GIS-Based Analytical Hierarchy Process Flood Hazard Mapping in Deli Serdang, Indonesia Using Satellite Images

Zaidan Hafizhahurrahman[1], Shafnanda Aulia Kamal[2]

[1] Ar-Rahmah Islamic Junior High School
[2] STIS Polytechnic of Statistics

*Corresponding author's email: 222212878@stis.ac.id

Abstract. As of the regions with a high frequency and significant impact of flood disasters, Deli Serdang in North Sumatera, Indonesia highly requires spatial-based hazard mapping as a foundation for mitigation efforts. This study aims to map the flood hazard levels by integrating the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS). Five parameters were analyzed to construct the model: elevation, slope, rainfall, Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI), with data acquired through the Google Earth Engine platform. The AHP weighting results indicate that rainfall is the most dominant factor (40%) influencing the hazard level. The resulting hazard map identifies a clear spatial pattern with a north-to-south gradation, where 50.17% of the total area falls into the high-hazard category, 47.57% into the moderate category, and the remainder into the low-hazard category. A significant finding reveals that all sub-districts within the study area are classified as either moderate or high hazard, confirming the northern coastal zone as the most critical area. The results of this research can serve as a scientific basis for local government in formulating more adaptive and targeted disaster mitigation policies and spatial planning.

Keyword: AHP, Deli Serdang, Flood Hazard, GIS, Remote Sensing.

1. Introduction

Flooding ranks as the third most frequent natural disaster in Indonesia, yet it is responsible for a greater human impact than any other catastrophe. In 2023 alone, Indonesia recorded 1,255 flood events, which resulted in 92 fatalities or missing persons, 4,788 injuries, and affected or displaced 3,871,667 individuals [1]. These events not only cause substantial material losses but also lead to significant social, economic, and public health disruptions. In 2023, North Sumatra Province was the region with the highest incidence of flooding in Indonesia [2]. Among the regencies and cities within this province, Deli Serdang Regency ranks highest in terms of flood frequency. Over the last five years, the occurrence of flooding in Deli Serdang has shown a fluctuating trend, with 1 incident in 2019, 4 incidents in 2020, 6 incidents in 2022, and a significant increase to 20 incidents in 2023 [3]. The damage caused by flooding is highly significant and difficult to recover from, affecting properties, infrastructure, and resulting in the loss of many lives [4]. The impact in 2023 was particularly severe, resulting in 4,611 submerged homes, 4 damaged houses [5], 2 fatalities or missing persons, and the displacement of 21,447 individuals [6]. A major flash flood at the end of 2023 further exacerbated the situation, causing four deaths and leaving two people missing [7].

The high vulnerability of Deli Serdang Regency can be attributed to a combination of geographic and hydrologic factors. The regency features a contrasting topography, ranging from coastal lowlands in the east, which directly border the Strait of Malacca, to hilly terrain in the west [8]. The presence of three major rivers—the Percut, Deli, and Belawan—that traverse densely populated areas and empty into the east coast establishes a primary drainage system that is highly sensitive to rainfall input. With an average annual rainfall exceeding 2,500 mmm [9], coupled with rapid land-use conversion in the lowland regions, the potential for river overflow and inundation is significantly heightened. This context underscores the urgent necessity for comprehensive hazard mapping [10].

Given the complexity of the factors that trigger flooding, an approach capable of systematically integrating multiple criteria is required. A Geographic Information System (GIS) provides an ideal platform for such multi-parameter spatial analysis [11]. owever, a primary challenge lies in determining the relative importance (weight) of each parameter. To address this challenge, Multi-Criteria Decision Making (MCDM) methods, such as the Analytical Hierarchy Process (AHP), are highly relevant. AHP enables the decomposition of a complex problem into a simpler hierarchical structure and assigns priority weights to each criterion based on pairwise comparisons [12]. Previous studies have demonstrated that integrating GIS with MCDM methods provides an effective approach for disaster hazard mapping. For instance, a study applied a GIS-based AHP approach to map flood risk zones in Hyderabad District, India, considering various physiographic, climatic, land use/land cover, and pedological parameters [13]. The study produced a flood risk map classified into low, moderate, and high zones. The results were validated against historical flood events, confirming their utility as a basis for developing flood mitigation strategies. Similarly, another study utilized a GIS-based multi-criteria analysis with AHP to identify optimal locations for developing green open spaces in Lilongwe, Malawi [11]. That research successfully mapped land suitability levels based on nine factors, including population density, slope, NDVI, land cover, and proximity to water bodies, generating a spatial suitability map to support sustainable urban planning. These findings affirm the importance of decision-making based on spatial data and weighted criteria in the context of environmental management.

Therefore, to address the identified knowledge gap and the urgent need for a localized assessment, this study aims to develop a comprehensive flood hazard map for Deli Serdang Regency by integrating the Analytical Hierarchy Process (AHP) with GIS. The model incorporates five critical parameters known to influence flood events: elevation, slope, rainfall, the Normalized Difference Vegetation Index (NDVI), and the Normalized Difference Built-up Index (NDBI) [14]. All geospatial data for these parameters were acquired and processed utilizing the cloud-computing capabilities of the Google Earth Engine (GEE) platform. The findings of this research are expected to provide a robust scientific basis for local authorities and stakeholders, serving as a crucial tool to inform the formulation of effective disaster mitigation policies, guide more resilient spatial planning, and enhance community preparedness in the most vulnerable areas.

