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Flood Hazard Zonation and Agricultural Vulnerability Assessment Using GIS in Indonesia

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ABSTRACT

Riau Province, a low-lying region dominated by peatlands and high rainfall, is highly susceptible to severe flooding, posing significant risks to its key agricultural sectors (oil palm and rice). This study seeks to delineate flood risk and agricultural susceptibility by amalgamating Geographic Information Systems (GIS) with Multi-Criteria Analysis (MCA). Flood hazard zonation was generated using weighted physical parameters—Digital Elevation Model (DEM), rainfall, soil type, land cover, and river proximity—processed through the Analytical Hierarchy Process (AHP). Agricultural vulnerability was assessed using exposure, sensitivity, and adaptive capacity indicators derived from 2020–2025 secondary data. The results reveal that 18.5% of Riau Province falls under high-hazard zones, predominantly in Indragiri Hilir and Indragiri Hulu. Rice and oil palm in Indragiri Hilir were found to be the most vulnerable commodities, with an estimated annual economic loss of 350 billion Rupiah [11]. The resulting spatial maps provide essential guidance for the Riau Provincial Government in designing targeted mitigation measures, risk-based spatial planning, and improved agricultural adaptation strategies.

Keywords: flood hazard zonation; agricultural vulnerability; GIS; Multi-Criteria Analysis (MCA); Riau Province; Indonesia.

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1. Introduction

Hydrometeorological disasters, most notably flooding, constitute a major impediment to the achievement of global Sustainable Development Goals (SDGs), particularly those related to food security (SDG 2), climate action (SDG 13), and the resilience of essential infrastructure (SDG 9). The rising frequency and intensity of global flood events are compounded by the acceleration of climate change and

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

unchecked urbanization practices, leading to the substantial loss of critical water catchment areas [1]. As a tropical archipelago nation boasting one of the world's longest coastlines and high rainfall levels, Indonesia faces an extraordinarily heightened level of disaster risk. National statistics consistently show that flooding is the predominant natural disaster incidence, impacting millions of lives, severely damaging vital infrastructure, and posing a tangible threat to macroeconomic stability, especially within primary sectors such as food production and agriculture. Consequently, geospatial studies focused on risk assessment and mapping are no longer limited to academic exercises; they represent a critical necessity for formulating effective, evidence-based adaptation and mitigation policies [2].

The Context of Flood Risk in Riau Province and Agricultural Vulnerability

Riau Province has unique geophysical characteristics that make it highly susceptible to flooding. The province is largely composed of extensive alluvial lowlands and vast peat swamps stretching along the eastern coast of Sumatra. The province is crisscrossed by major, complex river basin systems (DAS), including the Siak, Kampar, and Rokan rivers. The confluence of low-lying topography, high water saturation in peat soil, and limited river discharge capacity results in periodic flooding in Riau precipitated by high rainfall intensity. Beyond these local factors, powerful regional climatic dynamics—specifically, the influence of El Niño and La Niña phenomena—further exacerbate patterns of extreme precipitation. These patterns often yield alternating periods of severe drought followed by flash floods and extreme river overflow [3].

Despite this pervasive flood threat, Riau’s agricultural sector remains a vital economic pillar, contributing substantially to the province's Gross Regional Domestic Product (GRDP). Key commodities include oil palm plantations, rubber, and rice paddy fields. When floods strike, the resulting losses extend beyond immediate cash crop yield damage. Flooding causes the deterioration of irrigation and drainage infrastructure, a decline in soil quality due to erosion and sedimentation, and a long-term reduction in land productivity. Given the differential sensitivity of crops, rice—a crucial food commodity—exhibits extremely high sensitivity to standing water, while oil palm is vulnerable to prolonged waterlogging in peat soils. Therefore, a specific and systematic measurement of agricultural sector vulnerability is highly

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

warranted. This assessment must encompass not only the exposure of agricultural land but also the sensitivity of the specific crop types and the adaptive capacity of the supporting infrastructure [4]. Such an in-depth vulnerability analysis is indispensable for developing proactive regional food security strategies.

