

# Index-Based Spatial Assessment of Flood Hazard and Multi-Sectoral Vulnerability in Flood-Prone Areas

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**Abstract** Floods are among the most frequent and damaging natural hazards in Indonesia, particularly in flood-prone subdistricts. This study conducts an index-based spatial assessment of flood hazard and multi-sectoral vulnerability in Momunu Subdistrict, Buol Regency, Central Sulawesi. Using Geographic Information Systems (GIS), flood hazard mapping reveals that the total flood-prone area covers 3,022.02 hectares, consisting of low (1,674.18 ha), medium (958.05 ha), and high (389.79 ha) hazard classes. The most affected villages include Panimbul (low hazard), Pinamula (medium), and Lamadong I (high hazard), especially in areas with flat topography near river systems. The vulnerability analysis incorporates social, physical, economic, and environmental indicators. Social vulnerability is highest in villages such as Potugu, Pomayagon, and Guamomial. Physical vulnerability is generally low to moderate but increases near rivers and in settlements with non-permanent structures. Economic vulnerability shows significant variation, with the highest index value of 0.565568, indicating substantial exposure to potential economic losses. Environmental vulnerability peaks at an index value of 0.633431, reflecting ecological stress due to land-use

changes and diminished protected areas. Furthermore, the exposed population in Momunu Subdistrict is estimated at 8,637 people, including 39 persons with disabilities, 4,461 males, and 4,176 females. Estimated flood-related losses reach IDR 49.063 billion, comprising IDR 49.025 billion in physical damage, IDR 38.32 billion in economic losses, and environmental degradation over 869 hectares. These findings underscore the urgent need for targeted flood mitigation strategies and resilience planning based on spatially explicit risk assessments.

**Keywords** Flood Hazard, Vulnerability Index, Spatial Analysis, GIS, Disaster Risk Assessment

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## 1. Introduction

Indonesia, as an archipelagic country located in the tropics, is highly susceptible to various hydrometeorological disasters, with flooding being among the most frequent and devastating [1, 2]. The country experiences intense seasonal rainfall influenced by the

monsoon system and climate variability such as El Niño and La Niña, which contribute to frequent river overflows and surface water accumulation [3]. In many regions, especially lowland and riparian zones, flooding causes significant damage to infrastructure, disrupts livelihoods, and displaces populations. According to the Indonesian National Disaster Management Agency (BNPB), floods accounted for over 40% of natural disasters recorded annually between 2010 and 2023. This alarming frequency highlights the urgent need for improved flood risk management, especially in rural areas where institutional response capacity is limited.

Flood risk management requires not only an understanding of hazard occurrence but also the spatial and temporal dynamics of populations and assets exposed to such hazards. Spatial analysis, particularly through Geographic Information Systems (GIS), enables detailed mapping of flood-prone areas, identification of critical zones, and support for targeted policy interventions [4–6]. In addition to spatial assessment, incorporating a temporal dimension—such as historical flood frequency, rainfall trends, and seasonal variability—can significantly enhance predictive accuracy and long-term planning capacity. The integration of multi-year hydrological and climatic datasets allows hazard models to anticipate future risks under changing environmental conditions. Moreover, the addition of climate projection scenarios provides insights into potential shifts in hazard intensity and frequency, thereby informing resilience planning under climate change [7].

Flood hazard refers to the probability and intensity of flood events occurring in a given area, typically determined by factors such as rainfall intensity, land cover, elevation, and slope [8]. Meanwhile, vulnerability represents the susceptibility of human systems—communities, infrastructure, and the environment—to suffer damage or loss when exposed to flood hazards [9]. It is commonly classified into several dimensions: social vulnerability (demographics, education, health), physical vulnerability (building quality, infrastructure), economic vulnerability (income, livelihoods), and environmental vulnerability (land use, ecosystem services) [10]. A comprehensive flood risk assessment must therefore combine both hazard and vulnerability perspectives, while also accounting for temporal variability, as areas with moderate hazards but increasing vulnerability trends may face escalating risks over time.

Numerous studies in Indonesia have utilized spatial approaches to map flood-prone areas and assess risk levels [11]. For example, research in Java and Sumatra has applied GIS and remote sensing to delineate flood hazard zones and simulate flood extents based on historical rainfall and river discharge data [12]. Some studies have integrated social indicators to map vulnerability, particularly in urban settings such as Jakarta, Surabaya, and Bandung [13]. However, the majority of these efforts focus on large cities or densely populated areas, while rural subdistricts—

despite being equally vulnerable—remain under-researched [14]. Additionally, many existing studies consider hazard and vulnerability separately, without integrating them into a unified spatio-temporal risk assessment [15].

Recent advancements highlight the growing use of machine learning algorithms, such as Random Forests and Support Vector Machines, for predictive flood risk modeling in Indonesia and neighboring countries [16, 17]. Similarly, remote sensing applications using Sentinel-1 and Landsat imagery have enabled near-real-time flood mapping, particularly in data-scarce rural regions [18]. Moreover, participatory mapping approaches have been increasingly implemented in Southeast Asian contexts—such as in the Philippines, Vietnam, and Indonesia—to incorporate local and community knowledge into flood risk assessments, thereby improving both the accuracy and ownership of disaster mapping processes [18, 19]. In Indonesia, the *Technical Module for Preparing Disaster Risk Assessment: Flood Hazards* issued by BNPB [19] emphasizes the integration of participatory data collection and stakeholder engagement as essential components of effective disaster risk analysis. Comparative applications in neighboring countries, such as Thailand and Malaysia, have also shown that combining Geographic Information Systems (GIS) with multi-criteria decision analysis tools (MCDA, AHP) enhances the practical utility of flood risk models for spatial planning and disaster preparedness [14, 15]. These findings align with the *Regulation of the Head of BNPB Number 2 of 2012* [18], which underscores the importance of integrating scientific data, spatial modelling, and local policy instruments in disaster risk management frameworks. Collectively, these approaches demonstrate the value of hybrid methodologies that merge quantitative geospatial techniques with participatory governance mechanisms to strengthen the contextual relevance and policy applicability of flood risk assessments in Southeast Asia.

While there is a growing body of research on flood risk in Indonesia, several gaps remain. First, the integration of multi-sectoral vulnerability indices in rural areas is limited. Second, there is a lack of spatially disaggregated and temporally explicit data that combines hazard mapping with exposure and potential loss analysis. Third, the specific challenges faced by remote subdistricts—such as limited infrastructure, ecological degradation, and population fragility—are rarely addressed in a systematic manner. This study offers novelty by integrating spatial flood hazard mapping with a multi-dimensional vulnerability assessment using an index-based approach, while also acknowledging the importance of incorporating temporal dynamics in future research. Moreover, it provides estimates of potential losses, including exposed population and environmental degradation, which are often absent from prior assessments.

The main objective of this research is to assess flood risk in Momunu Subdistrict, Buol Regency, by integrating

spatial flood hazard mapping with multi-sectoral vulnerability analysis. The study applies an index-based approach to measure social, physical, economic, and environmental vulnerabilities and overlays them with flood hazard zones. In addition, the study estimates the number of people exposed to flood risk and calculates potential physical and economic losses. While the current analysis focuses on recent hydrometeorological and demographic data, we recognize that incorporating temporal datasets and climate projections would further enhance the predictive power of the model and support long-term resilience planning. The geographic focus is limited to the administrative boundaries of Momunu Subdistrict, while the temporal scope aligns with the availability of recent datasets.

Momunu Subdistrict, located in Buol Regency, Central Sulawesi, represents a rural area with significant flood exposure and diverse socio-ecological conditions. The region is characterized by a combination of flat lowland topography, dense settlement clusters near riverbanks, and increasing land-use changes that exacerbate hydrological risks. Despite recurring flood events, there is limited empirical data and spatial analysis available for local authorities to develop targeted mitigation plans. The lack of early warning systems, limited infrastructure quality, and vulnerable populations—such as persons with disabilities—further justify the need for a focused assessment. By choosing Momunu as a case study, this research seeks to address the spatio-temporal data gap and contribute to context-specific disaster risk reduction.

The strength of this study lies in its integration of flood hazard mapping and vulnerability indexing within a spatial framework. Rather than treating hazard and vulnerability as isolated concepts, the study overlays them to identify high-risk areas that require priority attention. For instance, areas with high hazard exposure and high social or economic vulnerability—such as Lamadong I and Potugu—emerge as critical intervention zones. This approach enables local planners to allocate resources more effectively and design targeted resilience-building programs.

The results of this study are expected to contribute directly to evidence-based disaster risk reduction (DRR) planning at the subdistrict level. By quantifying both the spatial extent of flood hazards and the dimensions of vulnerability, the findings offer valuable insights for updating local contingency plans, infrastructure development, and community preparedness programs. Furthermore, the estimated financial losses and population exposure figures can be used to justify budget allocations and advocate for increased institutional support from regional or national authorities.

This research provides significant contributions to both academic discourse and practical flood risk management in rural Indonesia. Academically, it enhances the body of knowledge by offering a comprehensive, index-based spatial assessment that integrates hazard, vulnerability, and

exposure dimensions at the subdistrict level—an approach rarely applied in rural contexts. The originality of this study lies in its methodological integration of geomorphological hazard mapping (via GFI and DEM data) with multi-sectoral vulnerability indexing and exposure analysis, explicitly incorporating gender and disability dimensions. Unlike previous studies, this approach not only quantifies spatial risk but also provides a framework directly linked to policy instruments such as the Buol Regency RTRW 2024–2043. The innovative results highlight critical intervention zones and estimate potential multi-dimensional losses, making the methodology replicable in other rural regions of Indonesia and Southeast Asia. This novelty contributes to both scientific advancement and practical disaster risk governance, while offering a foundation for further development of predictive models incorporating climate projections and machine learning.

## 2. Materials and Methods

This study employs geospatial analysis and index-based modeling to provide a comprehensive assessment of flood risk in Momunu Subdistrict, using datasets such as topographic maps, land use data, rainfall records, and demographic statistics processed through GIS. The analysis includes flood hazard mapping and multi-sectoral vulnerability assessment across social, physical, economic, and environmental dimensions, with normalized and weighted indicators combined into composite indices for spatial overlay. Exposure analysis further estimates the affected population and potential economic losses, supporting data-driven disaster risk reduction. To strengthen the predictive capacity, future research should integrate temporal datasets, such as historical flood records, rainfall variability, and land-use changes, which would capture both short-term variability and long-term hydrological trends. Incorporating climate projection scenarios would also enable planning for future flood dynamics under climate change conditions. Table 1 outlines the potential data sources and their contributions to enhancing hazard and vulnerability assessments.