2. Research Method

1.1. Data

This study used spatial data from Google Earth Engine (GEE), including elevation, slope, rainfall, NDVI, and NDBI. Table 1 summarizes each parameter and its effect on flood vulnerability, where rainfall and NDBI increase vulnerability, while NDVI, elevation, and slope reduce it [15].

Tabel 1. Data.

Data	Variable name	Data Sources	Contribution
Sub-district administrative boundaries	-	Badan Informasi Geospasial (BIG) via Indonesia-Geospasial.com (2023)	-
Elevation	x1	Digital Elevation Model SRTM (USGS/SRTMGL1_003) – USGS	Negative
Slope	x2	Digital Elevation Model SRTM (USGS/SRTMGL1_003) – USGS	Negative

Data	Variable name	Data Sources	Contribution
Annual rainfall	x3	CHIRPS Daily Precipitation (UCSB-CHG/CHIRPS/DAILY) – UCSB/USGS	Positive
Normalized Difference Vegetation Index (NDVI)	x4	Sentinel-2 Surface Reflectance (COPERNICUS/S2_SR) – Copernicus/ESA	Negative
Normalized Difference Built-up Index (NDBI)	x5	Citra Sentinel-2 Surface Reflectance (COPERNICUS/S2_SR) – Copernicus/ESA	Positive

1.2. Methodology

The research was conducted through the following stages:

1. Data Processing in Google Earth Engine (GEE)
    a. Sentinel-2 imagery was processed to derive the Normalized Difference Vegetation Index (NDVI) using the formula (B8 - B4) and the Normalized Difference Built-up Index (NDBI) using the formula (B11 - B8).
    b. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was utilized to derive elevation and slope parameters
    c. Rainfall data were obtained from the CHIRPS collection and aggregated to calculate the total annual precipitation.
    d. All geospatial parameters were clipped to the administrative boundaries of Deli Serdang Regency.
    e. This stage involved two distinct approaches:
        1) Direct Raster Approach: Parameter values were maintained in their original raster format without any aggregation.
        2) Spatial Aggregation Approach: Parameter values were averaged for each sub-district using the reduceRegions function, which is analogous to zonal statistics
2. Parameter Classification
    The mean value of each parameter was classified into five classes, scored from 1 to 5, corresponding to hazard levels ranging from very low to very high
3. Analytic Hierarchy Process (AHP) Weighting
    A pairwise comparison matrix was constructed to assess the relative importance of each parameter. The final weights for each parameter were derived from the AHP calculations, which included a consistency ratio test to ensure the reliability of the judgments
4. Flood Hazard Index Calculation
    The score of each parameter was multiplied by its corresponding AHP-derived weight. These values were then summed to produce a final flood hazard index for each sub-district.
5. Hazard Level Classification
    The resulting flood hazard index was subsequently classified into three categories: low, moderate, and high
6. Mapping and Areal Analysis
    The final classification results were visualized to produce a sub-district-based flood hazard map. This was followed by an analysis of the total area corresponding to each hazard level.

1.2.1. Analytical Hierarchy Process (AHP).

After classifying the flood vulnerability parameters, the subsequent step is to determine the weight of each parameter using the Analytical Hierarchy Process (AHP) method. AHP is a multi-criteria decision-making method that structures a complex problem into a hierarchical form. It then assesses the relative importance among parameters through pairwise comparisons using a scale ranging from 1 to 9 [16]. The details of

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this rating scale are presented in Table 2 [17]. The results of these comparisons are then normalized to obtain the priority weight for each parameter

Table 2. Criteria rating scale.

Intensity of Interest	Description
1	Equally important
2	Equal to moderately important
3	Moderately important
4	Moderate to strongly important
5	Strongly important
6	Strong to very strongly important
7	Very strongly important
8	Very to extremely strong important
9	Extremely important

Subsequently, a consistency test is performed by calculating the maximum eigenvalue, the Consistency Index (CI), and the Consistency Ratio (CR) using the following formulas [4]:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

where
CI = Consistency Index
λ_{max} = Maximum Eigenvalue
n = Number of criteria

$$CR = \frac{CI}{RI} \quad (2)$$

where

CR = Consistency Ratio

RI = Random Index

The Random Index (RI) value is obtained from the RI Table, as shown in Table 3.

Table 3. Random Index (RI) values.

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The result of the consistency test is considered acceptable (consistent) when the CR value is less than 0.1. [17]

