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Integrating Sentinel-1 SAR and Hydrometeorological Data for Flood Risk Mapping and Ecological Impact Assessment in Alluvial Regions

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Abstract

Flooding is a recurring hydrometeorological disaster affecting low-elevation coastal areas, yet real-time monitoring is often hindered by thick cloud cover on optical sensors. This study aims to conduct a spatial and temporal analysis of extreme flood events using the integration of radar satellite imagery and hydrometeorological data. The research focuses on the northern coastal region of Aceh, Indonesia (North Aceh Regency and Lhokseumawe City), which experienced severe flooding in November 2025. Flood extent was extracted using change detection analysis of Sentinel-1 Synthetic Aperture Radar (SAR) imagery processed through Model Builder, an automated workflow in ArcGIS Pro 3.6. The derived inundation maps were subsequently integrated with precipitation, land-cover, and population datasets to assess ecological and socio-economic impacts. The results indicate that the total inundated area reached 23,964.51 hectares, affecting 329 villages and more than 12,000 people. The cultivated crops sector was identified as the most extensively affected area, covering 20,559.10 hectares or 85.8% of the total affected area. Hydrometeorological analysis shows that, in addition to extreme rainfall exceeding 150 mm/day, upstream degradation due to tens of thousands of hectares of oil palm concessions and Forest Utilization Permits (PBPH) exacerbated water accumulation in the downstream alluvial plains. This study demonstrates that Sentinel-1 SAR is highly effective for rapid flood monitoring under adverse weather conditions and highlights the importance of integrated, watershed-based disaster risk management that transcends administrative boundaries.

Keywords : *Flood, Geospatial Analysis, Sentinel-1 SAR, Alluvial Plains, Disaster Mitigation*

INTRODUCTION

Coastal alluvial plains are geographically characterized by low-lying elevations and intricate networks of major river systems, making them inherently susceptible to recurrent hydrological hazards. These specific geomorphological features create a natural catch-basin effect, where minimal topographic gradients hinder efficient drainage and exacerbate the accumulation of surface runoff during high-intensity precipitation events. In regions with such characteristics, extreme weather phenomena often trigger catastrophic flooding that poses significant threats to human settlements, infrastructure, and local ecosystems. The increasing frequency of these hydrometeorological events aligns with global climate trends, where intensified variability is significantly heightening

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disaster risks in coastal zones worldwide. As established by Snyder (2023), these risks are particularly acute in tropical regions where low elevation gradients and high seasonal rainfall create a persistent state of environmental vulnerability.

A critical challenge in modern disaster management for these vulnerable landscapes is the lack of accurate, real-time inundation monitoring data, especially during periods of severe atmospheric instability. Conventional optical remote sensing platforms, while effective under clear skies, frequently fail to provide actionable intelligence due to the dense cloud cover that typically persists throughout extreme rain events. Furthermore, massive land-cover transformations in upstream catchment areas—most notably the expansion of large-scale monocure plantations—have fundamentally altered regional hydrological dynamics (Irmayanti & Syarief, 2025). These anthropogenic interventions reduce soil infiltration capacity and accelerate the time to peak discharge, turning manageable rainfall into destructive floods. Several approaches have been taken to address this. Effective river management is crucial for mitigating hydrometeorological hazards. Previous studies have highlighted the potential of information technology in sustainable riparian zone management (Prabawasari et al., 2025), and this research further expands such technological applications by integrating Sentinel-1 SAR for flood risk mapping. In the absence of robust spatial data integration, impact estimations for both the population and the agricultural sectors are frequently inaccurate, thereby hindering the effectiveness of emergency response operations and long-term adaptive planning. Flooding is a hydrometeorological threat that requires serious mitigation.

The present study aims to conduct comprehensive risk mapping and flood impact analysis through the integration of Sentinel-1 Synthetic Aperture Radar (SAR) imagery and hydrometeorological datasets. The research focus is directed at a representative alluvial region in the northern coastal area of Aceh (North Aceh Regency and Lhokseumawe City), which experienced a severe flood event in late 2025 with rainfall exceeding 150 mm per day (Rahmawan, 2025). Specifically, this research intends to identify the spatial extent of flood inundation, analyze the correlation between rainfall intensity and flood coverage, and evaluate the vulnerability of socio-economic assets within the affected zones. The overarching focus of this assessment is to provide a rigorous scientific foundation for formulating more adaptive and evidence-based mitigation policies.