### 2.1. Study Area Description

Momunu Subdistrict is located in Buol Regency, Central Sulawesi Province, Indonesia, positioned approximately between 0°53'–0°58' North Latitude and 121°16'–121°24' East Longitude. Covering a total area of about 18,600 hectares, the subdistrict comprises 12 administrative villages with varying topographic conditions. The region exhibits a combination of hilly terrain and lowland plains, where most of the settlements, agricultural fields, and public facilities are concentrated. Elevation ranges from 10 to 500 meters above sea level, with flatter areas located along riverbanks and valley floors. The dominant land use types include mixed garden areas, dryland farming, and

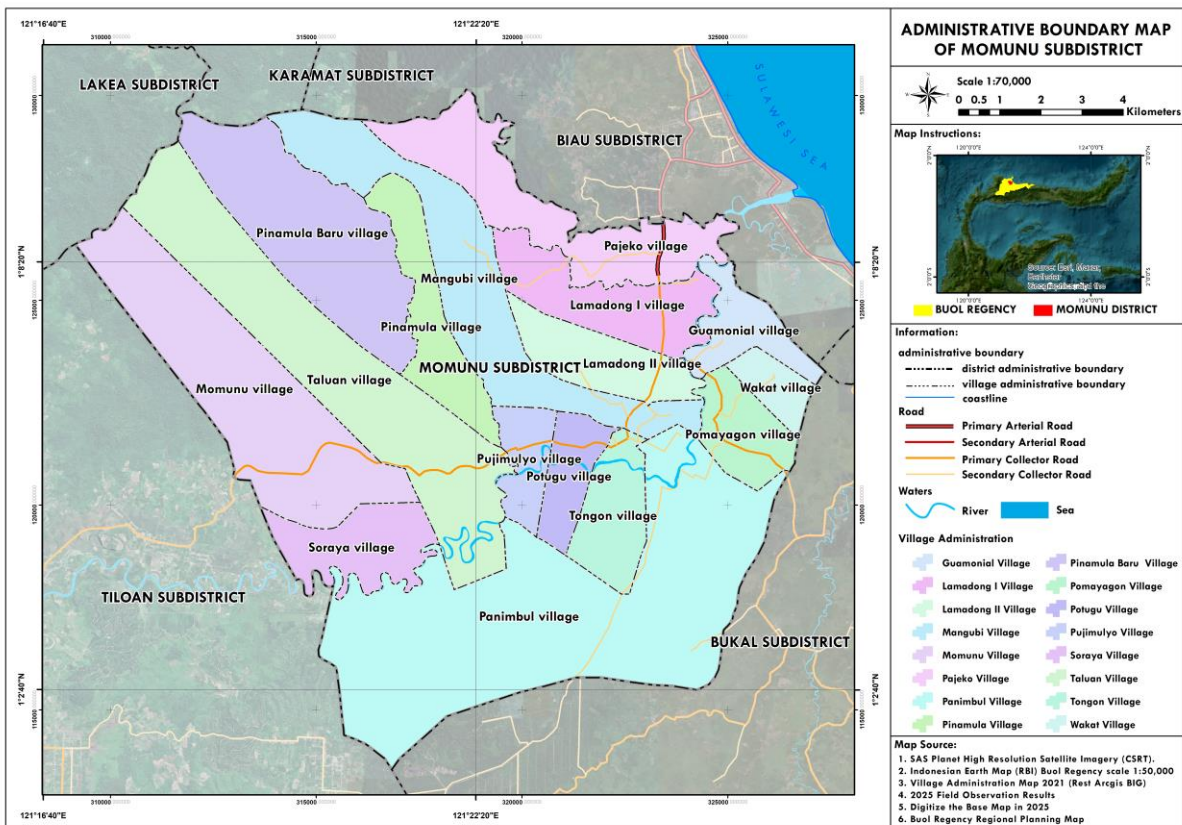
patches of secondary forest. Figure 1 presents the administrative boundaries and geographical location of Momunu Subdistrict within the regional context of Buol Regency.

Hydrologically, Momunu is influenced by several watershed systems, particularly the Momunu River and its tributaries, which function as primary drainage corridors. The region receives high annual rainfall, typically between 2,000 and 3,000 mm, making it susceptible to periodic surface runoff and river overflows during the rainy season

from November to April. The relatively flat terrain in certain areas, combined with insufficient drainage infrastructure and increased land surface sealing due to development, exacerbates flood risks. Several villages located near riverbanks or on floodplains have experienced repeated inundation events. Figure 2 illustrates the spatial distribution of historical flood occurrences in the subdistrict, compiled from community reports and disaster records, highlighting critical flood-prone zones.

**Table 1.** Integration of temporal data into the flood hazard model

Temporal Component	Data Sources	Integration Approach	Expected Contribution to Model
<b>Historical Flood Frequency</b>	Disaster records from BNPB, BPBD, or local archives	Overlay historical flood extents with current hazard zones	Validates hazard maps and captures recurrence intervals
<b>Rainfall Trends</b>	Multi-year rainfall data from BMKG (daily/monthly)	Time-series analysis of intensity and variability	Identifies changing precipitation patterns and flood triggers
<b>Seasonal Variability (El Niño/La Niña)</b>	Climate indices (ENSO, SOI) from global and regional datasets	Correlate ENSO phases with flood occurrence	Explains inter-annual variability and seasonal flood risk
<b>Land Use and Land Cover Change</b>	Satellite imagery (Landsat, Sentinel) over multiple decades	Detect land cover transitions and urban/rural expansion	Captures human-driven drivers of hydrological change
<b>Climate Projection Scenarios</b>	Downscaled GCM/RCM outputs for Indonesia (CMIP6, CORDEX-SEA)	Scenario-based modeling of future rainfall and runoff	Provides long-term foresight under climate change



**Figure 1.** Administrative boundaries and geographical location of Momunu districts

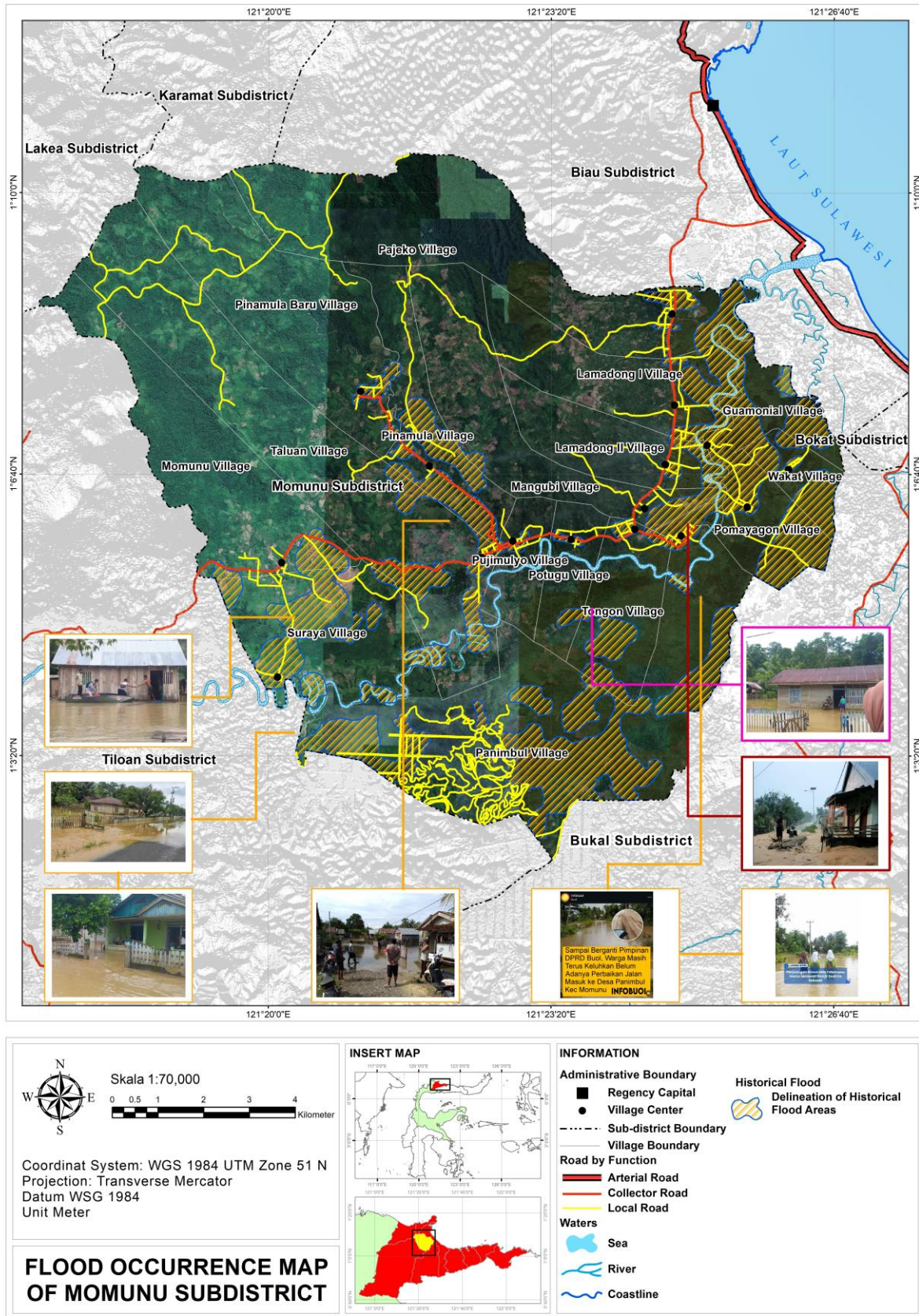


Figure 2. Spatial distribution of historical flood occurrences in the subdistrict

Socioeconomically, Momunu Subdistrict represents a typical rural area with a predominantly agrarian livelihood base. Most residents depend on smallholder farming, plantation labour, and informal market activities for income. Infrastructure conditions vary significantly between villages, with limited access to quality roads, sanitation, and drainage networks, particularly in more remote or low-lying areas. In addition, the governance and institutional capacity of the region play an important role in shaping its vulnerability to floods. The availability of early warning systems, the effectiveness of disaster response protocols, and the enforcement of land-use planning remain limited, thereby constraining adaptive capacity. The region has a history of flood-related disasters, with notable events occurring in 2017 and 2021 that caused substantial physical and economic damage, including to homes, crops, and transportation routes. These recurrent events underscore the combined influence of socioeconomic, environmental, and institutional factors on flood vulnerability in Momunu and justify the need for integrated, governance-aware flood risk assessments to support community resilience and disaster mitigation planning.

## 2.2. Types and Sources of Data

This study uses both qualitative and quantitative data to support the spatial analysis of flood hazard and vulnerability in Momunu Sub-district, Buol Regency. Qualitative data include non-numerical observations such as flood conditions and the state of public infrastructure, while quantitative data consist of numerical information like geographic features, topography, slope, soil type, geology, rainfall, land use, and infrastructure data. The data

are sourced from both primary and secondary means: primary data were obtained through direct field observation, and secondary data were gathered from official institutions such as BPS, BAPPEDA, PUPR, BPBD, the Momunu Sub-district Office, and INARISK BNPB. These datasets provided key information like administrative maps, land use, slope, rainfall, and vulnerability indices, which support the overall analysis.

## 2.3. Data Collection Techniques

This study used three main data collection techniques: field observation, spatial data collection, and literature review. Field observation involved directly observing physical conditions, infrastructure, and flood-prone areas in Momunu Sub-district to gather firsthand information. Spatial data collection focused on obtaining geospatial information such as maps of geography, topography, slopes, soil, geology, rainfall, and land use for hazard mapping and analysis. The literature review provided secondary data from books, journals, and official documents to support the study's theoretical framework. In addition, governance-related information was incorporated to address institutional capacity, including the availability of early warning systems, the effectiveness of disaster response protocols, and the enforcement of land-use planning regulations. These institutional and governance indicators were integrated to better capture the enabling or constraining role of local authorities in flood risk management. Not all data were used in the core analysis; some served to enrich understanding of the area's physical, social, economic, and institutional context. Table 2 summarizes the types of data, sources, and collection methods used.

**Table 2.** Types of data, sources, and data collection techniques

Data	Type of Data	Collection Technique	Source
Flood Hazard Area	Primary	Field Observation	BPS Momunu 2024
Public Infrastructure	Primary and Secondary	Field Observation	RTRW Buol Regency 2024–2043 and Analytical Result
Land Use Data and Maps	Primary	Field Observation, Spatial Collection	Ministry of Environment and Forestry (KLHK)
Geographic Data and Maps	Secondary	Spatial Data Collection	RTRW Buol Regency 2024–2043
Topographic Data and Maps	Secondary	Spatial Data Collection	RTRW Buol Regency 2024–2043
Slope Gradient Data and Maps	Secondary	Spatial Data Collection	DEMNAS
Soil Type Data and Maps	Secondary	Spatial Data Collection	RTRW Buol Regency 2024–2043 & National Soil Classification 2014
Geological Data and Maps	Secondary	Spatial Data Collection	RTRW Buol Regency 2024–2043
Rainfall Data and Maps	Secondary	Spatial Data Collection	RTRW Buol Regency 2024–2043

## 2.4. Flood Hazard Assessment Method

The flood hazard assessment in this study aims to determine two main aspects: the extent of the affected area and the hazard index. The extent refers to the spatial coverage of flood-prone areas, while the hazard index indicates the likelihood and intensity of flooding. Both probability (based on historical flood occurrences) and intensity (based on expected flood impacts) are considered to classify hazard levels. The hazard index values range from 0 to 1 and are categorized as follows: Low (0.000–0.333), Medium (0.334–0.666), and High (0.667–1.000) [16].

