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EVALUATION OF FLOOD SUSCEPTIBILITY MAPPING IN KEDAH WITH AHP AND GIS: A CASE STUDY OF KOTA SETAR AND PADANG TERAP, KEDAH MALAYSIA

Wan Nurnabila Imani[1], Ernieza Suhana Mokhtar[2*], Muhammad Hanif[3], Idrees Mohammed O.[4]

[1]*Faculty of Built Environment,*
UNIVERSITI TEKNOLOGI MARA, PERLIS BRANCH,
ARAU CAMPUS, MALAYSIA
[2]*Faculty of Built Environment,*
UNIVERSITI TEKNOLOGI MARA, PERAK BRANCH,
SERI ISKANDAR CAMPUS, MALAYSIA
[3]*Department of Geography,*
STATE UNIVERSITY OF PADANG, INDONESIA
[4]*Department of Surveying and Geoinformatics,*
UNIVERSITY OF ILORIN, NIGERIA

Abstract

Model estimations of flood susceptibility often face challenges in assigning appropriate weights to factors that contribute to flooding. This study focuses on evaluating flood-prone areas in Kota Setar and Padang Terap, Kedah, Malaysia, by applying optimum weights to proposed flood parameters using the Analytical Hierarchy Process (AHP) model integrated with a Geographic Information System (GIS). Physical features, including slope, elevation, topographic wetness index (TWI), and flow accumulation, were extracted using Interferometric Synthetic Aperture Radar (IFSAR) data, alongside land use and rainfall data. For validation, approximately 1,279 historical flood marks from the Department of Irrigation and Drainage (DID) were used. The resulting flood susceptibility map and historical flood data aligned well with an RMSE of 92.2% after weighted flood parameter integration. The most significant contributors to flood susceptibility were identified as slope (39%), land use (21%), rainfall (19%), and elevation (11%). The findings indicate that that optimizing parameters with weights improves susceptible area prediction for future flood mapping research using AHP and GIS.

Keywords: Analytical Hierarchy Process (AHP), GIS, Malaysia Flood Mapping, Weighted Overlay Analysis

[1] Corresponding author. Email: wanrnabilaimani@gmail.com

INTRODUCTION

Flood susceptibility is the most important component of early warning systems or strategies for preventing and mitigating flood impact (Dano et al., 2019). According to the Department of Irrigation and Drainage (DID), Kubang Pasu and Baling, Kedah had the highest number of floods in 2021, with 14 flood events reported (DID, 2020; 2022). DID released a 2023 report with infographic data showing that Kubang Pasu and Baling are frequently affected by floods, highlighting the urgent need for the government to implement more proactive and effective flood management strategies to mitigate the impact of future flooding events (DID, 2024). Although the government has allocated RM1.3 billion in the 12th Malaysia Plan (RMK12) to implement Flood Mitigation Plans (RTB) to minimize the impact of flood disasters in Kedah, the situation is getting worse due to developments near High-risk flood reservoir triggering flash floods, leading to the increasing number of flood victims (Bernama, 2022). The worsening flood situation pushed the authorities to continue monitor flood-prone areas, especially those near the riverbank (Zulkiffli, 2021). Several studies have been conducted to create a flood map (AlAli et al., 2023; Eslaminezhad et al., 2022; Narimani et al., 2021), focusing on identifying flood-prone areas and improving disaster management. However, due to the absence of proper preventive measures or the consideration of various parameters, inappropriate flood parameter selection for the flood-susceptible area estimation is still inaccurate (Tariq et al., 2022).