The methodological approach adopted for this study is quantitative, centered on advanced geospatial analysis. This research integrates SAR technology from the Sentinel-1 satellite, which possesses cloud-penetrating capabilities, with high-resolution daily precipitation data. A change detection method is applied to compare ground surface conditions before and during the flood event. SAR radar is widely regarded as the "gold standard" in global flood monitoring due to its consistency across diverse atmospheric conditions and its ability to provide high-frequency observations (Rowe & Paul, 2020). Subsequently, the extracted inundation data are integrated with demographic layers (GHS-POP) and land-use datasets via Model Builder in ArcGIS Pro. This systematic integration facilitates a comprehensive impact analysis, allowing for a more nuanced understanding of how flood hazards intersect with socio-economic vulnerability in complex alluvial environments. Unlike previous SAR-based flood mapping studies that focus primarily on inundation extent, this research explicitly integrates upstream land-use concessions and socio-economic exposure, providing a watershed-scale ecological interpretation of flood risk.

METHODS

Research Design and Framework

This study employs a quantitative research design integrated with advanced geospatial analysis to systematically evaluate flood phenomena within an alluvial coastal context. The research is structured around a descriptive-analytical framework, aiming to establish the causal relationship between biophysical drivers—such as extreme precipitation and topographic constraints—and the resulting spatial extent of inundation. In accordance with the standards for disaster risk assessment (UNDRR, 2019), the methodology adopts a risk-based spatial analysis paradigm. This approach considers flood risk as a dynamic interaction between hazard intensity (inundation depth and duration), physical vulnerability (land use and infrastructure), and demographic exposure (population distribution). By utilizing this framework, the study ensures that the results are not merely descriptive but also provide a robust foundation for spatial planning and disaster risk reduction strategies.

Data Acquisition and Integrated Datasets

To achieve high-accuracy results, this research integrates multi-source datasets, including satellite remote sensing, topographic models, and socio-demographic layers. The primary data source is Sentinel-1 Synthetic Aperture Radar (SAR) imagery, which is preferred over optical sensors due to its microwave-based imaging capability that can penetrate dense cloud cover and operate independently of solar illumination (Li et al., 2018). For topographic and hydrological modeling, the ASTER Global Digital Elevation Model (GDEM) with a 30-meter resolution is utilized to delineate watershed boundaries and evaluate slope gradients (Japan METI & NASA, 2024).

Hydrometeorological analysis is supported by the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), which provides daily precipitation estimates at a quasi-global scale, essential for correlating rainfall intensity with flood expansion (Climate Hazards Center, 2025). Furthermore, land cover classification is derived from the ESRI 2024 Living Atlas Land Cover, providing a high-resolution (10-meter) baseline for identifying impacted sectors. Demographic vulnerability is assessed using the Global Human Settlement Population (GHS-POP) and built-up surface layers (GHS-BUILT-S), which allow for the quantification of exposed populations and infrastructure within the inundated zones (Earth Observation Group, 2024).

Spatial Analysis and Automated Workflow via Model Builder

The core of the data processing is executed through an automated workflow developed in ArcGIS Pro 3.6 Model Builder. This systematic approach ensures process replicability and minimizes human error during complex raster-to-vector operations (Rahmawan, 2025). The workflow is divided into several critical phases:

1. Preprocessing and Calibration: Sentinel-1 images are pre-processed to remove speckle noise and undergo terrain correction using the ASTER GDEM. This step is vital to ensure that backscatter values accurately represent the dielectric properties of water surfaces versus dry land.

2. Threshold-based Inundation Extraction: Utilizing the 'Raster Calculator', the research establishes a backscatter threshold for identifying water bodies. A 'Baseline' raster (pre-flood) is compared against a 'Flood-up' raster (peak flood) to detect changes in surface water extent.
3. Change Detection (Erase Method): To isolate temporary flood inundation from permanent water bodies (rivers, lakes, and estuaries), the 'Erase' tool is applied. This process subtracts the baseline water features from the peak flood extent, resulting in a refined polygon representing the actual disaster-induced inundation.
4. Vectorization and Geometric Attributes: The resulting raster is converted into vector format (*Raster to Polygon*). The 'Multipart to Singlepart' tool is then used to separate individual flood units, followed by 'Calculate Geometry Attributes' to quantify the area and perimeter of each unit at the village and sub-district levels.

Impact Integration and Sectoral Analysis

The final phase involves the integration of flood polygons with socio-economic layers. The 'Intersect' and 'Zonal Statistics' tools are employed to overlay the flood extent with the land cover and population grids. This allows for a detailed assessment of which sectors—such as agriculture, settlements, or forest areas—suffered the greatest impact. According to Rowe and Paul (2020), this integration of multi-temporal SAR imagery with thematic datasets is the most consistent method for large-scale flood impact evaluation in diverse atmospheric conditions. By calculating the percentage of impacted area relative to the total administrative size, the study provides a vulnerability index that can be utilized by policymakers for prioritized disaster response and long-term mitigation (Rahmawan, 2025).