To produce flood hazard maps, this study applies a two-step geomorphological approach. First, flood-prone zones are identified using the Geomorphic Flood Index (GFI) derived from digital elevation models (DEM). The application of GFI offers methodological advantages in data-scarce areas such as rural subdistricts, as it relies on terrain morphology rather than extensive hydrological measurements. Locations with GFI values greater than 0.53 are classified as flood-prone areas. Second, flood depth is estimated based on elevation above river channels within these zones. The hazard index is calculated using fuzzy logic, which allows values between 0 and 1 to reflect degrees of risk rather than binary classifications. The spatial datasets used to generate the flood hazard map are presented in Table 3 below.

**Table 3.** Types, format, source, and year of data used for flood hazard mapping

No	Type of Data	Data Format	Source	Year
1	Digital Elevation Model (DEM)	Raster	COPERNICUS	2025
2	Flood-Prone Area Map	Vector (Polygon)	BIG / Spatial Plan (RTRW)	2024
3	Morphology / Land System Map	Vector (Polygon)	BIG / Spatial Plan (RTRW)	2024

The integration of fuzzy logic with Multi-Criteria Decision Analysis (MCDA) enhances the granularity and reliability of the hazard and vulnerability indices, as it incorporates multiple parameters into a unified spatial model. In this study, slope (with a median threshold of 5%) and horizontal distance from rivers (with a threshold of 100 meters) were weighted using fuzzy membership functions and combined through fuzzy overlay analysis to generate the final hazard index. To strengthen the applicability of the vulnerability assessment, exposure analysis incorporated gender-disaggregated population data and included vulnerable groups such as persons with disabilities [17].

Regarding the weighting process, the vulnerability indices were constructed by assigning 40% to social, 30% to economic, 20% to physical, and 10% to environmental dimensions. These proportions were established through a combination of literature review and expert judgment,

reflecting the predominant influence of social factors in shaping rural flood resilience, while also acknowledging the relatively lower institutional emphasis on environmental aspects. The overall procedure for generating and integrating these weights into the flood hazard index is illustrated in Figure 3, which outlines the analytical workflow applied in this study. Furthermore, the spatial representation of the flood-prone areas derived from geomorphic parameters is shown in Figure 4, which depicts the Geomorphic Flood Index (GFI) used to validate the hazard classification. In addition, the temporal dimension was partially considered by incorporating historical flood frequency records from the past decade to ensure consistency with observed flood recurrence patterns.

## 2.5. Flood Vulnerability Assessment Method

Flood vulnerability refers to the condition of a community that results in reduced capacity to anticipate, cope with, resist, and recover from the impacts of a disaster. The higher the vulnerability of a population, the greater the potential loss when a disaster occurs. Spatial analysis of vulnerability is performed by combining multiple components, each constructed from several parameters. These components include: social vulnerability, physical vulnerability, economic vulnerability, and environmental vulnerability.

All components and their associated parameters are integrated using the spatial Multi-Criteria Decision Analysis (MCDA) method. This method overlays spatial criteria using mathematical operations weighted by scores [18]. The general formula applied is:

$$v = FM_{\text{linear}}((w \cdot v_1) + (w \cdot v_2) + \dots (w \cdot v_n)) \quad (1)$$

Where:

- $V$  is the vulnerability index.
- $w$  is the weight of each component or parameter.
- $FM_{\text{linear}}$  is the linear fuzzy membership function ( $\min = 0$ ,  $\max = \text{highest weight}$ ).
- $n$  is the number of components or parameters.

Social, physical, economic, and environmental vulnerabilities are key components in disaster risk assessment. Social vulnerability considers factors such as population density, gender ratio, age group, poverty levels, and disability rates, with specific attention to gender-disaggregated population data and the inclusion of vulnerable groups such as persons with disabilities. Physical vulnerability focuses on the exposure of buildings and infrastructure like houses, public facilities, and critical services. Economic vulnerability relates to potential financial losses due to disruption of livelihoods and damage to assets across sectors, while environmental vulnerability refers to the sensitivity of natural systems, such as forests, rivers, and land cover, to hazards that may degrade or be degraded by disasters [19].

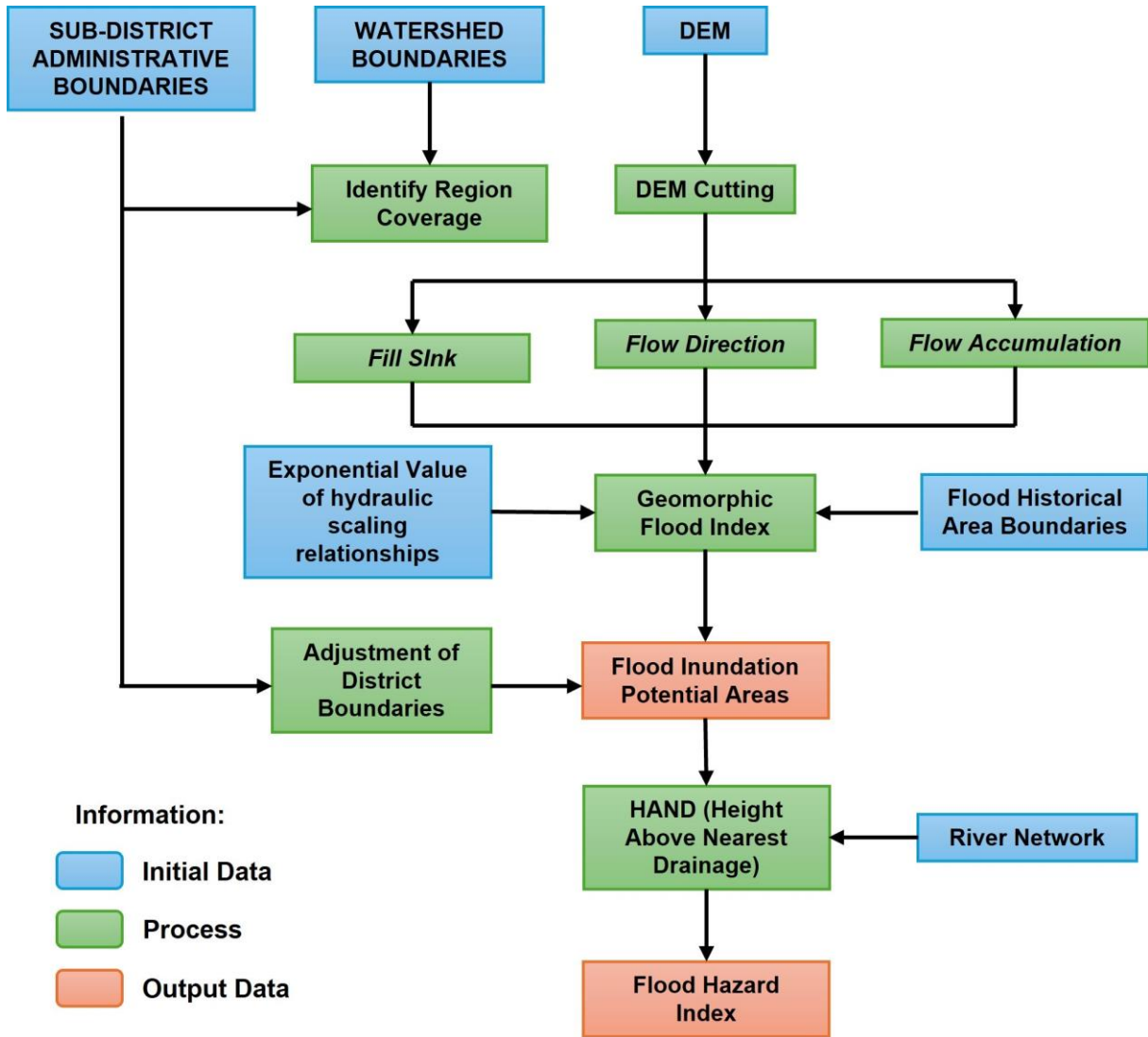


Figure 3. Workflow for generating the flood hazard index

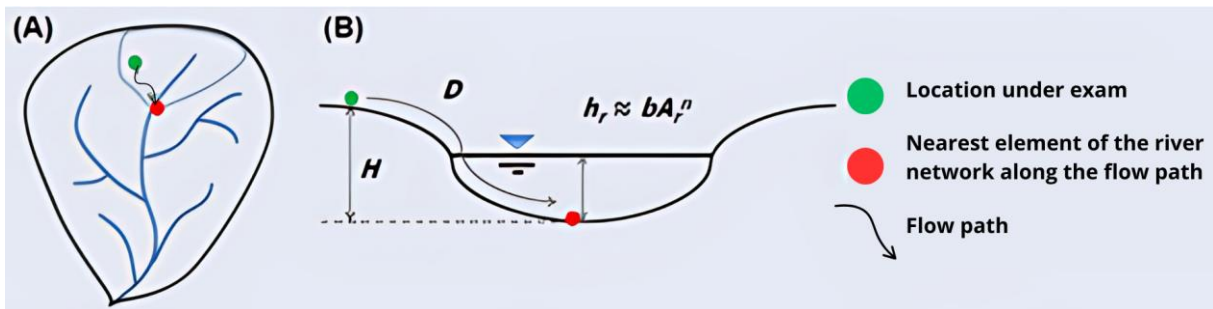


Figure 4. Geomorphologic Flood Index (GFI)

To calculate these vulnerabilities, each component is broken down into parameters and classified into low, medium, or high categories using set thresholds. A Multi-Criteria Decision Analysis (MCDA) method combined with fuzzy logic is applied, enhancing the granularity and reliability of the resulting indices. Spatial data are overlaid

in a GIS environment to generate composite indices for each type of vulnerability. For example, social vulnerability is calculated using demographic data and vulnerable group ratios, while economic vulnerability is derived from GDP by sector and employment structure.

**Table 4.** Vulnerability component weights

No.	Type of Vulnerability	Weight (%)
1	Social Vulnerability	40%
2	Physical Vulnerability	25%
3	Economic Vulnerability	25%
4	Environmental Vulnerability	10%

**Table 5.** Types, formats, sources, and years of data for vulnerability mapping

No.	Type of Data	Data Format	Data Source	Year
1	Village Administrative Boundaries	Polygon	Buol Regency Spatial Plan (RTRW)	2024
2	Land Use	Polygon	Ministry of Environment and Forestry (KLHK)	2023
3	Settlement Distribution	Point	Author's Analysis	2025
4	Public Facilities Distribution	Point	Buol Regency Spatial Plan (RTRW)	2024
5	Critical Facilities Distribution	Point	Buol Regency Spatial Plan (RTRW)	2024
6	Number of Persons with Disabilities	Tabular	BPS Momunu Sub-district (Momunu in Figures)	2024
7	Population by Gender Ratio	Tabular	BPS Momunu Sub-district (Momunu in Figures)	2024
8	Gross Regional Domestic Product (GRDP) by Sector	Tabular	BPS Buol Regency	2024

The weighting of each component follows both literature-based references and expert consultation to ensure contextual relevance. In this study, social vulnerability was given the highest weight (40%) due to its strong influence on disaster response capacity in rural settings, while environmental vulnerability received 10% as it was considered less prioritized in current local disaster management policies. Nonetheless, we acknowledge that future studies could strengthen this weighting process through participatory approaches to better capture local priorities. Finally, the temporal dimension was incorporated through historical flood frequency records from the last decade, which served as an important validation tool for the vulnerability assessment and provided additional robustness to the hazard–vulnerability integration. Table 4 shows the vulnerability component weights; Table 5 shows types, formats, sources, and years of data for vulnerability mapping.