The flood susceptibility mapping relies on various condition parameters to characterise the physical characteristics of the area of interest. The flood susceptibility mapping relies on various condition parameters to characterise the physical characteristics of the area of interest. The AHP model, with appropriate weights and ranks for each parameter, is used to estimate flood-prone areas and significant flood parameters, while the integration of AHP and GIS (AHP-GIS) enhances the visualization of flood susceptibility mapping and the evaluation of flooding risks sensitivity (AlAli et al., 2023; Lappas & Kallioras, 2019; Nsangou et al., 2022; Msabi & Makonyo 2021; Swain et al., 2020). AHP provides a structured decision-making hierarchy utilizing a specified reference scale, taking into consideration the variables that influence decisions and the significance of decision points relative to these factors (Mabahwi & Nakamura, 2024). Most of the data used to be embedded in the AHP is elevation, Landsat 8 OLI, soil map, geological map, drainage density, flow accumulation (FA), land use, and soil type (Dano et al., 2019; Lappas & Kallioras, 2019; Nsangou et al., 2021). In another study, Tariq et al. (2022) flood susceptibility map was generated using six parameters (slope, elevation, distance from the stream, drainage density, flow accumulation, land use/land cover (LULC), soil and geology). According to Saaty (1988), a Consistency Ratio (CR) value of less than 0.10 indicates a reliable ranking and weighting of significant flood parameters. However, the study's information fails to fully capture the physical characteristics of areas susceptible to flooding. As a result, estimate and map the susceptible area for development planning to ensure informed decision-making and sustainable land use practices is necessary.

Due to inconsistency in the selection of the flood parameters in producing the susceptible flood map, the study aims to improve flood management by providing a clearer identification of flood-prone areas, which supports better mitigation strategies. The comprehensive insights from the study can help local authorities prioritize resources, improve land use planning, and develop targeted disaster preparedness measures, making it highly relevant for shaping policies and strategies to minimize flood risks, strengthen community resilience, and ensure effective long-term flood management.

RESEARCH METHODOLOGY

Figure 1a shows the study area of this research: the distribution of the historical flood marks recorded the flood events from 2010 until 2021 for the Padang Terap and Kota Setar, Kedah. Figure 1b displays a bar graph of district flood incidents from 2010 to 2021. From 2010 to 2021, numerous districts in Kedah faced persistent flooding, with the frequency of incidents rising annually and affecting all districts by 2020-2021. In 2024, Said et al. assessed flood vulnerability in Padang Terap district due to its long history of flooding, with recorded incidents dating back to 1937 and a noticeable increase in flood frequency between 2000 and 2010, during which the district suffered total losses amounting to RM16,615,439.00. Table 1 indicates the data used to accomplish the objectives of the study. Historical flood marks which were recorded in non-spatial data from the DID Malaysia (http://sprhin.water.gov.my) only in 2010-2021 was then converted to the spatial based on shapefile format (.shp) were used to identify the spatial distribution of the flooded area at Kedah, Malaysia. The data on elevation, slope, and TWI of the study area were created using the IFSAR-DEM (5-meter resolution) provided by Intermap Technologies Malaysia. The land use and rainfall data were obtained from PLANMalaysia. All were georeferenced and projected to Kertau (MRSO).