Research Validity and Limitations

The validity of this methodology is maintained through the use of standardized satellite products and established GIS algorithms. However, certain limitations are inherent, such as the 10-meter spatial resolution of Sentinel-1, which may overlook micro-scale inundations in dense urban canyons. Furthermore, while CHIRPS provides reliable rainfall patterns, it is a modeled product that may have slight variations compared to local in-situ rain gauges. Despite these constraints, the methodology remains a

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scientifically robust approach for rapid disaster assessment in regions where ground-based monitoring infrastructure is limited.

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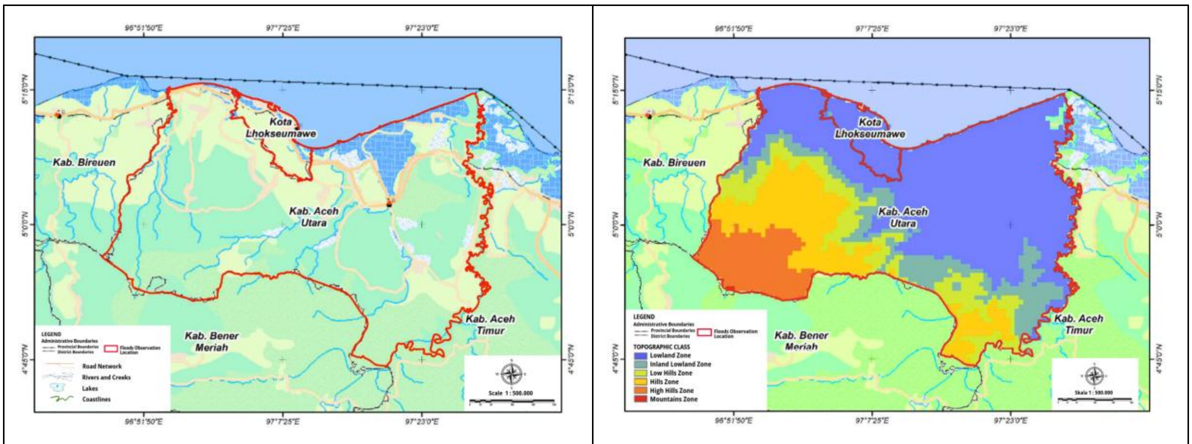
RESULTS

Geographic and Biophysical Baseline of the Study Area

The study focuses on the administrative regions of North Aceh Regency and Lhokseumawe City, which together form a strategic economic and agricultural corridor on the northern coast of Aceh Province. North Aceh Regency covers an expansive area of approximately 3,296.86 km^2, characterized by diverse terrain ranging from coastal lowlands in the north to mountainous highlands in the south. Lhokseumawe City, an autonomous urban entity, spans 181.06 km^2 and is characterized by high-density settlements. The administrative boundaries and spatial orientation of these regions are illustrated in **Figure 1 (a).**



(a) Administrative Boundary Map of Lhokseumawe City and North Aceh Regency	(b) Topographic Map of Lhokseumawe City and North Aceh Regency