3. Result and Discussion

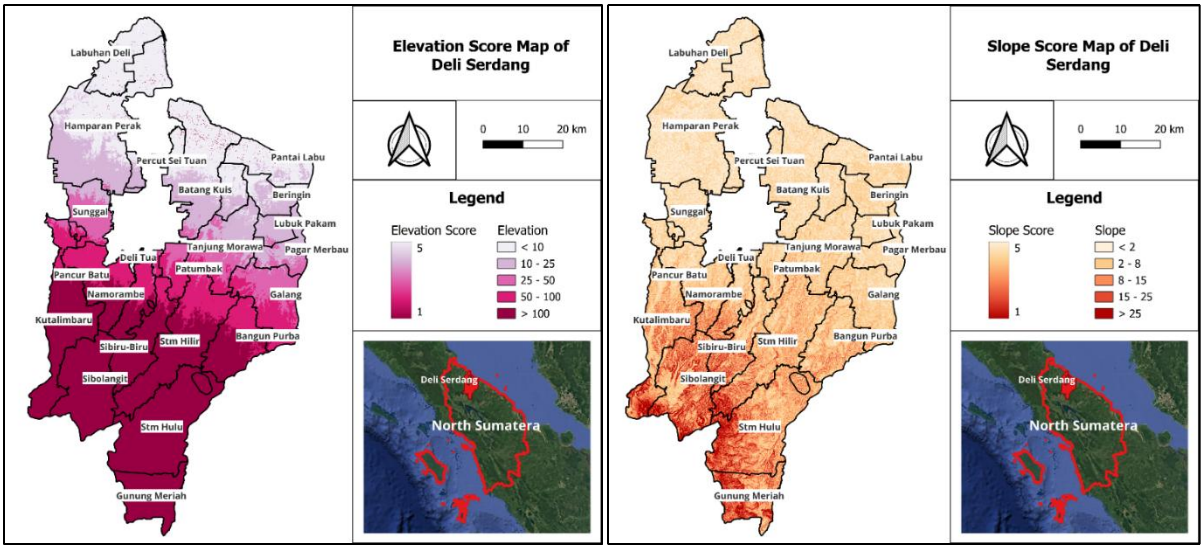
3.1. Descriptive Analysis

Each parameter was classified into five classes and given a score based on its relationship to flood hazard. Table 4 shows the elevation classification, where lower elevation receives a higher score. Slope and NDVI, which are negatively correlated with flood hazard, are shown with their score intervals in the same table. Rainfall and NDBI have a positive correlation, so higher values correspond to higher scores.

Table 4. Parameter class classification.

Parameters					Score
Elevation	Slope	Annual rainfall	NDVI	NDBI	
> 100	> 25	< 1000	0.7 - 1	< -0.2	1 (very low)
50 – 100	15 – 25	1000 – 1500	0.5 – 0.7	-0.2 – 0	2 (low)
25 – 50	8 – 15	1500 – 2500	0.2 – 0.5	0 – 0.1	3 (moderate)
10 – 25	2 – 8	2500 – 3500	0 – 0.2	0.1 – 0.3	4 (high)
< 10	< 2	> 35000	< 0	> 0.3	5 (very high)

Figure 1 illustrates the classification score maps for each parameter utilized in this study. The maps reveal that parameters inversely related to flood hazard, such as slope and NDVI, consistently exhibit high scores in the southern portion of the study area. Conversely, parameters with a direct relationship to flood hazard, including rainfall and NDBI, show high scores predominantly in the northern region. Figure 2 presents the results at a pixel level (raster-based), which allows for a more detailed visualization of the value variations across the entire study area. This visualization provides a direct depiction of the spatial patterns for each parameter, highlighting areas characterized by low elevation, gentle slopes, sparse vegetation, high precipitation, and a high density of built-up land.



(a) (b)