### 3. Results and Discussion

The Results and Discussion section presents the key findings derived from spatial and quantitative analyses conducted in this study, focusing on flood hazard, vulnerability components (social, physical, economic, and environmental), and risk levels within Momunu Sub-district, Buol Regency. This section interprets the data outcomes, explains patterns observed in the maps and indices, and highlights the area's most at risk. Furthermore, it provides a critical discussion of the implications of these findings in relation to the physical and socio-economic characteristics of the region, supporting disaster mitigation

planning and policy formulation.

#### 3.1. General Overview of Buol Regency-Momunu District

Buol Regency is situated in the northern part of Central Sulawesi Province, Indonesia, and is bordered by the Sulawesi Sea to the north, Tolitoli Regency to the west, and Gorontalo Province to the east. The regency covers an area of approximately 4,043 km<sup>2</sup> and consists of eleven sub-districts, including Momunu. Buol serves as an important regional center due to its strategic coastal location and its role in agriculture, trade, and public administration. The regional economy is supported primarily by agriculture, forestry, and small-scale fisheries. Among the sub-districts, Momunu is notable for its location in the southern inland part of the regency and functions as one of the primary agricultural zones. The area is also characterized by a mix of rural settlements and natural landscapes, contributing significantly to Buol's food production and ecosystem services. Over the years, population growth and land-use changes in Momunu have brought increased attention to the region's vulnerability to natural hazards, especially flooding.

The topographical landscape of Buol Regency is generally varied, comprising coastal plains, hilly regions, and highlands. Momunu Sub-district, in particular, features a combination of rolling hills and low-lying flood-prone valleys. The elevation in this area ranges from near sea level in the northern parts to more than 300 meters in the interior hilly zones. The slope gradient varies between gentle slopes in the settlement areas to steeper gradients toward the southeast hills. This variation in slope has a

direct impact on runoff behavior, soil erosion potential, and flood hazard distribution. Previous studies have noted that areas with slopes less than 15% tend to accumulate surface runoff and are often subject to prolonged inundation, particularly in areas lacking effective drainage infrastructure. These topographic conditions are consistent with flood vulnerability analyses conducted in similar geomorphological contexts within Central Sulawesi.

The dominant soil types in Momunu include alluvial soils, latosols, and hydromorphic soils, which are generally fertile but possess moderate to poor drainage capacity. These soil types are common in riverine and floodplain areas and tend to retain water, making them susceptible to waterlogging during heavy rainfall events. The geology of the region is composed of sedimentary and volcanic rocks, formed through tectonic uplift and alluvial deposition over time. Geological structures such as fault lines and fractured bedrock, influence groundwater movement and contribute to the complexity of the local hydrological system. These geological and soil characteristics are significant not only for agricultural productivity but also for understanding flood dynamics, as confirmed by hydrological hazard studies in neighboring regencies, which emphasize the correlation between soil infiltration rates and flood retention periods.

Momunu is part of a larger watershed system that includes several small and medium-sized rivers, most of which drain toward the north into the Sulawesi Sea. These rivers are seasonal, with peak discharges during the monsoon period, particularly from November to April. The area falls within the Buol watershed, which includes more than fifteen sub-watersheds, making the hydrological network relatively dense. River morphology in this region is generally dendritic, typical of tectonically formed basins with moderate relief. Flood events in Momunu are often caused by short-duration but high-intensity rainfall that exceeds the carrying capacity of the river systems. A 2023 study on watershed characteristics in Buol confirmed that drainage density and stream frequency are moderate to high, further supporting the high runoff potential in sub-districts like Momunu. Flash floods and river overflows are the most common types of flooding experienced in the region.

The population of Momunu Sub-district is approximately 16,342 as of 2023, reflecting a moderate increase compared to the 2010 census. Population density is relatively low to moderate, with clustering in village centers and along road networks. The majority of the population is engaged in agriculture, small-scale trade, and public service. Vulnerable demographic groups, such as the elderly, children, and people with disabilities, are present in notable proportions and are more likely to be affected during disaster events. The presence of gender disparities and the unequal distribution of social services further exacerbate the community's social vulnerability. A comparison with disaster risk studies in rural parts of Indonesia, such as in Sigi or Palu, indicates similar trends in demographic vulnerability, emphasizing the need for

community-based disaster preparedness and inclusive planning.

Buol Regency has a tropical rainforest climate characterized by high humidity, consistent temperatures, and abundant rainfall throughout the year. Rainfall patterns peak during the rainy season, with annual precipitation ranging from 2,000 mm to over 3,500 mm, depending on the elevation and proximity to the coast. In Momunu, rainfall intensity tends to be high during December to March, which coincides with the majority of flood occurrences. The combination of orographic rainfall and inadequate drainage infrastructure contributes to frequent localized flooding. Studies on climate variability in Sulawesi have found increasing trends in extreme rainfall events, aligning with recent flood records in Momunu between 2022 and 2024. This highlights the need for integrating climatic data into flood risk reduction strategies at the local level.

Land use in Momunu is predominantly agricultural, with rice paddies, maize fields, and coconut plantations being the main types of productive land. Built-up areas are concentrated in administrative villages, with supporting infrastructure including schools, health posts, mosques, and local markets. The sub-district also includes several critical and public facilities, although coverage remains limited in remote areas. Productive land, while economically vital, often overlaps with flood-prone zones, especially in lowland agricultural fields adjacent to rivers. Road infrastructure in Momunu includes asphalted district roads and gravel village roads, many of which are prone to disruption during heavy rains. Previous regional planning evaluations, such as those in the RTRW Buol 2024–2043, have pointed out the urgent need for road elevation improvements and drainage system upgrades to support flood resilience. Comparative studies in Tolitoli and Parigi Moutong regencies have highlighted the same structural vulnerabilities, suggesting that systemic infrastructure upgrades are essential to minimize disaster impacts in regions like Momunu.

### 3.2. Spatial Analysis of Flood Hazard Assessment

Areas categorized as flood-prone are typically flat and located near riverbanks. The classification of flood hazard levels is analysed based on inundation depth values. According to the *Disaster Risk Assessment Guidelines for Flood Hazards* by BNPB (2019), areas with an inundation depth of less than or equal to 75 cm are classified as low hazard; areas with a depth between 75 and 150 cm are considered moderate hazard; and areas with an inundation depth greater than 150 cm fall under the high hazard category [19].

Flood events occur when normally dry land becomes submerged due to various factors, such as overflowing water caused by high rainfall, among others. In certain situations, floods can become disasters that damage the

environment and even claim human lives. Therefore, addressing the causes of flooding is a matter of serious concern. Based on the calculation of flood hazard parameters, the hazard classes and the estimated flood-prone area in Momunu Sub-district can be determined. The extent of flood hazard and its classification in Momunu are presented in Table 6.

**Table 6.** Potential flood hazard in Momunu district

No	Village	Area (ha)			Total (ha)
		Low	Medium	High	
1	Panimbul	425.61	119.16	21.87	566.64
2	Pajeko	44.01	26.82	41.67	112.50
3	Guamonial	93.69	46.08	67.23	207.00
4	Wakat	27.36	14.85	43.20	85.41
5	Pomayagon	104.85	33.12	48.24	186.21
6	Lamadong I	69.03	38.07	69.30	176.40
7	Lamadong II	59.31	21.06	15.21	95.58
8	Mangubi	70.74	71.55	32.49	174.78
9	Pinamula Baru	45.36	49.23	-	94.59
10	Pujimulyo	75.60	41.04	18.99	135.63
11	Potugu	65.97	34.29	8.37	108.63
12	Tongon	126.54	58.41	14.49	199.44
13	Taluan	135.45	67.05	3.51	206.01
14	Momunu	73.62	72.27	-	145.89
15	Suraya	149.58	127.71	-	277.29
16	Pinamula	107.46	137.34	5.22	250.02
	Total	1,674.18	958.05	389.79	3,022.02

Table 6 shows the potential flood hazard area in Momunu District, which describes the total area of villages vulnerable to flood disasters based on the hazard assessment. The total flood hazard area is 3,022.02 Ha, categorized into three hazard classes: low hazard (1,674.18 Ha), medium hazard (958.05 Ha), and high hazard (389.79 Ha). Figure 5 presents the flood hazard map of Momunu District at a scale of 1:70,000, spatially delineating hazard zones into low (green), medium (yellow), and high (red). Administrative boundaries, river networks, and village markers are integrated to provide a clear geographical context, with high-hazard areas concentrated along major river courses in the northeastern part of the district, including Lamadong I and Guamonial. Medium hazard zones form transitional areas, while low hazard regions dominate the western and southern parts such as Momunu, Pinamula, and Suraya, highlighting the role of topography

and distance from rivers in shaping hazard levels.

While this hazard map provides a robust spatial overview, the assessment of vulnerability that underpins these classifications currently relies on predetermined weights and quantitative indicators. To enhance representativeness and local relevance, this study acknowledges the importance of incorporating participatory validation methods in future refinements. Approaches such as focus group discussions, household-level surveys, and participatory ranking of vulnerability factors could validate and adjust indicator weights based on community perceptions of risk and adaptive capacity. Supplementing the index construction with such field-based validation, supported by expert consultation, would ensure that the mapping framework not only reflects technical parameters (elevation, slope, land use, proximity to rivers) but also captures social realities and local knowledge. This integration would strengthen the practical utility of the hazard and vulnerability maps for disaster preparedness and localized mitigation planning.

To meaningfully compare this flood hazard map with previous research, access to prior studies focusing on Momunu District's flood vulnerability would be highly valuable. Such studies ideally detail their methodologies, data sources (e.g., rainfall data, river discharge rates, topographic surveys), and the resulting hazard zonation, which could help validate or refine the current findings. Consistency in identifying high-risk areas across different studies would strengthen confidence in the present map, while discrepancies might reveal changes in land use, environmental conditions, or advancements in hazard assessment techniques. Beyond technical comparisons, however, it is equally important to recognize that the current vulnerability assessment is based primarily on predetermined weights and quantitative indicators, which—while efficient—may overlook community-specific nuances. Future improvements should therefore integrate participatory approaches, such as focus group discussions, household surveys, or community-based ranking of vulnerability factors, to validate indicator weights and better capture local perceptions of risk and adaptive capacity. Incorporating such field-based validation, supported by expert consultation, would enhance the representativeness and legitimacy of the hazard and vulnerability maps, ensuring they not only reflect technical accuracy but also resonate with the lived realities of Momunu's residents. Overall, this integrated approach would increase the map's value as a tool for disaster risk management, supporting evidence-based infrastructure planning, reforestation programs, and community education to build resilience against future flood threats.