Figure 1 Administrative Boundary Map and Topographic Map

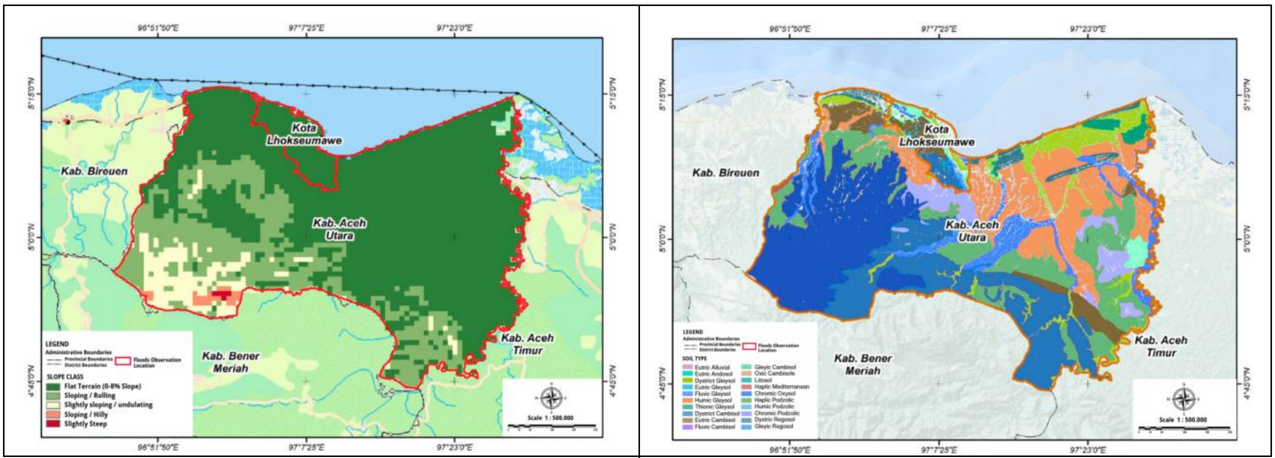
Source : ASTER GDEM, 2025

Topographic analysis using ASTER GDEM data confirms that Lhokseumawe City and the coastal fringe of North Aceh are situated entirely within a lowland zone with elevations below 50 meters above sea level (Figure 1 (b)). In contrast, the southern part of North Aceh serves as the hydrological headwaters, featuring rugged terrain with elevations peaking between 1,500 and 3,000 meters. Slope analysis (Figure 2(a)) indicates that the majority of urban and agricultural centers are located on flat terrain (0–8% slope), which inherently limits natural drainage efficiency during peak discharge events.

Furthermore, soil classification maps (Figure 2(b)) reveal a dominance of Eutric Alluvial and Gleysol types in the coastal plains. These soils are characterized by low permeability and high water saturation, significantly contributing to prolonged inundation periods.

Hydrometeorological Analysis and Upstream Anthropogenic Factors

The flood event in late 2025 was preceded by a significant increase in regional precipitation. Analysis of CHIRPS data for November 2025 shows that North Aceh received high cumulative rainfall, ranging from 150 mm to 300 mm. This extreme rainfall triggered a massive increase in the discharge of the Krueng Pase and Krueng Keureuto river systems, which eventually breached their embankments.



(a) Slope Map of Lhokseumawe City and North Aceh Regency	(b) Soil Type Map of Lhokseumawe City and North Aceh Regency

Figure 2 Slope Map and Soil Type Map of Lhokseumawe City and North Aceh Regency

Source : ASTER GDEM, 2025

Beyond natural drivers, sectoral land-use analysis in the upstream region reveals significant anthropogenic pressure. There are approximately 23 major oil palm concession companies operating within or adjacent to the watershed, covering tens of thousands of hectares. Notable concessions include PT Satya Agung (9,389.61 ha) and PT Wirya Perca (8,005.63 ha), as detailed in Table 1.

Additionally, Forest Utilization Permits (PBPH) cover extensive mountainous areas, such as PT Tusam Hutani Lestari which manages 86,579.39 hectares (Table 2). The presence of gold mining concessions (WIUP), specifically PT Linge Mineral Resources covering 36,420 hectares in the upper catchment of Central Aceh, further highlights the scale of land-cover transformation in the southern headwaters. Oil Palm Concession and Forest Utilization Business Permit Areas (PBPH) at Lhokseumawe City, North Aceh Regency and Surrounding Areas are illustrated on Map in **Figure 3.**

Table 1. Information on the 5 largest major oil palm concession companies in Lhokseumawe City, North Aceh Regency and Surrounding Areas

No.	Company Name	Area (Ha)
1.	PT. Satya Agung	9,389.61
2.	PT. Wirya Perca (I)	8,005.63
3.	PT. Perkebunan V (Cot Girek)	6,879.73
4.	PT. Perkebunan I (Alur Puntie)	6,720.65
5.	PT. Bumi Flora (I)	6,438.32

Source : https://data.globalforestwatch.org

Table 2. Information on Forest Utilization Business Permit Areas in Lhokseumawe City, North Aceh Regency and Surrounding Areas

No.	Company Name	Area (Ha)
1.	PT. Rimba Wawasan Permai	6,249.67
2.	PT. Rimba Timur Sentosa	6,762.17
3.	PT. Tusam Hutani Lestari	86,579.39
4.	PT. Rencong Pulp & Paper Industry	9,099.34
5.	PD. Pembangunan Tanoh Gayo	4,804.25

Source : https://data.globalforestwatch.org

Spatial Distribution of Flood Inundation

The processing of multi-temporal Sentinel-1 SAR imagery captured the dramatic transition from normal baseline conditions (**Figure 4 (a)**) to the peak flood extent on November 27, 2025 (**Figure 4 (b)**). The final flood extraction map (**Figure 5 (a)**) identifies a total inundated area of 23,964.51 hectares across the study region.

North Aceh Regency bore the brunt of the disaster, with 23,292.68 hectares submerged. Table 3 below shows data on the five sub-districts in North Aceh Regency that were most severely affected.