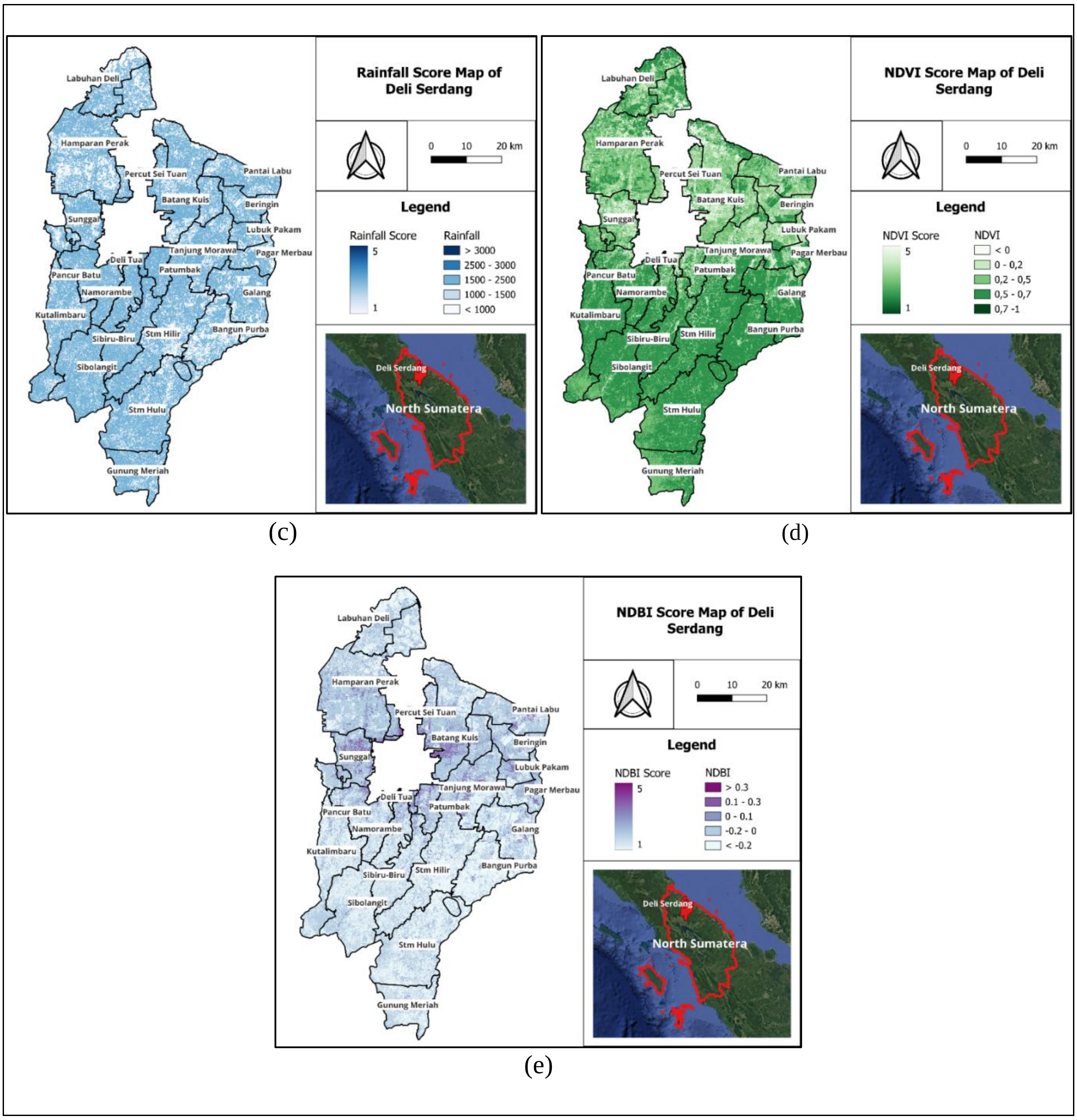
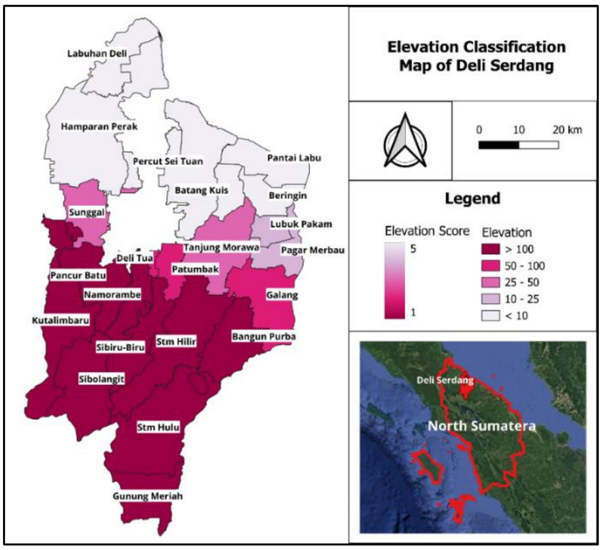
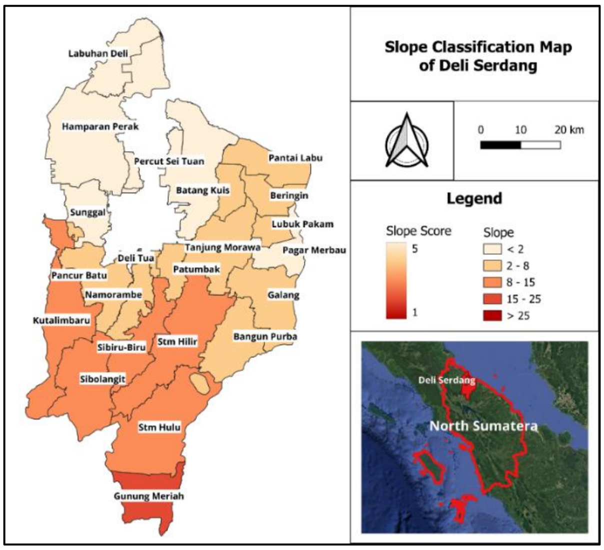


Figure 1. Parameter-based score maps of Deli Serdang District showing (a) elevation, (b) slope, (c) rainfall, (d) NDVI, and (e) NDBI.

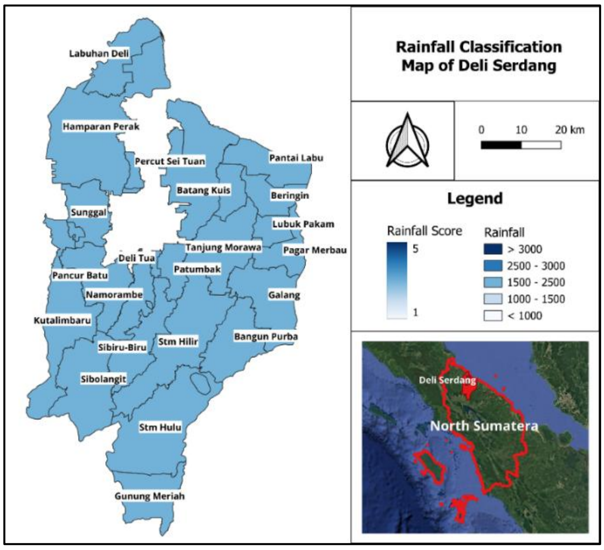
Subsequently, to facilitate analysis at the administrative level, a zonal statistics approach was employed. The mean value of each parameter was calculated for each sub-district and then classified into five classes according to the classification table previously mentioned. Figure 2 shows the sub-district classification maps, illustrating the spatial distribution of each parameter at the administrative level. The results visually support the raster-based analysis, indicating that parameters negatively correlated with flood hazard have higher values in the southern sub-districts, especially for elevation in STM Hulu, Sibolangit, STM Hilir, Sibiru-biru, and Kutalimbaru. In contrast, these same areas show lower NDBI values, which are positively correlated with flood hazard. Annual rainfall, however, appears relatively uniform across all sub-districts.