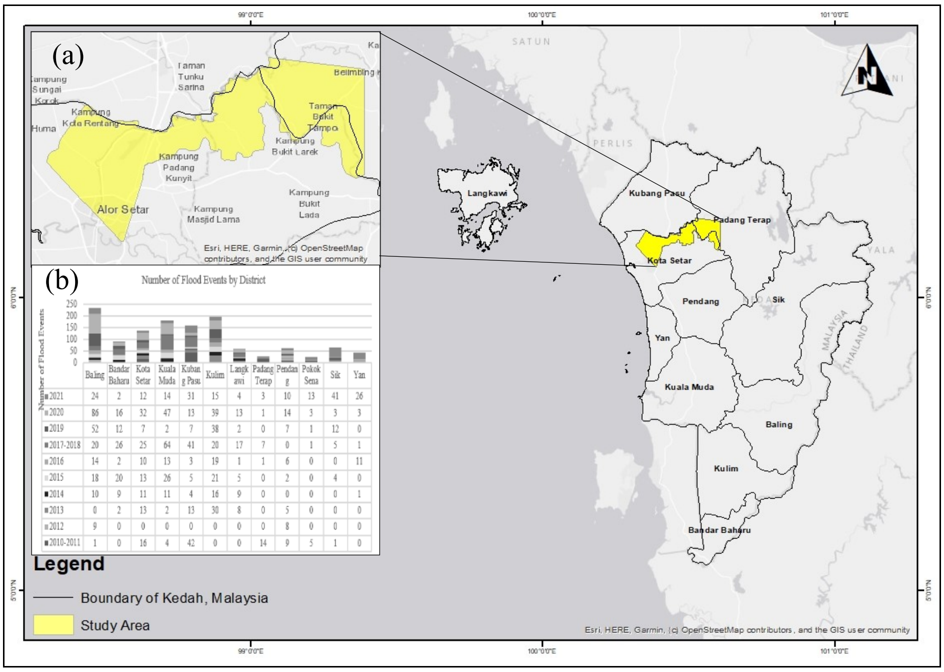

Figure 1: Map of Kedah. Study Area (a), Total of Flood Occurrences (b)
Source: Department Irrigation and Drainage (DID) Annual Report (2010-2022)

Table 1: Dataset of Study

Data Type	Date	Source	Scale/Resolution	Purpose
Historical flood mark	2010-2021	DID	Table with (x and y)	Validation of Results
IFSAR-DEM	2019	INTERMAP Technologies Malaysia	5 m, vertical accuracy ± 1 m	Topographic and hydrologic variables
Land-use	2019	PLANMalaysia	1:50,000	Land use
Rainfall	30 October – 4 November 2010	DID	Daily	Runoff

The elevation of the study area is determined in ranges between 0.185m to 290.974 m (Figure 2b). Most data used for hydraulic purposes, such as slope, flow accumulation, TWI, and elevation, were generated using the provided IFSAR DEM dataset. Figure 2a shows the slope map in degrees (°), which was generated from the DEM dataset with five classes ranging from 0° (green) to 64.4° (red). Figure 2c, which generates the flow accumulation based on the flow direction and catchment area, aids in comprehending the movement of water across the terrain. The higher the parameter value, the more susceptible the area is to flood because it shows the flow accumulation of the nearby pixels indicating the areas of run-off surface (Lappas & Kallioras, 2019). The ArcGIS environment prepares the TWI map by running the Raster Calculator (Nsangou et al., 2021). Figure 2d shows the TWI map where the class ratings range from 0 to 20.030 pixels. TWI levels are typically greater in situations near floodplains.

The land use map, another spatial dataset, falls into six categories: (i) agriculture, (ii) bare land, (iii) forest, (iv) impervious surfaces, (v) others, and (vi) water bodies (Figure 2e). To generate the cumulative rainfall map, the spatial interpolation of the Inverse distance weighted (IDW) model (González-álvarez et al., 2019) is generated using the points of the telemetry station with rainfall data volume provided by DID. Each of the rainfall data starting from October 30 until November 4, 2010, had been interpolated, showing the pattern of rainfall distribution (Figure 2f). The rainfall map is divided into different categories using the natural break (Jenks) method (Swain et al., 2020) and kernel density to identify areas with higher and lower flood risk within the study area. The process involved collecting spatial data, including flood marks, elevation, and slope which depicts the concentration of flood events, with higher density values indicating areas more vulnerable to flooding.