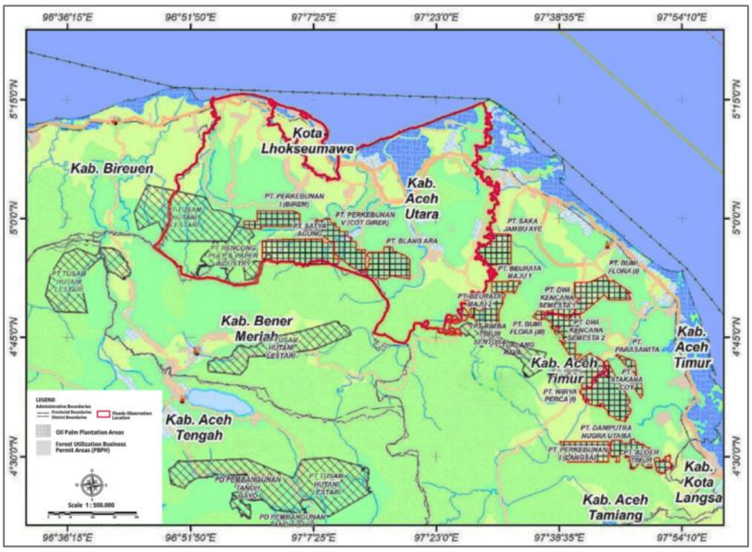
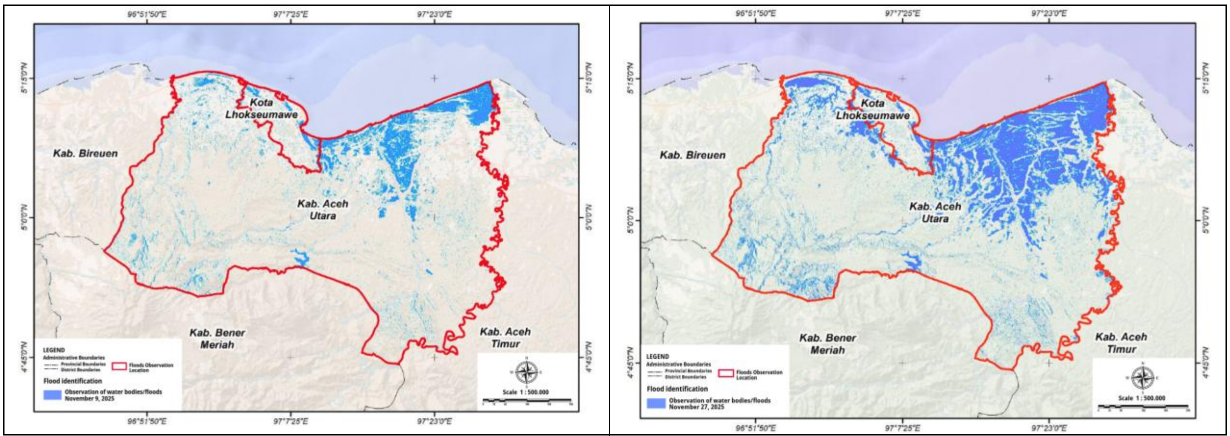


Figure 3. Map of Oil Palm Concession and Forest Utilization Business Permit Areas (PBPH) in Lhokseumawe City, North Aceh Regency and Surrounding Areas