Methodological Approach and Research Gap

Effectively mitigating complex risks like flooding demands a tool capable of efficiently integrating and analyzing diverse spatial data. Geographic Information Systems (GIS) provides a robust geospatial framework perfectly suited for this objective, enabling the seamless integration of physical data (topography, hydrology, land cover) and socio-economic data (agricultural land, demographics) within a single analytical platform. The most pertinent approach for hazard and vulnerability zonation is Multi-Criteria Analysis (MCA), typically utilizing the Analytical Hierarchy Process (AHP) for criteria weighting. The GIS-MCA methodology allows researchers to quantitatively measure and compare factors of varying importance, thereby producing hazard and vulnerability maps that are more objective, accurate, and visually detailed. The spatial maps generated thus serve as crucial instruments for location-based spatial planning and risk management.

While numerous studies on flood hazard zonation have been reported in the Indonesian literature (e.g., in Java, West Sumatra, and Kalimantan), comprehensive, integrated research focusing specifically on the agricultural sector vulnerability within the unique peatland context of Riau Province, employing the latest secondary data (2020–2025) and encompassing a full range of physical and social variables, remains insufficient. The distinctiveness of this research lies in its rigorous integration of physical hazard zonation (grounded in hydrology and geomorphology) with the vulnerability assessment of agricultural assets. The paramount importance of geospatial data-driven risk management is underscored in contemporary literature, particularly concerning input data quality. For instance, Hasan and Kuntoro (2022) emphasize that the accuracy of hydrological modelling, the core of hazard zonation, is fundamentally dependent on the quality of Digital Elevation Model (DEM) resolution and the validity of historical rainfall data [5]. Furthermore, Wahyuni and Subroto (2024) articulate that agricultural sector loss assessment must be holistic, covering estimates of lost commodity value, recovery costs, and, crucially, the socio-economic vulnerability of the threatened farming population [6]. This study aims to address the identified research gap by applying these methodological principles within the unique context of Riau's peatland and specific river basin characteristics.

Principal Aims and Significance

Based on the established background and the identified research gap, the principal aims of this study are (1) to develop a comprehensive flood hazard zonation map for Riau Province using the GIS-MCA approach, (2) to conduct a quantitative assessment of the agricultural sector's vulnerability to the mapped flood hazards, and (3) to propose spatially informed strategic recommendations for disaster mitigation and strengthening Riau's agricultural resilience. The scientific significance of this research lies in providing a replicable methodology for risk studies in other peatland-dominated tropical lowlands. Practically, the resulting maps will furnish the Riau Provincial Government (BPBD, Agricultural Agency, and Planning Board) with an evidence-based foundation for risk-informed spatial planning policy formulation. As a preliminary conclusion, we hypothesize that the integration of official secondary data and the GIS-MCA methodology provides an essential predictive tool for effective disaster risk management in Riau.

2. Materials and Method

Study Area and Temporal Scope

This research centers on Riau Province, Indonesia, strategically situated in the central eastern expanse of Sumatra Island. The region was specifically chosen due to its unique geographical attributes, including extensive low-lying terrain, prevalent peatland domination, and the presence of major river systems, which collectively make the province highly susceptible to severe flooding hazards. The data analysis period spans from 2020 through 2024, guaranteeing the integration of current historical data and the latest agricultural statistics. Selecting this precise timeframe is essential for accurately capturing recent extreme weather patterns and contemporary regional climate change dynamics [7].

Secondary Data Acquisition

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

The methodology relies entirely on the synthesis and analytical integration of diverse secondary data sources procured from official Indonesian governmental institutions. The datasets utilized are categorized into flood hazard layers and agricultural vulnerability layers.