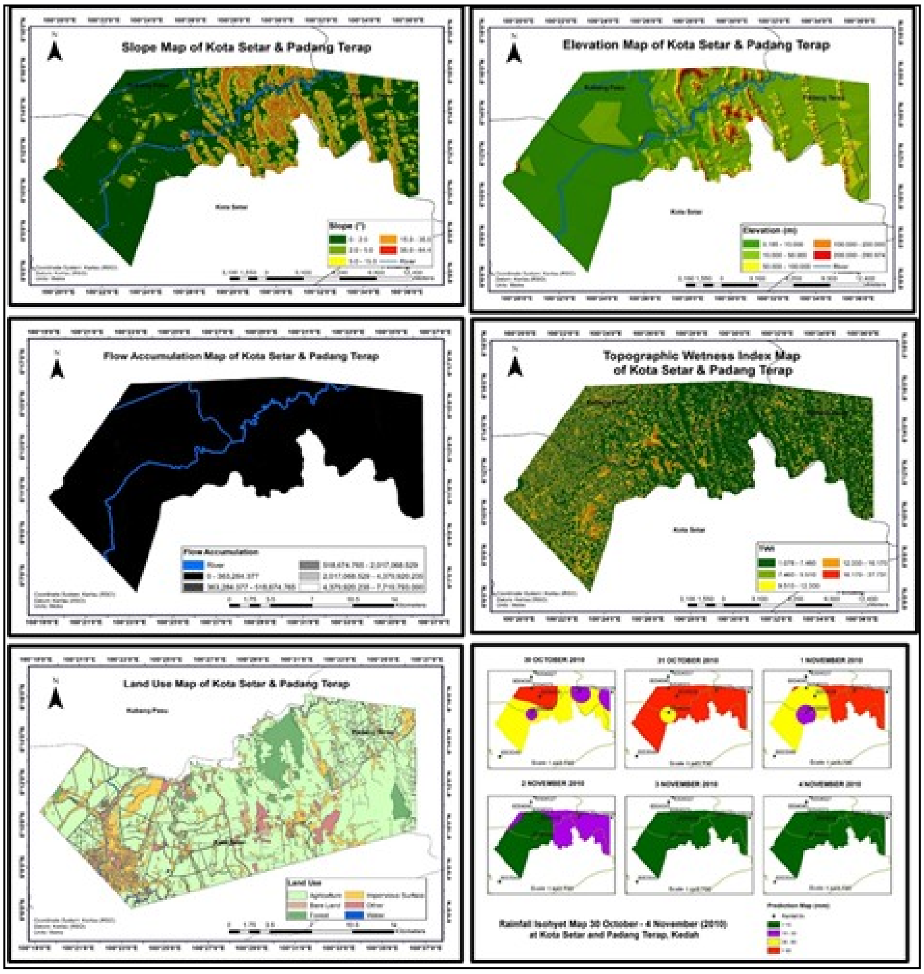

Figure 2: Slope Map (a), Elevation Map (b), Flow Accumulation (FA) (c), Topographic Wetness Index (TWI) Map (d), Land-use Map (e) and Rainfall Map (f)

This study used the Saaty (1988) approach, where the scale is 1 to 9, which indicates 1 is the least important and 9 is the most important. The relative rank of values in the AHP model is compared to determine the priority or importance of one element over another in pairwise comparisons (Table 2). Weights were assigned to all variables based on the authors' judgement and their relative significance, achieved through constructing a pairwise comparison matrix (Table 3). Subsequently, the scale weights were derived using an eigenvalue. The pairwise comparison matrix was then normalized using the weighted arithmetic mean method to produce the standard pairwise comparison matrix (Table 4) which conducted systematically to determine the weight of flood parameters (Das, 2019). It was calculated using a pairwise comparison matrix, applying a standardized rating scale.

Table 2: Pairwise Comparison Matrix Scale

Importance	Definition
1	Equally significant
2	Weak or slight
3	Moderately more significant
4	Moderate plus
5	Strongly more significant
6	Strong plus
7	Very strong more significant
8	Very, very strong more significant
9	Extremely more significant

Sources: Saaty, 1988

Table 3: Pairwise Comparison Matrix

Parameters	(A)	(B)	(C)	(D)	(E)	(F)
Slope (A)	1.00	2.00	3.00	4.00	5.00	7.00
Land use (B)	0.50	1.00	1.00	2.00	4.00	6.00
Rainfall (C)	0.33	1.00	1.00	2.00	3.00	5.00
Elevation (D)	0.25	0.50	0.50	1.00	2.00	3.00
TWI (E)	0.20	0.25	0.33	0.50	1.00	2.00
FA (F)	0.14	0.17	0.20	0.33	0.50	1.00
SUM	2.43	4.92	6.03	9.83	15.50	24.00