Source : https://data.globalforestwatch.org



(a) Water Cover Map on November 9, 2025

(b) Water Cover Map on November 27, 2025

Figure 4. Water Cover Map of Lhokseumawe City and North Aceh Regency

Source : Climate Hazards Center, 2025

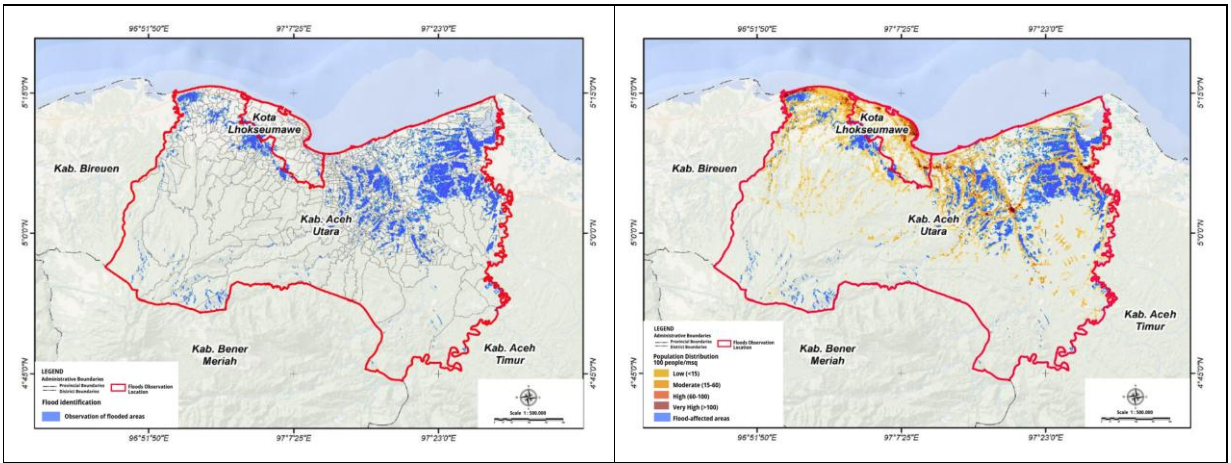
Demographic and Sectoral Impacts

The flood disaster directly impacted 12,798 individuals across 329 villages. Population vulnerability analysis shows that several villages faced extreme exposure, with Lhok Iboh Village recording the highest number of affected residents (335 people), followed by Meunasah Tutong (278 people) and Meunasah Geudong (245 people). The spatial distribution of affected populations is visualized in Figure 5 (b).

Table 3. The Most Severely Impacted Sub-districts in North Aceh Regency

No.	Location (Sub-district)	Area (Ha)
1.	Baktiya	4,341.38
2.	Tanah Jambo Aye	2,234.35
3.	Lhoksukon	2,223.67
4.	Baktiya Barat	2,057.81
5.	Tanah Luas	1,240.34

Source : Analysis, 2025



(a) Flood Analysis Map (November 2025)

(b) Flood-Affected Population Distribution Analysis Map (November 2025)

Figure 5. Flood Impact Analysis Map (November 2025) Lhokseumawe City and North Aceh Regency

Source : Spatial Analysis, 2025

The impact on built-up land was also extensive, totaling 586,679 m² of residential and institutional structures. Villages within the highest impact category demonstrate a strong correlation between population density, settlement area, and flood vulnerability. Villages such as Meunasah Tutong (15,893 m²), Lhok Iboh (14,293 m²), and Ujong Pacu (12,032 m²) experienced the most significant inundation of built-up areas, reflecting their locations within low-lying zones, proximity to river channels, or areas with limited drainage systems. These villages are not only densely populated but also serve as centers for community activity; consequently, inundations ranging from 8,000 to 15,000 m² have a profound impact on mobility, safety, and the daily lives of the residents.

Sectoral analysis of land cover (Table 4) underscores the vulnerability of the local economy, as the Cultivated Crops class accounted for 20,559.10 hectares (85.8%) of the total inundation. Other affected classes include natural trees/forests (1,932.26 ha), grasslands (797.61 ha), and urban built-up areas (312.25 ha). These findings indicate that the agricultural heartland of North Aceh was the most severely compromised sector during the late 2025 event.

Table 4. Flood-affected Land Cover Analysis (November 2025)

Land Cover	**Regency/City Area (Ha)**		**Total**
	North Aceh Regency	**Lhokseumawe City**	
Built-up Area	302.12	10.14	312.25
Grasslands	778.85	18.76	797.61
Trees/Forests	1,925.59	6.68	1,932.26
Bare land	6.50	0.07	6.57
Cultivated Crops	19,934.53	624.56	20,559.10
Water body	337.21	11.62	348.83
Flooded Vegetation	4.85	-	4.85
Total	23,289.65	671.83	23,961.48

Source : Spatial analysis, 2025

DISCUSSION

Interaction of Hydrometeorological Extremes and Geomorphological Constraints

The catastrophic flooding occurred in late 2025 across the coastal regions of North Aceh and Lhokseumawe represents a multifaceted disaster driven by the interaction of extreme precipitation and inherent geomorphological vulnerabilities. As shown in the results, cumulative rainfall exceeding 150 mm/day acted as a primary triggering factor. According to Malik et al. (2019), such intensities in tropical regions often surpass the soil's natural infiltration capacity, leading to instantaneous surface runoff.

However, the magnitude of the inundation was exacerbated by the downstream topography. Most of the affected areas, including Lhoksukon and Baktiya, are situated on alluvial plains with elevation gradients of less than 50 meters and slopes ranging from 0% to 8% (Figure 1(b) & 2(a)). This flat terrain results in very low hydraulic gradients, causing river currents to slow down significantly upon reaching the coast. Combined with the poorly drained Eutric Alluvial and Gleysol soils (Figure 2(b)), which are naturally prone to water saturation, the floodwater became stagnant, leading to prolonged inundation periods that hindered emergency response and recovery efforts.