Elevation Classification Map of Deli Serdang
0 10 20 km
Legend
Elevation Score
5
1
Elevation
> 100
50 - 100
25 - 50
10 - 25
< 10
Labuhan Deli
Hamparan Perak
Percut Sei Tuan
Pantai Labu
Batang Kuis
Beringin
Sunggal
Lubuk Pakam
Tanjung Morawa
Pagar Merbau
Deli Tua
Pancur Batu
Patumbak
Namorambe
Galang
Kutalimbaru
Sibiru-Biru
Stm Hilir
Bangun Purba
Sibolangit
Stm Hulu
Gunung Meriah
Deli Serdang
North Sumatera

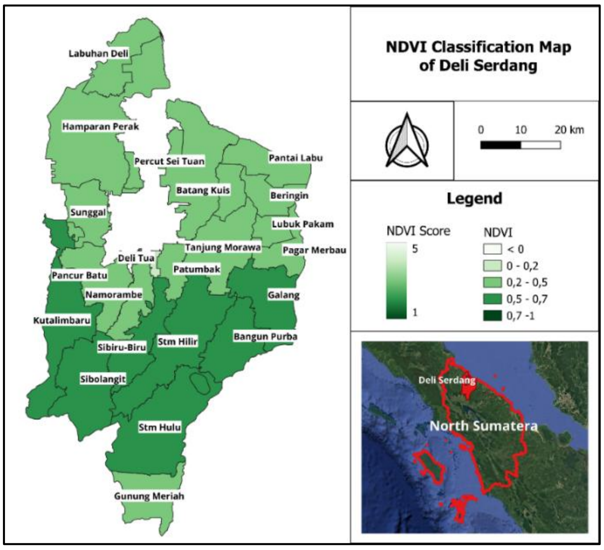
(a)


Slope Classification Map of Deli Serdang
0 10 20 km
Legend
Slope Score
5
1
Slope
< 2
2 - 8
8 - 15
15 - 25
> 25
Labuhan Deli
Hamparan Perak
Percut Sei Tuan
Pantai Labu
Batang Kuis
Beringin
Sunggal
Lubuk Pakam
Tanjung Morawa
Pagar Merbau
Deli Tua
Pancur Batu
Patumbak
Namorambe
Galang
Kutalimbaru
Sibiru-Biru
Stm Hilir
Bangun Purba
Sibolangit
Stm Hulu
Gunung Meriah
Deli Serdang
North Sumatera

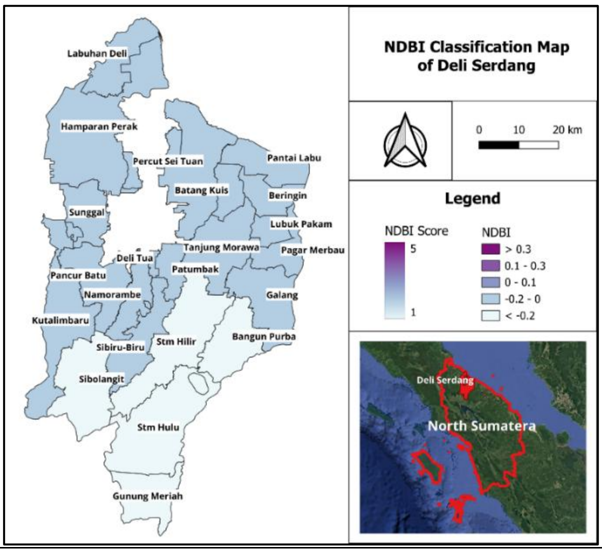
(b)


Rainfall Classification Map of Deli Serdang
0 10 20 km
Legend
Rainfall Score
5
1
Rainfall
> 3000
2500 - 3000
1500 - 2500
1000 - 1500
< 1000
Labuhan Deli
Hamparan Perak
Percut Sei Tuan
Pantai Labu
Batang Kuis
Beringin
Sunggal
Lubuk Pakam
Tanjung Morawa
Pagar Merbau
Deli Tua
Pancur Batu
Patumbak
Namorambe
Galang
Kutalimbaru
Sibiru-Biru
Stm Hilir
Bangun Purba
Sibolangit
Stm Hulu
Gunung Meriah
Deli Serdang
North Sumatera

(c)


NDVI Classification Map of Deli Serdang
0 10 20 km
Legend
NDVI Score
5
1
NDVI
< 0
0 - 0,2
0,2 - 0,5
0,5 - 0,7
0,7 -1
Labuhan Deli
Hamparan Perak
Percut Sei Tuan
Pantai Labu
Batang Kuis
Beringin
Sunggal
Lubuk Pakam
Tanjung Morawa
Pagar Merbau
Deli Tua
Pancur Batu
Patumbak
Namorambe
Galang
Kutalimbaru
Sibiru-Biru
Stm Hilir
Bangun Purba
Sibolangit
Stm Hulu
Gunung Meriah
Deli Serdang
North Sumatera

(d)


NDBI Classification Map of Deli Serdang
0 10 20 km
Legend
NDBI Score
5
1
NDBI
> 0.3
0.1 - 0.3
0 - 0.1
-0.2 - 0
< -0.2
Labuhan Deli
Hamparan Perak
Percut Sei Tuan
Pantai Labu
Batang Kuis
Beringin
Sunggal
Lubuk Pakam
Tanjung Morawa
Pagar Merbau
Deli Tua
Pancur Batu
Patumbak
Namorambe
Galang
Kutalimbaru
Sibiru-Biru
Stm Hilir
Bangun Purba
Sibolangit
Stm Hulu
Gunung Meriah
Deli Serdang
North Sumatera

(e)

Figure 2. Sub-district classification maps of Deli Serdang based on (a) elevation, (b) slope, (c) rainfall, (d) NDVI, and (e) NDBI.