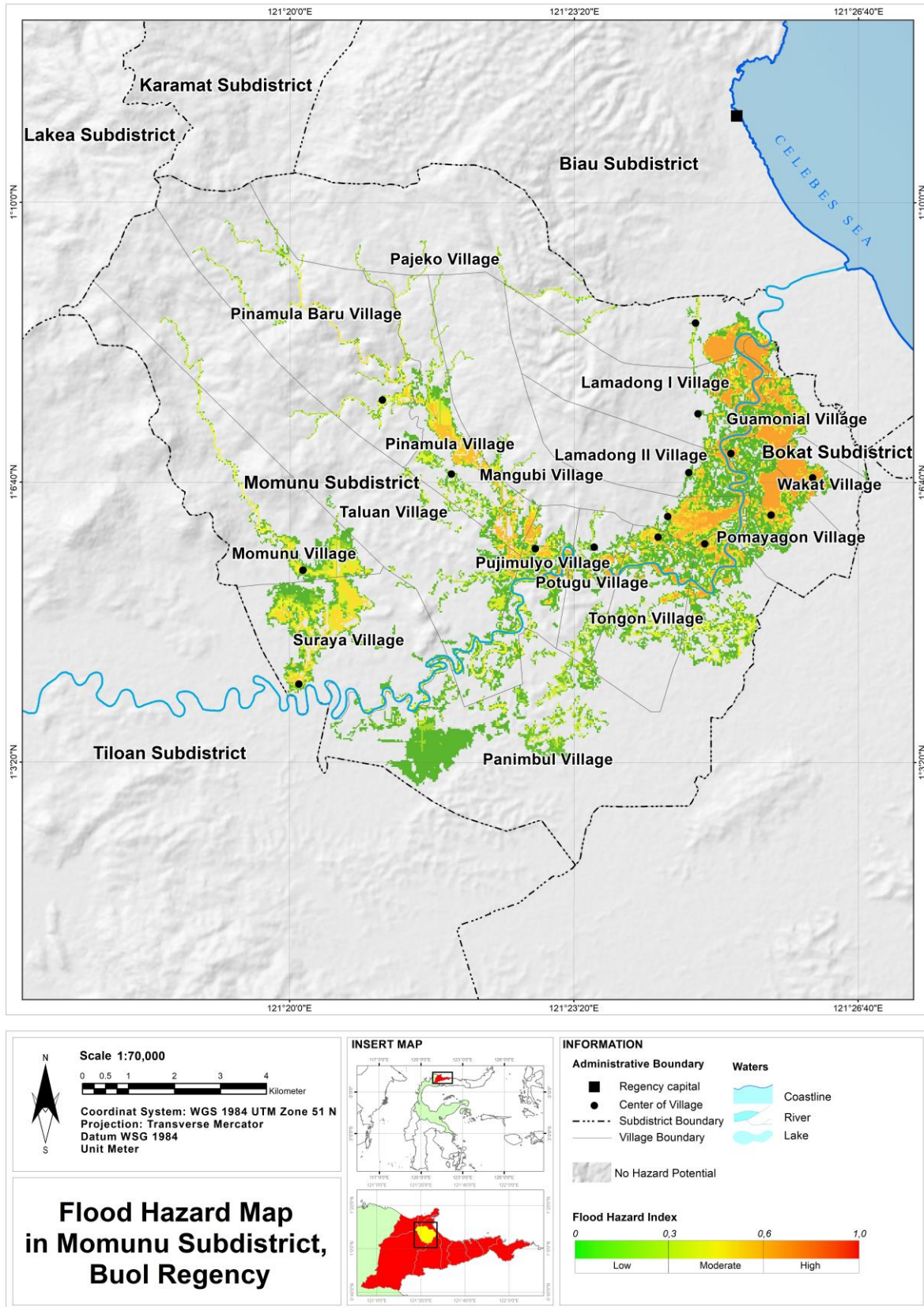


Figure 5. Flood hazard in Momunu districts

### 3.3. Spatial Analysis of Flood Vulnerability

Assessing the flood vulnerability index is a crucial stage in disaster risk analysis to determine the extent to which an area is susceptible to the impacts of flooding. Vulnerability is a condition that describes the degree to which a community, infrastructure, economic activities, and the environment can be affected by a disaster. In the context of floods, vulnerability is assessed through four main dimensions: social, physical, economic, and environmental. While this study initially relied on predetermined weights and quantitative indicators, such an approach may overlook community-specific nuances. To enhance representativeness, the assessment is supplemented with participatory methods, including focus group discussions and household-level surveys, which help refine the vulnerability indicators and validate their assigned weights.

This participatory validation allows local perceptions of risk and adaptive capacity to be integrated into the analysis, thereby strengthening the credibility of the vulnerability index. Ultimately, combining quantitative evaluation with field-based input ensures that the resulting flood vulnerability index is both technically robust and contextually grounded.

#### 3.3.1. Social Vulnerability Index

The Social Vulnerability Index is one of the important dimensions in flood disaster risk assessment, reflecting the social capacity of a community to cope with and recover from the impacts of floods. Based on the map presented in Figure 6, it can be observed that the level of social vulnerability in Momunu District and its surrounding areas exhibits significant spatial variation.

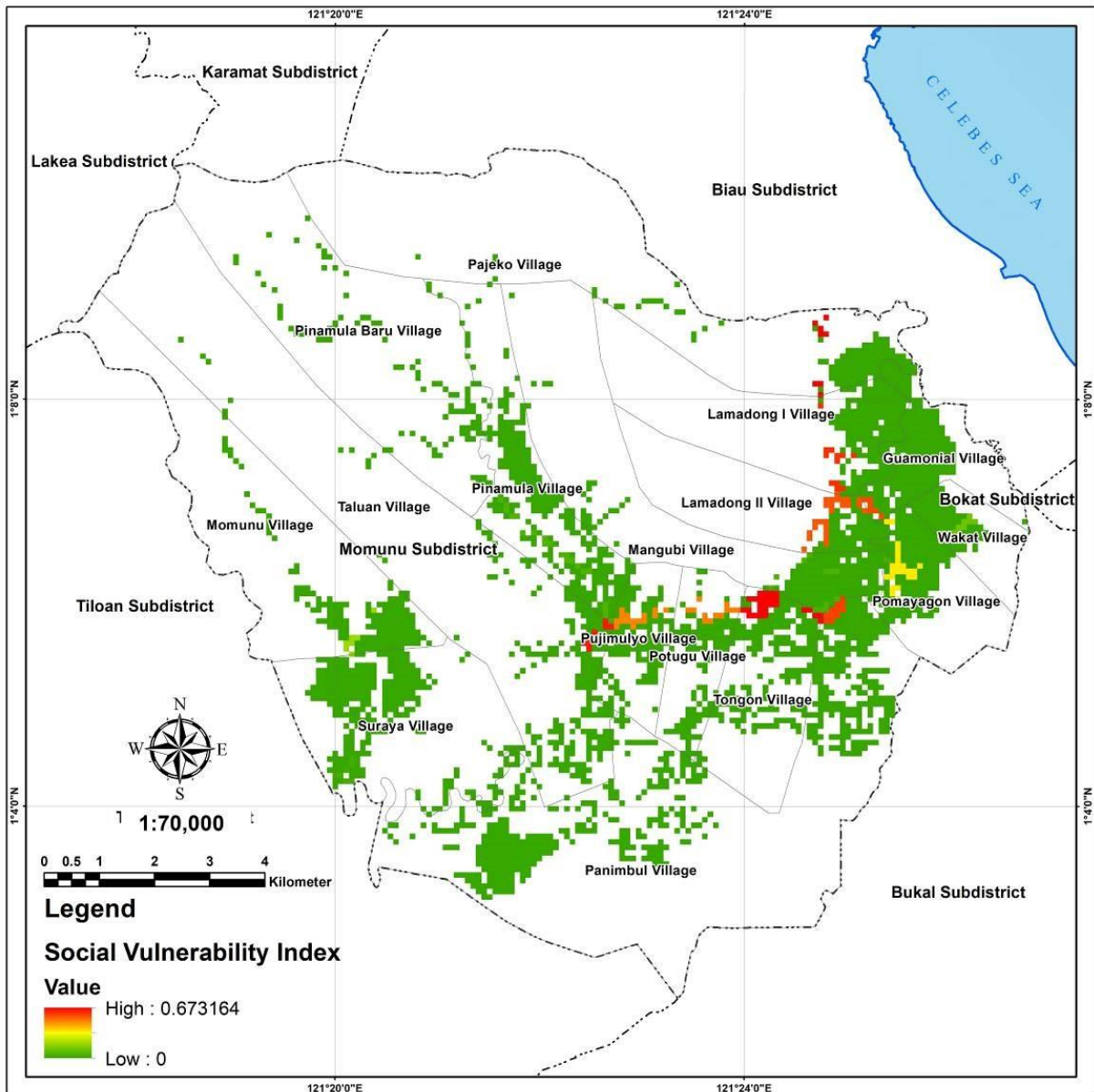


Figure 6. Social vulnerability index in Momunu districts

The distribution pattern of social vulnerability predominantly falls into the low category (indicated by green shading) across most village areas, including Panimbul, Suraya, Taluan, and Pinamula Baru. These regions are characterized by relatively robust social attributes, often manifested by low to moderate population densities, higher educational attainment, and notably active community participation in social initiatives. These indicators collectively suggest a greater inherent capacity for self-organization, resource mobilization, and collective action during and after a flood event, thereby contributing to lower social vulnerability scores.

Conversely, distinct clusters of high social vulnerability (depicted in red) and moderate social vulnerability (yellow) are identifiable, particularly concentrated along riverine areas and low-lying plains. Specifically, regions exhibiting high social vulnerability include parts of Potugu, Pomayagon, and Guamomial villages. These areas often correlate with higher population densities, lower socio-economic status, potentially limited access to information and resources, and reduced community cohesion, which collectively diminish their adaptive and coping capacities in the face of flood hazards. The spatial correlation with hydrological features underscores the compounded risk for communities residing in close proximity to active flood zones.

The highest recorded value for the social vulnerability index is 0.673164, which, while not indicating extreme social vulnerability (where values approach 1.0), still denotes areas requiring substantial attention. This suggests that while a catastrophic breakdown of social support systems is not pervasive, specific communities face significant challenges in preparedness, response, and recovery. For robust disaster risk reduction, local government bodies and relevant stakeholders should prioritize targeted programs focused on social capacity building, community-based disaster education, and the establishment of robust communication networks within these moderately to highly vulnerable areas. This could involve strengthening local governance, empowering community leaders, and facilitating access to social safety nets.

From a technical and academic perspective, this spatial analysis of social vulnerability provides critical input for a comprehensive flood risk assessment model. The identification of specific vulnerable pockets, even amidst a generally low vulnerability landscape, allows for a granular approach to mitigation. Future research could integrate these social vulnerability layers with physical exposure data (e.g., building types, infrastructure density) and flood hazard maps (as discussed previously) to generate a holistic multi-dimensional risk profile. This integrated approach is essential for developing spatially differentiated and socially equitable disaster preparedness and response

strategies, ensuring that interventions are tailored to the unique needs and capacities of each community.

In summary, these findings underscore that despite a general prevalence of low social vulnerability across much of Momunu District, critical high-vulnerability pockets are dispersed, notably in densely populated areas adjacent to riverine systems. These localized vulnerabilities have the potential to significantly exacerbate the impacts of flood events, even those of moderate magnitude, if appropriate and context-specific mitigation measures are not diligently implemented. The map thus serves as a foundational diagnostic tool, guiding the strategic allocation of resources for resilience-building initiatives and fostering a more adaptive and prepared community in the face of recurrent flood threats.

### 3.3.2. Physical Vulnerability Index

The Physical Vulnerability Index describes the level of an area's vulnerability to flooding based on the physical conditions of the environment and existing infrastructure. This aspect assesses the extent to which the characteristics of residential buildings, public facilities, and critical facilities influence the level of exposure and potential damage from floods. Figure 7 shows the physical vulnerability index map.

The Physical Vulnerability Index offers a comprehensive overview of an area's susceptibility to flooding, based on the intrinsic physical conditions of its environment and existing infrastructure. According to the Physical Vulnerability Index map, it is evident that the majority of the Momunu District and its surrounding areas exhibit low to moderate physical vulnerability, with a maximum recorded index value reaching 0.318328. This quantitative range suggests that while complete immunity to flood-induced damage is not present, the predominant built environment demonstrates a significant degree of resilience.

The widespread dominance of green coloration across the map signifies that a substantial portion of the territory possesses low physical vulnerability. This outcome strongly suggests that the physical integrity and characteristics of buildings and critical infrastructure within these regions are comparatively robust. Factors likely contributing to this favourable assessment include, but are not limited to, the prevalence of permanent construction materials (e.g., reinforced concrete, brick masonry), the implementation of adequately designed and maintained drainage systems, and the strategic siting of structures outside of historical or projected inundation zones. Such attributes enhance the capacity of physical assets to withstand flood pressures, minimizing structural damage and ensuring quicker post-event functional recovery.