Flood Hazard Geospatial Layers (GIS Data):

- Topographic/DEM Maps: The SRTM Digital Elevation Model (DEM), provided by the Geospatial Information Agency (BIG) at a 30-meter resolution (2022 Data), was employed to derive critical parameters such as elevation and slope. High-resolution elevation data is crucial for precise flow direction modeling and water retention analysis, especially in the low-lying study area.
- Rainfall Data: Historical mean daily and monthly rainfall records (2020–2024) were obtained from the official climate stations operated by the Agency for Meteorology, Climatology, and Geophysics (BMKG) Riau Regional Office. This point data was subsequently spatially interpolated using the Inverse Distance Weighting (IDW) technique to generate an isohyet map, essential for estimating rainfall distribution across the entire study region.
- Soil Type and Geological Maps: Data provided by the Geological Agency / Ministry of Energy and Mineral Resources (ESDM) at a 1:50,000 scale informed the calculation of the soil's infiltration rate. Soil composition, particularly the prevalence of peat, is a key determinant affecting surface runoff volumes.
- Land Use / Land Cover Maps: The 2023 Land Cover Map from the Ministry of Environment and Forestry (KLHK) served to distinguish between impervious surfaces (e.g., settlements) and high-infiltration areas (e.g., forest, agriculture), thereby establishing the runoff coefficient for hydrological analysis.
- River Network and Watershed (DAS) Data: Geospatial data detailing the principal river channels and watershed boundaries, supplied by the Sumatera River Basin Organization (BWS Sumatera) (PUPR), underwent buffer analysis to quantify spatial proximity to water bodies, which serves as a proxy for fluvial overflow risk [8].
- Historical Flood Records: Precise location points and severity levels of actual flood incidents recorded between 2020 and 2024 were collected from the Riau Provincial Disaster Management Agency (BPBD). This dataset was employed as the ground truth for validating the final hazard model.

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

Agricultural Vulnerability Layers (Spatial and Tabular Data)

- Agricultural Land Maps: Spatial data identifying the distribution and area of key agricultural commodities, including rice paddies, oil palm, and rubber plantations (2024 Data), were provided by the Riau Provincial Agriculture Office and the Central Statistics Agency (BPS). This information explicitly defines the exposed assets [9].
- Productivity and Economic Value Data: Tabular statistics (2020–2024) from BPS Riau (Agricultural Statistics) were utilized to quantify economic metrics, such as production volume and monetary value, which are core elements in assessing potential economic losses and sensitivity [10].
- Agricultural Demographic Data: Data from the 2023 Agricultural Census (BPS), specifically focusing on the number of farming households (KK) and the population density reliant on the sector, were included to measure socio-economic sensitivity.
- Irrigation Infrastructure Maps: Spatial data concerning the availability and operational status of the irrigation network were sourced from the Riau Water Resources Office. This infrastructural measure acts as a quantitative proxy for local adaptive capacity.

Flood Hazard Zonation Analysis Procedure

The flood hazard zonation map was produced by integrating the weighted physical parameters within a Multi-Criteria Analysis (MCA) framework executed in a Geographic Information System (GIS) environment.

Data Normalization and Pre-processing

Each individual geospatial layer (elevation, slope, rainfall, soil type, land cover, and river proximity) underwent normalization to a standardized, dimensionless scale (e.g., 1 to 5 or 1 to 10). This step guarantees that all criteria contribute proportionally based on their allocated weight, irrespective of their original measurement units.

Criterion Weighting using the Analytical Hierarchy Process (AHP)

Agricultural Power Journal, November **2025**, Vol 2, No 4

The Analytical Hierarchy Process (AHP) methodology was applied to determine the relative weight (W_i) contribution of each parameter to overall flood hazard susceptibility. A pairwise comparison matrix was constructed based on expert opinion and regional scholarly literature. The consistency of this judgment process was confirmed by calculating the Consistency Ratio (CR); a CR value below 0.1 validates the reliability of the derived weights.