1.3. Determination of Priority Weights Using AHP

Weighting was performed using the AHP method on the five classified and scored parameters. Table 5 shows the results of the pairwise comparison of importance between the parameters, based on the criteria rating scale. It is evident that the rainfall parameter was judged to have the highest level of importance compared to the others; for instance, it was considered five times more important than NDVI and three times more important than elevation [18]. In contrast, the NDVI parameter was deemed to have a lower importance than nearly all other parameters, with a value of only 0.20 when compared to rainfall and 0.33 when compared to elevation.

Table 5. Pairwise comparison matrix of importance.

Parameters	Elevation	Slope	Rainfall	NDVI	NDBI
Elevation	1.00	0.50	0.33	3.00	2.00
Slope	2.00	1.00	0.50	4.00	3.00
Rainfall	3.00	2.00	1.00	5.00	3.00
NDVI	0.33	0.25	0.20	1.00	0.50
NDBI	0.50	0.33	0.33	2.00	1.00
Sum	6.83	4.08	2.36	15.00	9.50

Table 6 displays the weighting results derived from the importance comparison matrix. The highest priority was assigned to the rainfall parameter, accounting for 40%. The subsequent priorities were slope at 26.6% elevation at 16.4%, NDBI at 10.15% and the lowest priority was NDVI at 6.3%.

Table 6. Normalized Pairwise Comparison Matrix.

Parameters	Elevation	Slope	Rainfall	NDVI	NDBI	Sum	Priority	Eigen value
Elevation	0.146	0.122	0.140	0.200	0.211	0.819	0.164	1.119
Slope	0.293	0.245	0.212	0.267	0.316	1.332	0.266	1.087
Rainfall	0.439	0.490	0.423	0.333	0.316	2.001	0.400	0.946
NDVI	0.049	0.061	0.085	0.067	0.053	0.314	0.063	0.942
NDBI	0.073	0.082	0.141	0.133	0.105	0.534	0.107	1.015

Sum	1	1	1	1	1	5	1	5.110

Based on the calculations from Table 6, the maximum eigenvalue was found to be 5.110. With five parameters, this yielded a Consistency Index (CI) of 0.027. According to the standard consistency table, a Random Index (RI) value of 1.12 is used for five parameters. The resulting comparison between the CI and RI produced a Consistency Ratio (CR) of 0.0245. Since the obtained CR value is less than 0.1, it can be concluded that the resulting priority weights are consistent and valid for use. Therefore, the Flood Hazard Index (FHI) was calculated using the following equation [19]:

$$FHI = (X_1 \times W_1) + (X_2 \times W_2) + (X_3 \times W_3) + (X_4 \times W_4) + (X_5 \times W_5) \quad (1)$$

where

FHI = Flood Hazard Index

X_i = Classification score for the i-th parameter

W_i = Priority weight for the i-th parameter

1.4. Hazard Level Classification

Based on the flood hazard index calculations, the results were classified into three levels as presented in Table 7.

Table 7. Flood hazard levels.

Number	Hazard level	Interval	Area (ha)	Percentage(%)
1	Low	< 2	5893.079	2.256
2	Moderate	2 – 3	124296.028	47.573
3	High	> 3	131083.386	50.171

As shown in Table 7. the high hazard level constitutes the largest area. covering approximately 50.17% of the total study area. This is followed by the moderate hazard level at 47.57%. The low hazard level represents the smallest portion, accounting for only 2.26% of the study area. These findings demonstrate that the study area is. in general. a vulnerable region that requires significant attention in flood disaster mitigation planning.

Comparable findings have been reported in several recent flood hazard mapping studies across Indonesia and other regions. Studies conducted in North Sumatra have identified considerable flood vulnerability associated with environmental factors such as sea-level rise, land subsidence, and topographic variation [20]. Other assessments across Sumatra also reported extensive high-risk zones when multi-hazard interactions were considered [21]. In South Sumatra, approximately 30.3% of the area was classified as high flood risk [22]. Similar patterns were observed in regional and international studies, where high- and very-high-risk zones covered between one-fourth and one-half of the total study area [23] and smaller high-risk proportions were identified in global GIS–AHP analyses [24]. These comparisons indicate that the 50.17% high-hazard area identified in this study falls within the upper range of previous research findings, reflecting the combined influence of flat topography, high rainfall, and environmental conditions in Deli Serdang District.