Source: Author's Calculation

Table 4: Normalized Factor Weights

Parameters	(A)	(B)	(C)	(D)	(E)	(F)	SUM	Criteria Weight
Slope (A)	0.41	0.41	0.50	0.41	0.32	0.29	2.34	0.39
Land use (B)	0.21	0.20	0.17	0.20	0.26	0.25	1.29	0.21
Rainfall (C)	0.14	0.20	0.17	0.20	0.19	0.21	1.11	0.19
Elevation (D)	0.10	0.10	0.08	0.10	0.13	0.13	0.64	0.11
TWI (E)	0.08	0.05	0.06	0.05	0.06	0.08	0.39	0.06
FA (F)	0.06	0.03	0.03	0.03	0.03	0.04	0.23	0.04
SUM	1.00	1.00	1.00	1.00	1.00	1.00	6.00	1.00

Source: Author's Calculation

The weighted overlay technique overlays several raster layers by giving the relative weights calculated using AHP to each raster layer according to their importance (Saaty, 1988). This study used the weighted overlay method (Narimani et al., 2021) to produce the flood susceptibility map. The previous study (Kaya & Derin, 2023) determined the relative importance of the weights, assigning them both externally and internally. The total of the external weights must be 100 and the internal weights are referred as the class values (Munier & Hontoria, 2021; Saaty, 1988). Root Mean Square Error (RMSE) is a statistical measure used to validate flood susceptibility mapping by comparing flood susceptibility maps generated from AHP with recorded flood mark data from recent flood marks (Mokhtar et al., 2017). The process involves calculating the differences between the predicted susceptibility values and the measured flood marks, squaring these differences to eliminate negative values, averaging the squared differences, and then taking the square root of this mean to obtain the RMSE. Lower RMSE values indicate a better fit between the predicted values and actual flood marks, suggesting that the mapping is reliable, while higher RMSE values indicate significant discrepancies, highlighting the need for model refinement (Eslaminezhad et al., 2022). Table 5 shows each column under a country's name references a specific study, indicating which parameters were used in that study.

Table 5: Flood's Parameters on Flood Susceptibility Mapping

Parameters	Korea	Greece	India	Tanzania	China
	Narimani et al. (2021)	**Lappas & Kallioras (2019)**	**Das (2019)**	**Msabi & Makonyo (2021)**	**Wang et al. (2019)**
Land use	✓	✓	✓	✓	✓
Slope	✓	✓	✓	✓	✓
Rainfall	✓	✓	✓		✓
Flow Accumulation	✓	✓	✓	✓	
TWI	✓	✓	✓		✓
Plan Curvature	✓				
Elevation	✓	✓	✓	✓	✓
Lithology					✓
NDVI					✓
Distance from the drainage network		✓	✓		✓
Drainage Network		✓			
Soil			✓		✓
TRI			✓		
Stream Power Index (SPI)					✓
Population Density					✓
Sewer System Density					✓

ANALYSIS AND DISCUSSION

Based on Table 6, the parameters are ranked based on their calculated weights and found that the highest weight was assigned to the slope (39%), and land-use

(21%), followed by rainfall (19%), elevation (11%), TWI (6%), and flow accumulation (4%) and additionally, the total weight is equal one. This study successfully achieved acceptable values for the CI and CR, which are CI = 0.02 and CR = 0.01, which are below the threshold, which is 0.1, indicating that the judgments were consistent, and the weights were acceptable (Dano, 2021). Higher weights indicate greater importance, establishing a hierarchy that reflects their contribution to flood susceptibility. In this study CI and CR are considered better compared to Lappas & Kallioras (2019), with the consistency of the threshold value being 0.058. The authors used similar flood parameters such as TWI, elevation, and distance from drainage, while the factors for geology, soil types, and flow accumulation. Historical flood marks indicate that most flood distribution marks occur in high-risk zones, while only a few are found in the yellow regional area, which is classified as moderate-risky. This study achieved a better accuracy rate of 92.2% in comparison to the previous study (Vojtek et al., 2021), which 70.9% of historical flood episodes aligned with the flood-susceptible mapping.