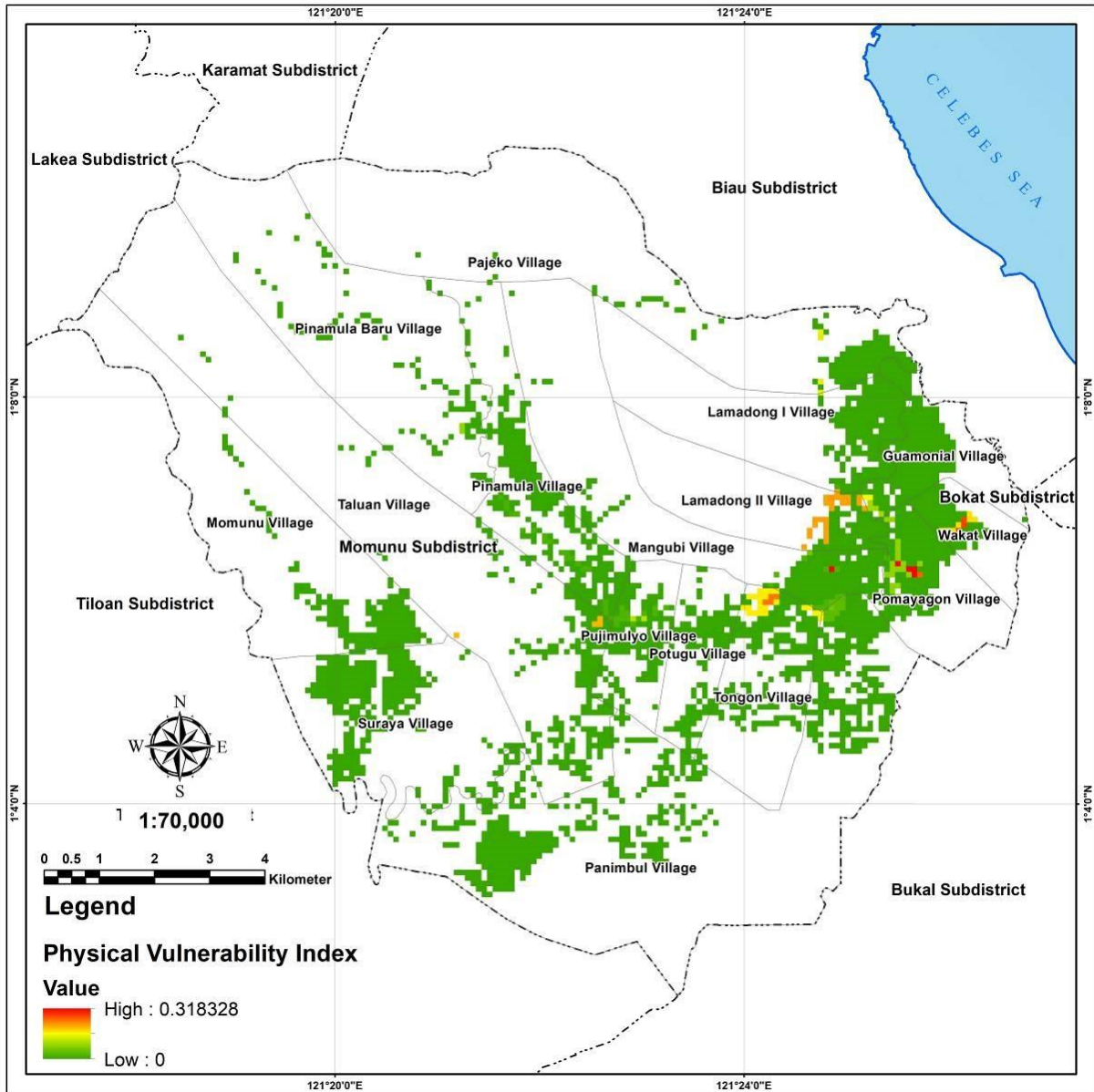


Figure 7. Physical vulnerability index in Momunu districts

While the overall trend points to low to moderate vulnerability, the maximum index value of 0.318328 indicates that certain areas, though not critically, do exhibit higher susceptibility. These zones of moderate vulnerability (likely represented by lighter green or nascent yellow if present, though not explicitly mentioned as a distinct colour category in this description) might possess older infrastructure, less resilient building typologies (e.g., non-engineered structures, traditional materials less resistant to water damage), or localized drainage deficiencies. Understanding the specific attributes contributing to this moderate vulnerability is crucial for targeted mitigation, such as retrofitting existing structures, upgrading localized drainage networks, or enforcing stricter building codes for new constructions in these areas.

From an academic and technical standpoint, the

quantification of physical vulnerability provides an indispensable layer for comprehensive flood risk assessment models. These data, when integrated with flood hazard intensity (e.g., depth, velocity of inundation) and duration maps, allow for probabilistic damage estimations for various asset classes (residential, commercial, public facilities, transport networks). The results can directly inform urban planning regulations, land-use zoning policies, and infrastructure investment decisions, guiding development away from the most vulnerable sites or mandating specific flood-proofing measures. Furthermore, this index can serve as a baseline for monitoring the effectiveness of resilience-building interventions over time, ensuring that spatial development contributes to a reduction in overall physical exposure to flood events.

In essence, the prevailing low to moderate physical

vulnerability in Momunu District suggests a relatively resilient built environment. However, the identified pockets of higher physical vulnerability, even if not extreme, demand a proactive, evidence-based approach to disaster risk reduction. The map serves as a vital diagnostic tool, highlighting areas where focused engineering interventions, policy adjustments, and investment in resilient infrastructure are most warranted to safeguard physical assets and ensure the continued functionality of critical services in the face of future flood challenges.

3.3.3. Economic Vulnerability Index

The Economic Vulnerability Index consists of the parameters GRDP (Gross Regional Domestic Product) and productive land. Each parameter is analyzed using the MCDA (Multi-Criteria Decision Analysis) method based

on BNPB Regulation No. 2 of 2012 to obtain the economic vulnerability index value [18]. Figure 8 shows the economic vulnerability index map in the study location. Based on the Economic Vulnerability Index Map presented in Figure 8, it is clearly discernible that the level of economic vulnerability in Momunu District and its surrounding areas exhibits significant spatial variation. With an index range from 0 (low) to 0.565568 (high), this map provides crucial insights into the extent to which economic activities and productive assets in various areas are potentially susceptible to the impacts of flood disasters. The highest recorded value, while not approaching 1.0, indicates a concentration of regions with substantial economic vulnerability, necessitating particular attention in disaster mitigation planning.

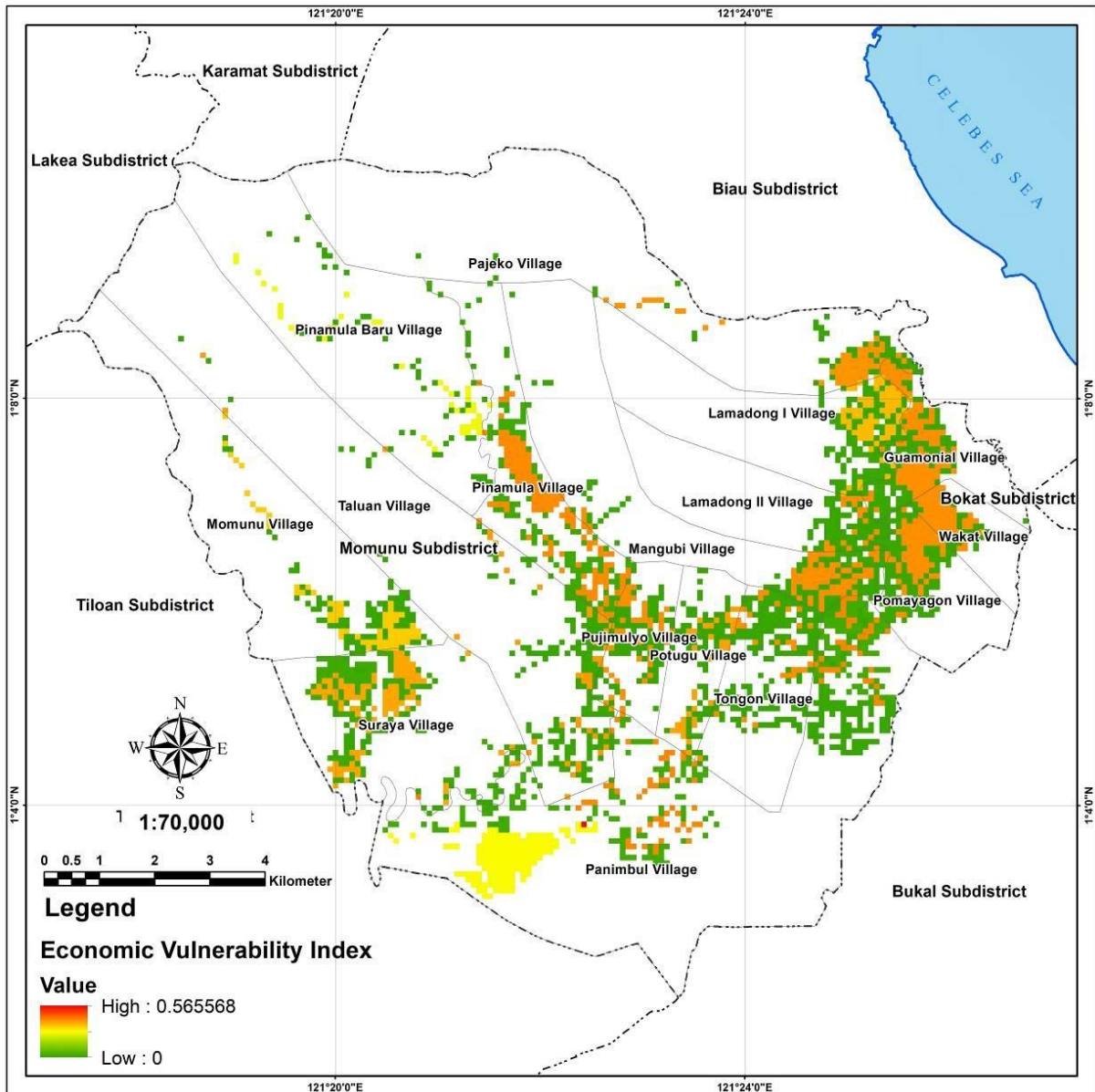


Figure 8. Economic vulnerability index in Momunu districts

The spatial distribution pattern of economic vulnerability on the map indicates that areas with low economic vulnerability (green colour, approaching a value of 0) dominate a significant portion of the territory, particularly in the southwest and in several pockets within the central part. These areas are most likely characterized by the presence of more diversified economic sectors or productive lands that are relatively resilient to inundation, such as perennial plantations (e.g., oil palm or cacao on higher ground) or non-agricultural sectors less dependent on low-lying topography. The widespread density of green pixels suggests that many areas in Momunu possess a relatively stable economic base and are less susceptible to shocks resulting from floods. However, economic vulnerability in flood-prone regions cannot be fully understood without also considering governance and institutional capacity. The presence or absence of early warning systems, the effectiveness of disaster response protocols, and the enforcement of land-use planning significantly influence how communities experience and recover from economic disruption. Incorporating these governance indicators either within the economic vulnerability index or as a complementary assessment, strengthens the analytical framework by capturing both the material and institutional dimensions of flood risk. This integration ensures that local economic resilience is evaluated, not only in terms of physical exposure and asset dependence, but also through the enabling role of governance in supporting or constraining adaptive capacity.