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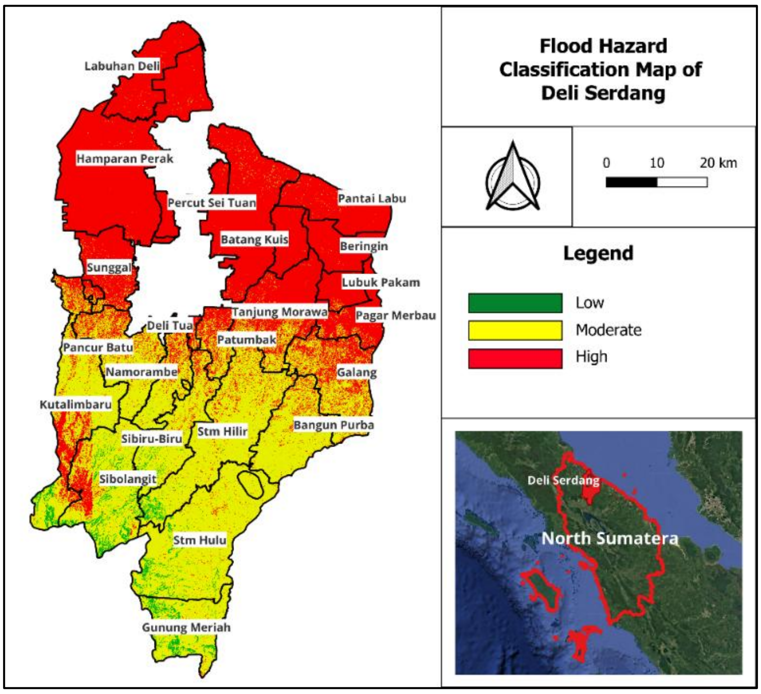

Figure 3. Flood hazard classification map of Deli Serdang showing three hazard levels: low (green), moderate (yellow), and high (red).

Figure 3 shows that the northern part of the study area has the highest flood hazard. This corresponds with the parameter classification, where factors increasing hazard—high rainfall, low elevation, and dense built-up areas—are concentrated in the north. In contrast, factors that reduce hazard, such as steeper slopes and denser vegetation, are more common in the south. These patterns align with previous findings that high rainfall, flat topography, and low vegetation density contribute to flood risk in tropical lowlands [25], while steeper slopes and dense vegetation help reduce susceptibility by increasing infiltration and lowering runoff [26]. Therefore, mitigation efforts should prioritize high-hazard zones in the north, followed by moderate and low-hazard areas.

Table 8. Flood hazard class per sub-district.

No	Sub-district name	Area (ha)			Percentage (%)		
		Hazard class					
		Low	Moderate	High	Low	Moderate	High
1	Beringin	0	12.60	5754.91	0	0.22	99.78
2	Batang Kuis	0	12.98	4516.6	0	0.29	99.71
3	Hamparan Perak	0.47	122.02	30515.77	0	0.40	99.60
4	Labuhan Deli	0	79.54	12389.53	0	0.64	99.36
5	Pantai Labu	0	96.44	8581.71	0	1.11	98.89
6	Percut Sei Tuan	0	281.38	18929.96	0	1.47	98.54
7	Lubuk Pakam	0	87.85	3293.23	0	2.6	97.40
8	Pagar Merbau	0	496.11	5900.64	0	7.76	92.24

No	Sub-district name	Area (ha)			Percentage (%)		
		Hazard class					
		Low	Moderate	High	Low	Moderate	High
9	Sunggal	0	722.32	7374.96	0	8.92	91.08
10	Tanjung Morawa	0	3101.19	10347.59	0	23.06	76.94
11	Deli Tua	0	222.57	592.27	0	27.31	72.69
12	Patumbak	0	2165.73	2233.42	0	49.23	50.77
13	Galang	0	7625.82	5431.61	0	58.40	41.6
14	Pancur Batu	5.60	9085.94	3223.49	0.05	73.78	26.18
15	Kutalimbaru	589.65	13399.67	4463.76	3.20	72.62	24.19
16	Namorambe	29.60	5008.41	1461.34	0.46	77.06	22.48
17	Sibolangit	1838.61	12421.84	1972.67	11.33	76.52	12.15
18	Bangun Purba	6.35	11141.52	1079.23	0.05	91.12	8.83
19	Sibiru-Biru	430.20	9544.06	869.82	3.97	88.01	8.02
20	Stm Hilir	534.67	19104.17	1659.82	2.51	89.70	7.79
21	Stm Hulu	1108.35	21397.15	382.68	4.84	93.49	1.67
22	Gunung Meriah	1349.59	8166.74	108.39	14.02	84.85	1.13

Table 8 shows clear spatial variation in flood hazard across sub-districts. Beringin, Batang Kuis, Labuhan Deli, Hamparan Perak, Pantai Labu, and Percut Sei Tuan have over 98% of their areas classified as high hazard, making them intervention priorities. STM Hulu, Bangun Purba, STM Hilir, and Sibiru-biru are mostly moderate hazard (more than 88%). Gunung Meriah has the largest low-hazard area (14.02%). Overall, most sub-districts fall within moderate to high hazard levels.

