulnerability. Therefore, the resulting vulnerability map not only serves as a technical output but also has important implications for risk-based spatial planning, strengthening land use control policies, and protecting vulnerable communities in the context of urban development in the city of Medan.

However, this study has several limitations that need to be considered. The flood vulnerability analysis is based only on two main parameters, namely river proximity and land use, so it does not fully represent the complexity of physical and social factors that influence flood vulnerability, such as rainfall, drainage capacity, elevation, population density, and community adaptive capacity. In addition, this study focuses on the Dynamic Pressure aspect of the PAR Model, so that the root causes and unsafe conditions have not been analyzed in depth. Therefore, further research is recommended to integrate more physical and social variables, using a multi-criteria approach or hydrological modeling, and expanding the analysis to all components of the PAR Model so that the understanding of flood vulnerability and its implications for urban communities becomes more comprehensive.

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