Spatial Overlay and Hazard Index Calculation

The final Flood Hazard Map (H) was calculated using the Weighted Overlay Summation function on all normalized and weighted criterion layers within the GIS:

$$H = \sum_{i=1}^{n} (W_i \times C_i)$$

Where H represents the total flood hazard index for a given grid cell, W_i is the weight of criterion i determined by AHP, and C_i is the normalized score of criterion i.

Hazard Classification and Validation

The continuous (H) index values were segmented into five discrete hazard classes: Very Low, Low, Moderate, High, and Very High. Classification utilized the Natural Breaks (Jenks) method. The predictive accuracy of the model was validated by comparing the resulting hazard map with the distribution of historical flood event points (BPBD Riau) and calculating the proportion of documented incidents located within the High and Very High zones.

Agricultural Vulnerability Assessment Procedure

The Agricultural Vulnerability Assessment was conducted based on the standard disaster risk framework, where vulnerability (V) is defined as a function of exposure (E), sensitivity (S), and adaptive capacity (A). In this framework, agricultural vulnerability represents the degree to which farming systems are likely to be adversely affected by flood hazards.

The vulnerability index was calculated using the following formula:

$$V = (E + S) - A$$

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

- Exposure (E): the degree to which agricultural areas (such as rice fields and oil palm plantations) are physically located in flood-prone zones.
- Sensitivity (S): the susceptibility of crops to flooding, based on crop type characteristics, productivity level, and soil conditions.
- Adaptive Capacity (A): the ability of farmers and local agricultural systems to cope with and recover from flood impacts, including irrigation infrastructure, farmer resources, and institutional support.

This formula follows the conceptual foundations used in disaster risk assessments, where higher exposure and sensitivity increase vulnerability, while higher adaptive capacity decreases it.

Indicator Definition and Scoring

Indicators for each component were meticulously defined using the compiled agricultural datasets:

- Exposure (E): Quantified by the area (in hectares) of agricultural land (paddy/palm oil/rubber) spatially overlaid onto the High and Very High Flood Hazard zones.
- Sensitivity (S): Evaluated based on three sub-indicators: (1) Commodity Type Sensitivity (e.g., rice is assigned a higher score than oil palm due to less tolerance for waterlogging); (2) Low Productivity Rate (below the provincial average); and (3) Farmer Density (high density signifies elevated social sensitivity).
- Adaptive Capacity (A): Assessed using two indicators: (1) Irrigation Infrastructure Status (high functionality reduces vulnerability); and (2) Access to Disaster Information (a qualitative proxy derived from BPS data).

Composite Vulnerability Index (CVI)

The E, S, and A indicators were normalized, weighted (using AHP or validated expert judgment), and aggregated to develop a Composite Vulnerability Index (CVI) map specifically for the agricultural sector.

Vulnerability Zonation

The CVI map was subsequently classified into three final categories: low, moderate, and high vulnerability, providing essential spatially explicit information for targeted mitigation and adaptation planning within Riau Province's agricultural sector.

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

3. Result

Geospatial Characteristics of Riau Province

DEM Analysis and Mapping: Geospatial analysis conducted on the Digital Elevation Model (DEM) of Riau Province confirms a prevailing low-lying topographical nature. The resulting spatial maps illustrate that the majority of Riau's territory, specifically areas along the coastline and the main River Basin Systems (DAS), exhibit critically low elevations, typically ranging from 0 to 50 meters above mean sea level (amsl). This inherently flat landscape decelerates natural water discharge processes and elevates the probability of prolonged inundation events.

Rainfall Climatological Analysis: Climatological data processed from BMKG stations reveal that Riau receives a substantial annual average rainfall, falling within the range of 2,000 to 3,000 mm. This high precipitation is further marked by significant spatial and temporal fluctuations. Importantly, during the peak wet season, monthly rainfall intensity often surpasses the critical threshold of 200 mm/month, leading to the generation of extreme surface runoff.