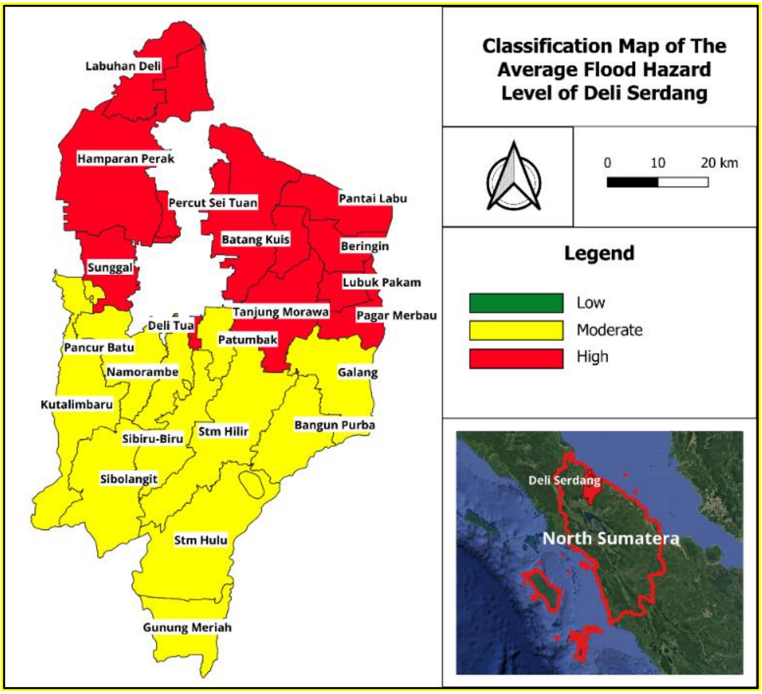

Figure 4. Sub-district average flood hazard classification map of Deli Serdang District.

Figure 4 presents the sub-district flood hazard classification map, which was generated by applying AHP weights to the previously classified parameters for each sub-district. It is evident from the map that no sub-district falls into the low flood hazard category. This finding underscores the need for comprehensive flood disaster mitigation planning across the entirety of Deli Serdang Regency to reduce potential losses from future disaster impacts.

Table 9. Grouping of sub-districts by hazard level.

	Sub-district name		
	Hazard level		
Number	Low	Moderate	High
1		Kutalimbaru	Labuhan Deli
2		Pancur Batu	Hamparan Perak
3		Namorambe	Sunggal
4		Sibolangit	Percut Sei tuan
5		Patumbak	Batang Kuis
6		Sibiru-biru	Pantai Labu
7		Stm Hilir	Beringin
8		Galang	Tanjung Morawa
9		Bangun Purba	Lubuk Pakam

10	Stm Hulu	Pagar Merbau
11	Gunung Meriah	Deli Tua

Table 9 categorizes the sub-districts based on their final flood hazard classification. Out of 22 sub-districts, 11 are classified as having a high flood hazard level, while the other 11 are classified as having a moderate level. This confirms that no single sub-district can be considered entirely safe or at low risk for flood events. This geographic grouping is highly consistent with the topographic conditions of Deli Serdang Regency. The 11 sub-districts identified with high hazard are predominantly located in the northern region, which consists of low-lying coastal plains adjacent to the sea. Conversely, the sub-districts with a moderate hazard level are generally situated in the southern region, which is characterized by higher elevations and constitutes the upstream area.

To verify the reliability of the flood hazard classification results, the high-hazard areas identified in Table 9 were compared with historical flood event data obtained from the Indonesian National Disaster Management Agency (BNPB, 2013–2023). The comparison shows that sub-districts such as Lubuk Pakam, Percut Sei Tuan, and Sunggal, which were classified as high-hazard zones, recorded the highest number of flood events during this period. Furthermore, data from Statistics Indonesia (BPS) also show a similar pattern. Based on the number of villages/urban villages (desa/kelurahan) affected by floods, Batang Kuis (10), Tanjung Morawa (5), Percut Sei Tuan (4), Sunggal (3), and Pantai Labu (2) were identified as the most flood-affected sub-districts [27]. Notably, all five of these sub-districts are categorized as high hazard zones in Table 9. This consistency between the AHP-GIS classification, BNPB records, and BPS data confirms that the developed model provides a reliable representation of actual flood conditions in the study area.

4. Conclusion

This research has successfully mapped the flood hazard levels in Deli Serdang Regency by integrating the Analytical Hierarchy Process (AHP) with Geographic Information Systems (GIS) based on an analysis of five key parameters. The AHP weighting results indicate that rainfall is the most dominant parameter influencing hazard levels in the study area (40%), followed by slope (26.6%), elevation (16.4%), NDBI (10.2%), and NDVI (6.3%). Spatially, the mapping reveals a distinct hazard pattern with a clear north-to-south gradation, where the northern coastal region is predominantly classified as high hazard (50.17%) and the southern hilly region is dominated by a moderate hazard level (47.57%).

Lowland areas in the north, such as Percut Sei Tuan, Labuhan Deli, Hamparan Perak, Beringin, Batang Kuis, and Pantai Labu, are consistently identified as high-hazard zones. Conversely, the more elevated southern areas, including STM Hulu, Bangun Purba, and Sibiru-biru, generally fall into the moderate category. A crucial finding of this analysis is that all 22 sub-districts in Deli Serdang Regency are classified as either moderate or high hazard, confirming that flood risk is a widespread and significant issue across the entire regency.

Based on these conclusions, several strategic recommendations are proposed for relevant stakeholders. For the Deli Serdang Regency Government and the Regional Disaster Management Agency (BPBD), it is highly recommended that the resulting hazard map be used as a scientific basis for revising the Regional Spatial Plan (RTRW), particularly for controlling land-use conversion in the northern zone, and for prioritizing mitigation infrastructure development in the 11 high-hazard sub-districts. Furthermore, it is vital to disseminate these findings to the public to build community awareness and preparedness for disasters. For future researchers, this study can be expanded by incorporating socio-economic parameters to conduct a more comprehensive risk analysis or by performing extensive field validation to enhance the model's accuracy. Thus, this research not only fills a spatial information gap but also provides a practical tool for improved disaster management in Deli Serdang Regency.

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