Conversely, concentrations of areas with high economic vulnerability (orange/red colour, approaching 0.565568) are clearly visible in several clusters, particularly in the northeastern part of the district, extending into parts of Bokat and Biau Subdistricts, as well as some spots in the central region. This pattern is highly likely correlated with the presence of productive land highly sensitive to flooding, such as irrigated rice fields or food crop agriculture on alluvial plains. The GRDP (Gross Regional Domestic Product) from dominant agricultural sectors in these areas would be highly vulnerable to crop failures or damage to agricultural infrastructure (e.g., irrigation channels) due to prolonged inundation. The loss of productivity from these lands can directly and significantly impact household incomes and the local economy. In addition to these economic aspects, institutional capacity and governance factors—such as the presence of early warning systems, effectiveness of disaster response mechanisms, and enforcement of land-use planning—play a critical role in determining how quickly affected communities can recover from economic shocks. Areas where governance support is weak may experience more severe and prolonged economic impacts despite similar levels of physical exposure. Therefore, this analysis integrates not only economic parameters such as GRDP and productive land but also highlights the enabling or constraining role of governance in shaping local economic vulnerability. This broader perspective strengthens the relevance of the

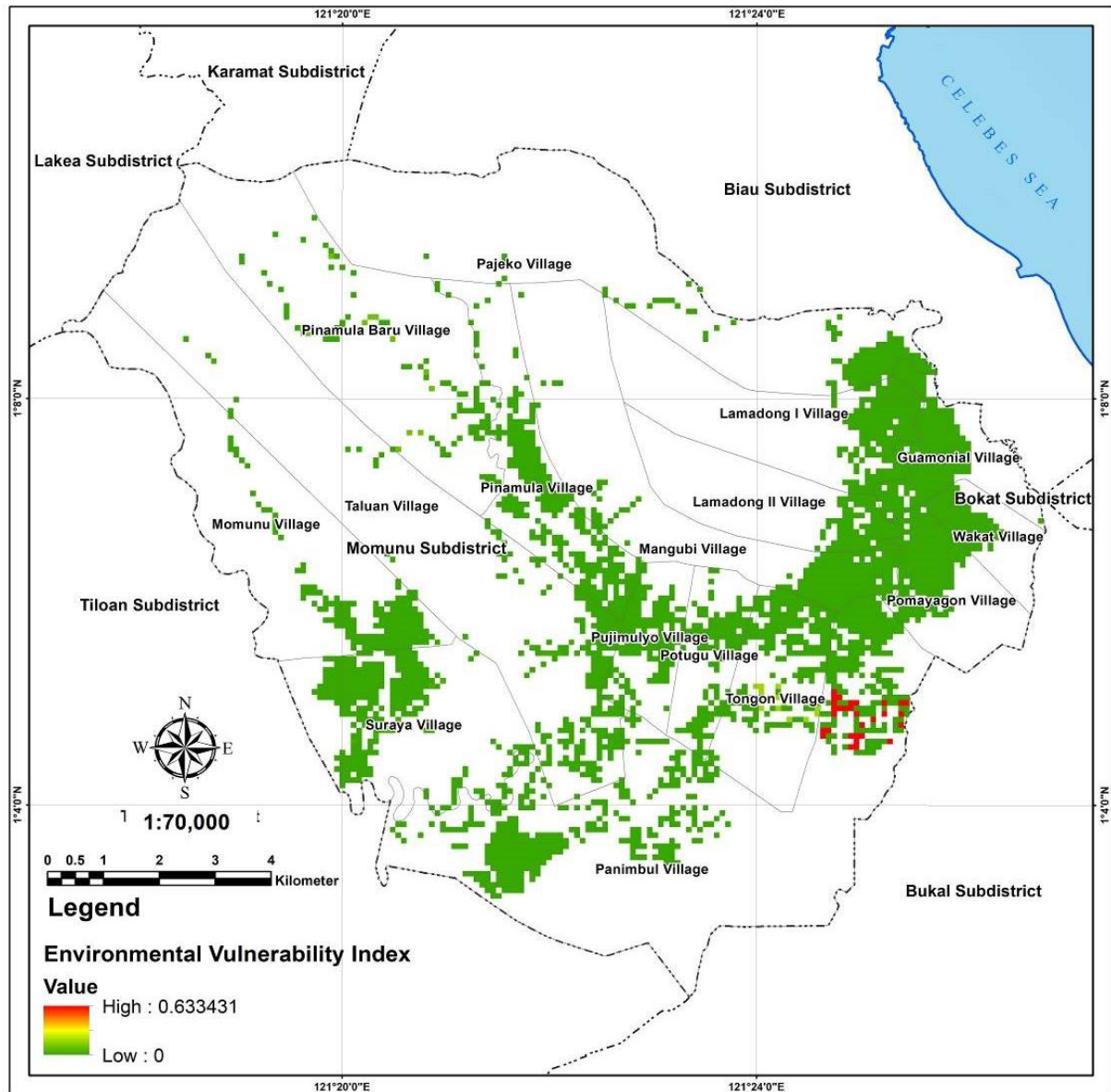
vulnerability framework for informing targeted development policies and disaster mitigation strategies.

#### 3.3.4. Environmental Vulnerability Index

The Environmental Vulnerability Index consists of parameters such as protected forests, natural forests, mangrove forests, shrubs/bushes, and swamps. Each parameter is used based on the determined type of disaster and analyzed using the MCDA (Multi-Criteria Decision Analysis) method based on BNPB Regulation No. 2 of 2012 to obtain the environmental vulnerability index value. Figure 9 shows the environmental vulnerability index map in Momunu District. The map provides a critical spatial representation of how natural ecosystems and land cover types contribute to or mitigate flood risk, with an index range from 0 (low vulnerability) to a maximum of 0.633431 (high vulnerability). The highest recorded value signifies the presence of environmental zones that are critically susceptible to flood disasters, requiring focused ecological management and conservation interventions.

The predominant green coloration across large parts of the district indicates widespread low environmental vulnerability, reflecting intact ecosystems that regulate runoff, stabilize soils, and act as natural retention basins. In contrast, clusters of high vulnerability (red zones) appear in the southeastern region, especially around Potugu village and extending towards Bokat District, where ecological degradation—deforestation, mangrove conversion, and swamp drainage—has significantly reduced natural buffering capacity. This pattern underscores how environmental conditions exacerbate or mitigate hydrological extremes. However, beyond ecological conditions alone, it is also necessary to recognize that governance capacity shapes the effectiveness of environmental protection. Weak enforcement of land-use planning, insufficient regulation of mangrove conversion, and limited institutional support for reforestation can accelerate environmental degradation, thereby amplifying flood vulnerability.

The inclusion of governance indicators such as early warning system availability, disaster response protocols, and land-use regulation effectiveness, would therefore strengthen the assessment of environmental vulnerability. These institutional dimensions determine whether ecological assets are preserved, degraded, or restored, directly influencing the district's flood resilience. By complementing ecological indicators with governance variables, the vulnerability framework can capture not only the biophysical conditions but also the enabling or constraining role of institutions in risk management. This integrated approach provides stronger evidence for policy recommendations, emphasizing that ecological restoration efforts must go hand in hand with improved institutional preparedness, enforcement mechanisms, and community-based governance to sustainably reduce flood vulnerability in Momunu District.



**Figure 9.** Environmental vulnerability index in Momunu districts

### 3.3.5. Flood Vulnerability Index

Vulnerability refers to the conditions that influence a community's ability to anticipate, cope with, and recover from the impacts of a disaster. In the context of floods, vulnerability encompasses the physical aspects of buildings, the socio-economic conditions of the community, and infrastructure. The flood disaster vulnerability map for Momunu District illustrates the level of susceptibility to flood impacts, based on a spatial index derived from physical, social, and environmental parameters, and is classified into three categories: low (green), moderate (yellow), and high (red). Spatially, areas with high vulnerability (red) are concentrated along the main river channels in the eastern and southeastern parts of the district, such as Pujimulyo, Potugu, Tonggon, and parts of Pomayagon villages, where settlements are close to river bodies, located in low-lying plains, and have limited flood

control infrastructure. Moderate vulnerability areas (yellow) are distributed in central and eastern zones, including Lamadong II and Mangubi villages, where exposure is significant but communities possess partial capacity to manage risks. Low vulnerability areas (green), such as Taluan, Suraya, and parts of Panimbul villages, are located in higher topographic zones, at greater distance from rivers and with relatively better access to infrastructure. To strengthen the robustness of this analysis, future research should incorporate temporal datasets such as historical flood frequency, rainfall variability, and seasonal influences (e.g., El Niño and La Niña), as well as multi-year hydrological and climatic records. The integration of climate projection scenarios would further inform long-term resilience planning by anticipating future flood dynamics under climate change conditions. Figure 10 shows the map of flood vulnerability index in Momunu District.

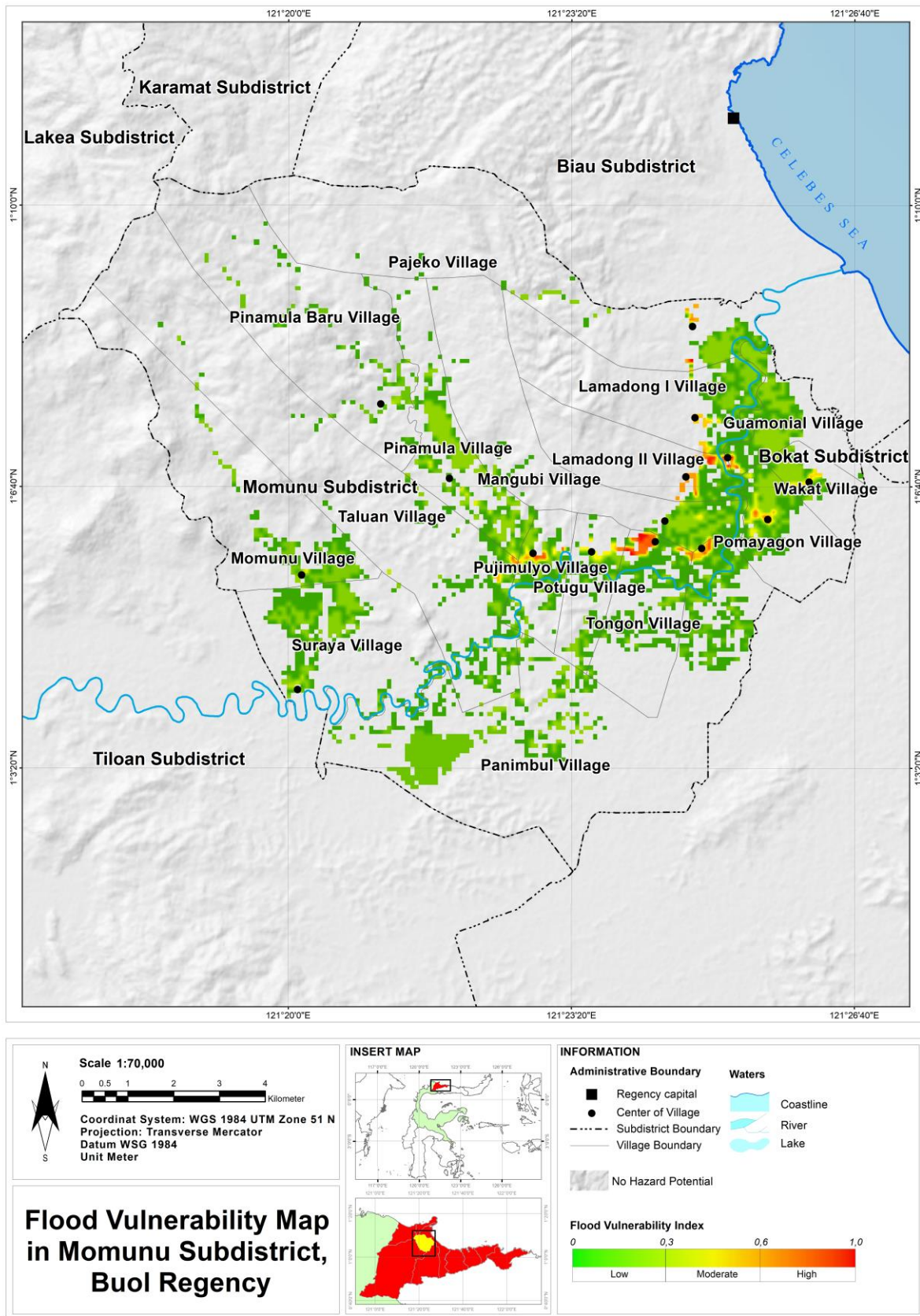


Figure 10. Flood vulnerability index in Momunu districts

### 3.4. Potential Population Exposure and Potential Losses from Flood Disasters in Momunu District

The vulnerability assessment for flood disasters in Momunu District was derived from the potentially exposed population and vulnerable groups, as well as the potential losses, encompassing physical, economic, and environmental damage. This potentially exposed population and potential losses were analyzed and then presented in the form of flood disaster vulnerability classes. A recapitulation of the potentially exposed population likely to be affected by flood disasters in Momunu District can be seen in Table 7.