Flood Hazard Zonation Map

AHP Criterion Weighting:

The relative contribution of the influencing factors to flood susceptibility was determined using the Analytical Hierarchy Process (AHP). Table 1 outlines the derived weights (W):

Table 1. Flood Hazard Zonation Criterion Weighting (AHP)

Factor	Weight (W)
Elevation (DEM)	0.35
Distance from River	0.28
Rainfall	0.17
Soil Type	0.12
Land Cover	0.08
Total	1.00

As presented, elevation (DEM) and distance from river received the highest weights (0.35 and 0.28, respectively). This result confirms the dominant role of geomorphological and hydraulic factors in driving overflow flooding in Riau. The computed Consistency Ratio (CR) of 0.07 is below the acceptance threshold of 0.1, thus validating the logical consistency of the expert judgment.

Flood Hazard Map Generation: The results from the Weighted Overlay Summation modeling indicate that 18.5% of the total provincial area of Riau is classified into High and Very High Hazard zones. The areas facing the most extreme hazards are concentrated in Indragiri Hulu, Indragiri Hilir, and specific sections of the Kampar regencies. These high-risk zones consistently share characteristics such as immediate proximity to major river courses, elevations generally less than 10 meters amsl, and soil types exhibiting low infiltration capacity.

Model Validation: The generated hazard model was rigorously validated against 85 historical flood incidence points sourced from BPBD data (2020–2024). Validation was performed by spatially overlaying the point data of historical flood incidents onto the final raster layer of the classified flood hazard map. The validation demonstrated a model accuracy of 79.2%, as 67 out of 85 historical events were correctly located within the Moderate, High, or Very High Hazard categories.

Agricultural Vulnerability Assessment Map

Exposure and Sensitivity Analysis:

The spatial overlay analysis indicates substantial exposure within Riau's agricultural sector. The key commodities whose land area is most exposed to the high/very high hazard zones are:

- Oil Palm Plantations: 450,000 Hectares
- Rice Paddy Fields: 55,000 Hectares

The exposure data above were derived from the spatial overlay between the Flood Hazard Map (H) and the agricultural land datasets provided by the Riau Provincial Agriculture Office and the 2024 BPS data [9].

Although oil palm accounts for the largest area of exposure, the sensitivity assessment ranked rice paddy fields highest in intrinsic sensitivity. This is primarily because rice crops experience rapid and complete irreversible damage when subjected to prolonged submergence, making them far more susceptible to inundation than oil palm.

Agricultural Vulnerability Map: The resulting Composite Vulnerability Index (CVI) Map reveals that the Regencies of Indragiri Hilir (Inhil) and Rokan Hulu

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

possess the highest overall agricultural vulnerability. The severe vulnerability observed in Inhil results from a convergence of two primary issues: (1) the massive exposure of oil palm areas located in frequently inundated tidal zones and (2) low adaptive capacity, specifically linked to the limited availability and inadequate condition of essential drainage and irrigation infrastructure.

4. Discussion

Interpretation of Hazard Zonation

The flood hazard zonation results (Section 3.2) exhibit strong coherence with findings from regional hydrological studies, which consistently pinpoint low elevation and spatial proximity to the River Basin System (DAS) network as the primary catalysts for flood susceptibility across Sumatra. Research conducted by Suprapto et al. (2023) specifically on the hydrological analysis of Sumatra's coastal territories further supports the conclusion that the low-lying topography is the fundamental determinant of inundation events [11]. The high AHP weights allocated to these factors (0.35 for Elevation and 0.28 for Distance from River) therefore validate the logical and scientific prioritization applied to the geospatial modeling within Riau. Furthermore, the model accuracy of 79.2% affirms the reliability of the GIS-Multi-Criteria Analysis (MCA) model as a dependable predictive instrument for policymakers.

Implications for Agricultural Vulnerability

The high vulnerability identified in both the oil palm and rice sectors represents a serious dual threat to Riau's regional economic stability and food security. Flooding not only causes immediate yield loss but also reduces product quality and long-term market value, thereby intensifying economic impacts on farming communities. Sitorus and Tambunan (2024) report that post-flood disruptions in the oil palm sector often contribute to fluctuations in global commodity prices, leading to broader macroeconomic consequences [12].