Table 6: Pairwise Comparison Matrix for Sub-Criteria of the Six Parameters

Criteria	Weight	Sub-criteria / Class	Pairwise Comparison Matrix	CR	Sub Weight
		0.0 - 2.0	1.00 4.00 5.00 6.00 8.00		0.504
		2.0 – 5.0	0.25 1.00 4.00 5.00 6.00		0.261
Slope	0.390	5.0 – 15.0	0.20 0.25 1.00 4.00 3.00	0.005	0.129
		15.0 – 35	0.17 0.20 0.25 1.00 2.00		0.063
		> 35	0.13 0.17 0.33 0.50 1.00		0.043
		Water bodies	1.00 2.00 4.00 5.00 6.00 7.00		0.410
		Impervious Surface	0.50 1.00 2.00 3.00 5.00 6.00		0.250
Land Use	0.210	Other	0.25 0.50 1.00 2.00 3.00 4.00	0.020	0.140
		Bare Land	0.20 0.33 0.50 1.00 2.00 3.00		0.090
		Agriculture	0.17 0.20 0.33 0.50 1.00 2.00		0.060
		Forest	0.14 0.17 0.25 0.33 0.50 1.00		0.040
		> 60	1.00 2.00 3.00 6.00		0.496
Rainfall	0.190	30.0 - 60.0	0.50 1.00 2.00 3.00	0.003	0.267
		10.0 - 30.0	0.33 0.50 1.00 2.00		0.154
		<10	0.17 0.33 0.50 1.00		0.083
		0.185-10.000	1.00 4.00 6.00 7.00 9.00		0.519
		10.000-50.000	0.25 1.00 4.00 6.00 7.00	0.005	0.259
Elevation	0.110	50.000-100.000	0.17 0.25 1.00 4.00 5.00		0.131
		100.000-200.000	0.14 0.17 0.25 1.00 2.00		0.055
		200.000-290.974	0.11 0.14 0.20 0.50 1.00		0.036
		16.170 - 27.131	1.00 4.00 5.00 6.00 7.00		0.487
		12.330 - 16.170	0.25 1.00 4.00 5.00 7.00		0.263

TWI	0.060	9.510 - 12.330	0.20	0.25	1.00	4.00	5.00	0.005	0.143
		7.460 - 9.510	0.17	0.20	0.25	1.00	3.00		0.069
		1.078 - 7.460	0.14	0.14	0.20	0.33	1.00		0.038
Flow Accumulation	0.040	4,379,920.235 - 7,719,793.000	1.00	4.00	5.00	6.00	7.00	0.011	0.495
		2,017,068.529 - 4,379,920.235	0.25	1.00	4.00	5.00	6.00		0.262
		518,674.765 - 2,017,068.529	0.20	0.25	1.00	3.00	5.00		0.137
		363,284.377 - 518,674.765	0.17	0.20	0.33	1.00	2.00		0.064
		0 - 363,284	0.14	0.17	0.20	0.50	1.00		0.042
								Consistency Index	0.02
								Consistency Ratio	0.01