The assessment of flood vulnerability in Momunu District integrates data on the potentially exposed population, including specific vulnerable groups, alongside potential physical, economic, and environmental damages. This approach ensures that the human dimension of disaster risk is explicitly quantified and contextualized within both spatial and temporal dynamics. Based on overlay analysis between population distribution and flood hazard maps, the total exposed population is 8,637 individuals, distributed across varying vulnerability classes (Table 7). Importantly, this figure includes 39 persons with disabilities who face heightened risks due to mobility and accessibility constraints, as well as 4,461 males and 4,176 females whose exposure may be shaped by gender-specific roles and access to resources. To strengthen the predictive value of the assessment, temporal datasets—such as historical flood frequency, rainfall variability, and ENSO-driven events—are incorporated to highlight seasonal and inter-annual fluctuations in exposure. Moreover, the integration of climate projection scenarios allows anticipation of future dynamics, including potential shifts in rainfall intensity and flood recurrence, thereby informing long-term resilience planning.

The identification of vulnerable subgroups, combined with an understanding of temporal flood patterns, is critical for designing targeted and adaptive disaster risk reduction strategies. By integrating population exposure with multi-year hydrological and climatic datasets, local authorities can anticipate not only where but also when vulnerabilities are likely to peak, such as during El Niño or La Niña phases that alter rainfall extremes. This enables more precise planning for evacuation, early warning systems, and livelihood protection tailored to seasonal risk windows. To complement this, the study incorporates an economic loss estimation framework that distinguishes between direct, indirect, and long-term loss components. At the village scale, losses (IDR 49.063 billion) primarily reflect direct damages to assets and productive lands, while the macro-level estimate (IDR 12.023 trillion) captures broader indirect and cascading economic disruptions across the district, including impacts on regional trade, supply chains,

and service provision. The higher figure is interpreted as a worst-case scenario derived from district-wide extrapolations, while village-level estimates provide localized insights into immediate damages. These methodological clarifications improve transparency by outlining the assumptions, calculation procedures, and interpretive framework used to generate Table 5. This ensures that both scales of analysis can be meaningfully compared and appropriately applied to disaster risk management planning.

Crucially, the spatial outputs of hazard and vulnerability mapping hold direct policy relevance for regional development and disaster governance. For example, the results can be aligned with the Buol Regency RTRW 2024–2043 to identify high-risk zones where settlement expansion should be restricted, and agricultural land management needs stricter regulation. The vulnerability maps can also inform disaster contingency plans by prioritizing infrastructure investment in flood-prone areas, such as strengthening drainage networks or embankments, and by guiding the placement of community-based early warning systems. Moreover, the integration of these findings with land-use planning instruments enhances the enforceability of zoning regulations, ensuring that environmental conservation and disaster mitigation objectives are embedded in local policy frameworks. This explicit linkage between scientific outputs and governance instruments reinforces the practical utility of the study, enabling decision-makers to operationalize the results in both short-term preparedness and long-term resilience strategies.

The potential losses stemming from flood disasters in Momunu District encapsulate both the direct and indirect impacts on physical assets and the socio-economic well-being of the community. As elucidated by the flood vulnerability maps, this region contains numerous zones characterized by moderate to high vulnerability levels, thereby indicating a significant potential for incurring substantial damages when inundation events occur. Table 7 provides a detailed recapitulation of these potential disaster losses in Momunu District, broken down by village and category.

The total potential flood disaster loss in Momunu District, as presented in the introductory text, is stated to be IDR 12.023 trillion. This figure represents a macro-level, district-wide estimate that includes direct damages to physical assets as well as indirect and cascading economic effects, such as prolonged disruption of livelihoods, impacts on regional trade and supply chains, and reductions in GRDP. Within this broader estimate, physical losses are valued at IDR 5.678 trillion and economic losses at IDR 6.344 trillion. This approach reflects a worst-case scenario projection, derived from extrapolating flood impacts across the entire district under severe hazard conditions.

**Table 7.** Recapitulation of potentially exposed population to flood disaster in Momunu District

No.	Village	Number of exposed population (people)	Potential population exposed (people)		
			Vulnerable groups		
			Disabled population	Male population	Female population
1	Guamomial	437	0	233	221
2	Lamadong I	707	5	354	350
3	Lamadong II	725	1	375	349
4	Mangubi	472	4	242	229
5	Momunu	369	0	188	180
6	Pajeko	417	2	207	209
7	Panimbul	526	2	265	260
8	Pinamula	538	2	279	259
9	Pinamula Baru	67	1	35	30
10	Pomayagon	933	4	490	439
11	Potugu	438	1	221	216
12	Pujimulyo	667	3	350	316
13	Suraya	282	3	149	132
14	Taluan	612	4	325	286
15	Tongon	1,160	4	592	567
16	Wakat	287	2	155	130
Total		8,637	39	4,461	4,176

**Table 8.** Potential disaster losses in Momunu District

No.	Village	Losses (Million Rupiah)			Potential Environmental Damage (ha)
		Physical Loss	Economic Loss	Total Loss	
1	Guamomial	3,766.43	4.81	3,771.24	-
2	Lamadong I	4,129.25	3.42	4,132.66	-
3	Lamadong II	1,498.65	0.71	1,499.36	-
4	Mangubi	17,395.00	2.60	17,397.60	-
5	Momunu	671.75	1.84	673.58	84.50
6	Pajeko	3,137.85	2.63	3,140.48	4.50
7	Panimbul	1,798.72	2.98	1,801.70	450.00
8	Pinamula	1,392.71	3.94	1,396.65	12.50
9	Pinamula Baru	767.50	1.07	768.57	144.00
10	Pomayagon	3,974.23	3.17	3,977.40	-
11	Potugu	760.69	1.09	761.79	-
12	Pujimulyo	2,058.99	1.75	2,060.74	-
13	Suraya	862.50	2.98	865.48	32.00
14	Taluan	1,936.03	1.40	1,937.42	29.00
15	Tongon	1,982.31	1.01	1,983.33	112.50
16	Wakat	2,892.50	2.93	2,895.43	-
Total		49,025.11	38.32	49,063.43	869.00

By contrast, the more granular analysis in Table 8 provides village-level loss estimates, expressed in million rupiah, which primarily capture direct damages to households, infrastructure, and localized economic activities. According to the table, the total physical loss amounts to IDR 49,025.11 million ( $\approx$  IDR 49.025 billion), while the economic loss reaches only IDR 38.32 million, yielding an aggregated loss of IDR 49,063.43 million ( $\approx$  IDR 49.063 billion). The significant disparity between the trillion-scale estimates and the billion-scale figures thus arises from differences in methodological scope and scale: the macro-level values incorporate indirect and long-term impacts across the entire district, whereas the village-level estimates are limited to immediate, localized, and directly quantifiable damages.

From the detailed village-level data, Physical Loss constitutes the overwhelming majority of the potential damage. Villages exhibiting exceptionally high physical losses include Mangubi (IDR 17,395.00 million), Lamadong I (IDR 4,129.25 million), and Guamonial (IDR 3,766.43 million), reflecting extensive damage to residential buildings, public infrastructure, and private property. Conversely, Economic Loss appears considerably lower in magnitude at the village scale, with the highest values seen in Guamonial (IDR 4.81 million), Pinamula (IDR 3.94 million), and Pomayagon (IDR 3.17 million). These values represent short-term disruptions to livelihoods and income, rather than comprehensive assessments of long-term recovery costs or secondary economic impacts.

Finally, the table also provides data on Potential Environmental Damage in hectares, with notable figures for Panimbul (450.00 ha), Pinamula Baru (144.00 ha), and Tongon (112.50 ha). Environmental damage in this context involves soil erosion, water contamination, agricultural land degradation, and loss of ecosystem services. The presence of “—” entries suggests either no recorded environmental losses or data gaps in certain villages.

In conclusion, the potential loss assessment for Momunu District, when interpreted carefully across different methodological scales, provides both localized detail and broader district-wide projections. The distinction between direct, indirect, and long-term loss components enhances transparency and explains the apparent discrepancy between the IDR 12.023 trillion and IDR 49.063 billion estimates. This dual-scale approach is essential for supporting evidence-based disaster risk reduction, where village-level data inform targeted interventions, while district-level projections guide macro-level planning, resource allocation, and climate adaptation strategies. Beyond its analytical value, the results also provide direct policy implications: the loss maps can be aligned with the Buol Regency RTRW 2024–2043 to identify high-risk zones that should be excluded from future settlement expansion, integrated into disaster contingency frameworks to prioritize infrastructure reinforcements in flood-prone areas, and embedded in land-use regulations to

strengthen ecological conservation in critical buffer zones. Moreover, these outputs can serve as a reference for designing early warning systems and targeted recovery programs, ensuring that resilience-building efforts are systematically integrated into local governance.

## 4. Conclusions

Spatial analysis results indicate that Momunu District exhibits a high level of vulnerability to flood disasters, with a total potential flood hazard area reaching 3,022.02 hectares. This area comprises low hazard class covering 1,674.18 hectares, moderate hazard covering 958.05 hectares, and high hazard covering 389.79 hectares. The villages predominantly affected by the low hazard class include Panimbul village, while the moderate hazard class is dominated by Pinamula village, and the largest high hazard class area is found in Lamadong I village. Regions situated near river courses and characterized by flat topography tend to exhibit higher levels of susceptibility.

From the vulnerability perspective, the assessment reveals considerable variation across villages in terms of social, physical, economic, and environmental vulnerability. Several villages, such as Potugu, Pomayagon, and Guamonial, are noted to have high social vulnerability. Meanwhile, physical vulnerability is generally categorized as low to moderate, but risks persist in areas with non-permanent structures and proximity to rivers. Economic vulnerability shows significant variation, with the highest value reaching 0.565568, indicating high exposure to potential economic losses in certain villages. As for the environmental aspect, the highest index value is 0.633431, which suggests ecological pressure in specific areas due to the reduction of protected zones and land-use changes.

The study also indicates that the total population potentially exposed to flood disasters in Momunu District amounts to 8,637 individuals, including 39 persons with disabilities, 4,461 males, and 4,176 females. Regarding potential losses, the total estimated losses due to flood disasters reach IDR 49.063 billion, with physical losses amounting to IDR 49.025 billion and economic losses to IDR 38.32 billion, along with potential environmental damage spanning 869 hectares. Thus, the results of this analysis unequivocally demonstrate that Momunu District faces a high level of flood disaster risk, encompassing physical hazards, socio-economic vulnerability, and potential losses.

In practical terms, the spatial outputs generated by this study—particularly the hazard and vulnerability maps—can serve as a vital reference for local governments in formulating evidence-based disaster risk reduction strategies. These findings can be directly aligned with the Buol Regency RTRW 2024–2043, which emphasizes sustainable spatial planning, zoning regulation, and environmental protection. Accordingly, several policy recommendations are highlighted: high-hazard zones

should be excluded from residential or industrial development and designated as ecological buffer zones, while moderate-hazard areas can guide infrastructure priorities such as flood embankments, resilient housing, and improved drainage systems. At the same time, social protection measures—including inclusive early warning systems, evacuation planning, and targeted assistance for vulnerable groups such as persons with disabilities, women, and children—are crucial to strengthen community preparedness. Economic resilience should be enhanced through livelihood diversification and insurance mechanisms, while environmental sustainability requires stricter land-use regulation, reforestation, and conservation of riparian ecosystems. By embedding these measures into existing spatial and disaster management policies, this study not only advances academic knowledge but also provides actionable strategies for local and regional authorities to enhance resilience and adaptive capacity in rural flood-prone areas.

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This work represents a collaborative effort to enhance resilience and inform evidence-based disaster risk reduction strategies for Momunu District.

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