The application of the vulnerability formula:

$$V = (E + S) - A$$

It effectively identifies locations where high flood hazard intersects with highly sensitive agricultural assets and insufficient adaptive capacity. This alignment

Agricultural Power Journal, November **2025**, Vol *2*, No *4*

underscores areas requiring urgent intervention, particularly where exposure and crop sensitivity are high while structural and institutional resilience remains limited.

Comparison and Research Contribution

Methodologically, these findings strengthen the framework outlined by Sutikno and Hariadi (2023), particularly the emphasis on using detailed spatial data—such as high-quality Digital Elevation Models (DEMs)—and ensuring the validity of hydrological inputs for accurate hazard modeling [13]. Unlike previous disaster risk studies that focused mainly on public infrastructure or settlement vulnerability, this research specifically highlights the susceptibility of major agricultural commodities (oil palm and rice). This tailored approach aligns with the guidance of the National Development Planning Agency (Bappenas) in its 2024 national disaster mitigation plan, which calls for a holistic focus on the economic impacts of disasters on the food sector, including loss estimation at the specific commodity level [14]. Consequently, the produced spatial maps offer the granular location details required for precise, targeted interventions by relevant agencies in Riau Province.

Study Limitations

Although the model achieved a satisfactory accuracy level of 79.2%, the primary constraint of this study resides in the use of interpolated station rainfall data. This interpolation process may not fully capture the spatial variability of highly localized, intense extreme rainfall events across the Riau region. Furthermore, the assessment of adaptive capacity relied exclusively on physical infrastructure proxies (irrigation and drainage) and did not fully incorporate critical elements such as social capital, institutional governance, or intrinsic farmer capacity. For future studies, integrating advanced data sources—such as weather radar or satellite-derived rainfall data—is recommended to further enhance the model's predictive accuracy.

5. Conclusions

Conclusion

This study successfully produced detailed spatial representations, including a flood hazard zonation map and an agricultural vulnerability map for Riau Province, Indonesia, using a Geographic Information System–Multi-Criteria Analysis (GIS-

Agricultural Power Journal, November **2025**, Vol 2, No 4

MCA) framework with compiled secondary data from 2020 to 2025. The key insights derived from this analysis are:

- The analysis confirms that Riau's low-lying geomorphological characteristics, especially in the lower reaches of major watershed systems, make a significant proportion of the province (approximately 18.5%) highly susceptible to extreme flood hazards.
- The agricultural sector, with major commodities concentrated in the Indragiri Hilir and Rokan Hulu Regencies, shows the highest composite vulnerability. This high vulnerability results from a combination of extensive physical exposure and inherently low adaptive capacity, highlighting the need for targeted interventions.
- The resulting spatial maps and indices are confirmed as valid and essential resources, providing critical spatial intelligence to support evidence-based policy formulation for disaster mitigation and the enhancement of Riau's regional food security strategy.

Suggestions and Recommendations

- Mitigation Strategy: It is strongly recommended that the Riau Provincial Government prioritize investment in, and prompt implementation of, drainage infrastructure and other essential flood prevention measures within the identified High Vulnerability zones.
- Adaptation Strategy: The Riau Agricultural Department (Dinas Pertanian) should design and implement adaptation programs tailored for farmers in high-risk areas. Key initiatives should include promoting and distributing flood-resilient rice varieties and upgrading existing irrigation networks to meet technical standards.
- Future Research Directions: Future studies should incorporate advanced hydrodynamic modeling techniques (such as HEC-RAS) for more refined flood simulation outputs. Additionally, integrating a broader range of socio-economic data on farming households is essential to provide a more accurate and comprehensive assessment of local adaptive capacity.

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Agricultural Power Journal, November **2025**, Vol *2*, No *4*

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Agricultural Power Journal, November **2025**, Vol *2*, No *4*

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