Upstream Land-Use Dynamics and Ecological Connectivity

A critical finding of this study is the hydrological connectivity between the southern highlands and the northern coastal plains. The southern part of North Aceh, extending into the mountainous regions of Central Aceh and Bener Meriah, serves as the primary catchment area for the Krueng Pase and Krueng Keureuto rivers. However, this study identifies a severe imbalance in land-use management within these headwaters.

The presence of expansive oil palm concessions, such as those held by PT Satya Agung and PT Wirya Perca, has fundamentally altered the watershed's response to rainfall. "…field observations and public analyses circulating during the event further illustrated the scale of upstream ecological disturbance (Rahmadi, 2025)." Integrating the ecological insights from Rahmadi (2025), it is evident that the conversion of natural forests into monoculture plantations has severely compromised the region's "sponge effect." In natural forest ecosystems, infiltration rates typically reach 100–200 mm/hour. In contrast, oil palm plantations in this region exhibit infiltration rates of only 10–30 mm/hour. This drastic reduction is associated with soil compaction resulting from the use of heavy machinery during land clearing and maintenance phases. Furthermore, the shallow root systems of oil palms (concentrated at 0–60 cm depth) compared to deep-rooted forest trees (1–2 meters) significantly lower soil permeability, preventing water from reaching deeper aquifers and forcing it to flow as surface runoff.

Anthropogenic Drivers and Sedimentation Processes

The ecological degradation is not limited to plantation activities. The inclusion of Forest Utilization Permits (PBPH) and Mining Business Permits (WIUP) in the upper catchment adds another layer of anthropogenic pressure. According to Irmayanti and Syarief (2025), large-scale forest product extraction and mining operations disrupt soil structures and remove protective canopy layers. Without a diverse vegetative canopy, raindrops hit the ground with higher kinetic energy, accelerating soil erosion.

The eroded sediment is transported downstream, leading to severe siltation in riverbeds. This process reduces the cross-sectional area of the rivers, thereby lowering their discharge capacity. During the peak flood in late 2025, evidence of this upstream instability was visible through the large quantities of logs and organic debris carried by the current into residential areas in Langkahan and Lhoksukon. This indicates that the flood was not merely a water management issue but an ecological signal of systemic watershed failure.

Socio-Economic Vulnerability and Food Security

The integration of spatial flood data with land-cover layers (Figure 6) highlights an extreme sectoral vulnerability. The fact that 85.8% of the inundated area (20,559.10 hectares) consisted of Cultivated Crops (Table 4) carries profound implications for regional food security and the economic stability of agrarian households. North Aceh’s economy is heavily dependent on rice and secondary crop production. The timing of the flood in late 2025 likely coincided with critical planting or harvesting cycles, potentially leading to total crop failure for thousands of farmers.

In urban contexts, specifically within Lhokseumawe City, the flood risk is intensified by rapid and often unplanned urbanization. The expansion of built-up surfaces has reduced urban green spaces and natural retention basins. As noted in the results, while the flood extent in Lhokseumawe was smaller (671.83 hectares), it affected high-density areas. This urban flood risk is further complicated by "tidal flooding" (*rob*) during high sea levels, which prevents river water from emptying into the sea, a phenomenon characteristic of low-lying coastal cities.

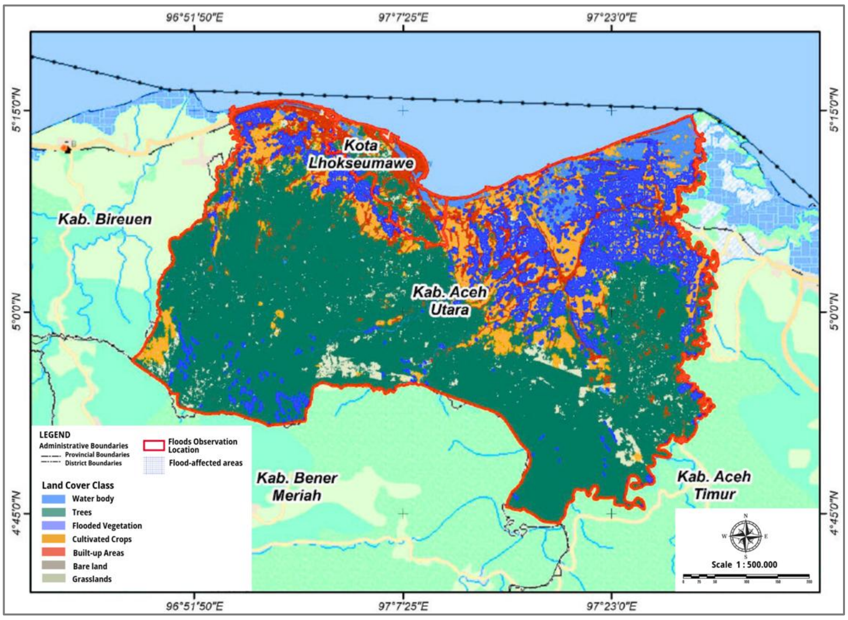


Figure 6. Flood-Affected Land Cover Analysis Map (November 2025)
Lhokseumawe City and North Aceh Regency

Source : Spatial Analysis, 2025

Policy Implications for Integrated Disaster Mitigation

The findings of this study underscore the urgent need for a shift from reactive disaster response to proactive, integrated watershed management. Currently, mitigation efforts are often fragmented across administrative boundaries. For instance, Lhokseumawe cannot resolve its flood issues without addressing the hydrological conditions in North Aceh, and North Aceh cannot succeed without regulating activities in the hulu (upstream) highlands of Central Aceh.

As advocated by the UNDRR (2019), disaster risk reduction must be evidence-based. The use of Sentinel-1 SAR in this study demonstrates that real-time geospatial data can bridge the information gap during crises. However, technology must be paired with policy. Recommendations include:

1. **Strict Regulation of Consessions:** Reviewing and enforcing stricter environmental compliance for oil palm and mining companies in the upstream regions to restore infiltration capacities.

2. **Nature-Based Solutions (NbS):** Implementing reforestation and "green infrastructure" such as retention ponds and bioswales in both urban and rural areas to manage runoff (Rahmadi, 2025).
3. **Cross-Administrative Cooperation:** Establishing a formal DAS (Watershed) Management Authority to synchronize flood mitigation policies from the mountains to the coast.

CONCLUSION

Summary of Findings

The catastrophic flood event of November 2025 in the northern coastal region of Aceh serves as a definitive case study of how extreme hydrometeorological triggers intersect with systemic ecological degradation. This research concludes that the inundation, which covered a total of 23,964.51 hectares, was not solely a result of anomalous rainfall exceeding 150 mm/day, but was significantly amplified by the loss of hydrological buffering capacity in the upstream catchments. The integration of Sentinel-1 SAR imagery proved to be a highly resilient methodology for rapid disaster assessment, overcoming the persistent cloud-cover limitations that typically hinder optical sensors during monsoon periods.

The spatial analysis reveals a disproportionate impact on the agricultural sector, with 85.8% of the affected area consisting of cultivated crops, thereby threatening the primary livelihood of the North Aceh population. Furthermore, the findings highlight a critical "policy gap" in watershed management, where upstream land-use conversions—specifically into large-scale oil palm plantations and mining zones—have doubled the surface runoff coefficient, shifting the burden of disaster risk onto the vulnerable downstream alluvial communities.

Limitations and Critical Assessment

Despite the robust findings, this study acknowledges several critical limitations that may influence the interpretation of the results. First, the 10-meter spatial resolution of the Sentinel-1 SAR sensor, while adequate for regional mapping, may result in the "under-detection" of small-scale inundations in complex urban environments or areas with dense forest canopies where the radar signal cannot reach the ground surface. Second, the reliance on the CHIRPS quasi-global precipitation dataset introduces a degree of modeled uncertainty compared to localized in-situ rain gauges. Third, the vulnerability assessment was limited to spatial exposure (area and population counts) and did not incorporate high-resolution socio-economic data, such as income levels or structural building integrity, which are vital for a comprehensive loss-and-damage estimation. These limitations stem from data availability constraints during a rapid assessment phase rather than methodological errors, yet they underscore the need for more granular data integration in future studies.

Recommendations for Future Policy and Research

To enhance regional resilience, this study recommends that local governments transition from reactive emergency response to an Integrated Watershed Management (IWM) approach. Specifically, there is an urgent need to re-evaluate upstream land-use permits (PBPH and WIUP) and enforce mandatory reforestation zones to restore soil infiltration capacities. From a technical perspective, the implementation of a real-time, IoT-based hydrological monitoring system is essential to provide early warnings that are integrated with the spatial risk maps produced in this study. For future academic research, it is recommended to employ 2D hydrodynamic modeling and high-resolution LiDAR data to simulate flood depths and flow velocities more accurately. Ultimately, disaster mitigation in alluvial plains must be treated as a trans-administrative responsibility, requiring seamless cooperation between the highland and coastal governments to ensure sustainable ecological and demographic security.

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