Source: Author's Calculation

Figure 3 shows the flood susceptibility map with 3D elevation and the percentage of areas classified as flood-vulnerable of Kota Setar and Padang Terap, Kedah, Malaysia. The finding shows that area coverage for the 'Moderate' potentially susceptible area is 69.553 km^2 (34.860%), which includes Kampung Bukit, Kampung Padang Lalang, Kampung Pokok Machang, Kampung Rambutan, Kampung Seberang Paya Empa, and Kampung Tanjung Putus. As for the TWI, the areas with moderate susceptibility have slight degree slopes, resulting in some water accumulation. The difference between moderate and low-risk areas is that the flow accumulation in moderate-risk areas causes more water to collect during heavy rainfall. As for the area coverage for flood susceptibility classes, the 'High' susceptible level covers a surface of 49.274% of the study area, mainly belonging to the flat area. Based on DID flood reports, over the past eleven years, flooding has occurred frequently in seven (7) places. Floods have inundated Kampung Alor Senjaya seven times, Kampung Alor Gunong six times, Kampung Bukit Pinang, Taman Nakishah, and Taman Uda four times, and two times occurred at Taman Sireh and Kampung Derang. These seven places had the highest frequency among the other areas where floods in the past year had inundated. As a result, Kampung Alor Senjaya and Kampung Alor Gunong are highly susceptible to future flood occurrences. Kampung Alor Senjaya and Kampung Alor Gunong used the impervious surface on land. As mentioned in the literature review by Loumi & Redjem (2021) the bare lands and impervious surfaces increase the surface run-off rate, which has a high possibility of flooding. Table 7 shows the flood-prone region impacted, categorized by the classes with the lowest to highest area coverage in the study area: very low (more tangible), low (moderately affected), and very high (Highly affected).

Table 7: Flood Risk Area Coverage and Place Affected.

Flood Susceptibility	Area (Km^2)	Area (%)
Very High	0.056	0.028
High	98.311	49.274
Moderate	69.553	34.860
Low	31.270	15.673
Very Low	0.327	0.164

Source: Author's Calculation

The flood susceptibility maps validated using the 90 historical flood marks shows a very good agreement between the flood susceptibility map and the historical flood marks, with 92.22% falling within the 'High' class. The 'Low' and 'Very Low' susceptibility areas are characterized by higher slopes and elevations, significantly reducing the flood-prone area. As supported by the literature, areas with higher vegetation tend to have a reduced probability of flooding (Saleh et al., 2022). In these regions, water runoff is facilitated by steeper slopes, while lower TWI values and minimal flow accumulation further decrease the likelihood of flooding. The 'Moderate' susceptibility areas are associated with sloped surfaces, typically ranging between 5° and 15° (Vojtek et al, 2021). These areas are more likely to accumulate water during heavy rainfall due to moderate flow accumulation and land use, such as agriculture and bare land (Vojtek et al, 2021; Loumi & Redjem, 2021). The higher flow accumulation causes more water to collect. However, the moderate slopes still allow for some water drainage, reducing the likelihood of extensive flooding compared to the high-susceptibility areas.

The 'Very High' and 'High' susceptibility levels have the lowest slope and elevation, the land is dominated by impervious surfaces and the rainfall is high intensity. Elevation is a key conditioning factor for floods, where the lowest elevation classes (0.185–10.000 m) significantly increase flood susceptibility. Additionally, the areas with the highest TWI values tend to be more susceptible to flooding, particularly in the TWI classes of 9.510– 12.330, 7.460–9.510, and 1.078–7.460. This indicates that TWI is a crucial factor in triggering floods in the study area. Heavy rainfall, particularly one with a cumulative 60 mm or more, also plays a significant role in increasing the flood risk. The lowest slope classes (0–2°) are the most prone to flooding due to the water's static position in flat areas, as observed in Tella & Balogun (2020).

In contrast to Vojtek et al. (2021) where only 70.9% of flood markings agreed with the "Very High" and "High" susceptibility categories, this research shows higher agreement between historical flood marks and the flood susceptibility map. The findings indicate locations in Kota Setar and Padang Terap that are most susceptible to flooding, which serves as a basis for more focused flood control measures. This data can be used by local government entities to set priorities for flood control and drainage system upgrades.

CONCLUSION

The flood susceptibility map for Kota Setar and Padang Terap was created using an AHP model integrated with GIS based on assigning a numerical weight to each flood parameter. The flood susceptibility indices were computed utilizing the weighted overlay technique, and subsequently, the flood susceptibility map was generated within the ArcGIS environment. The flood susceptibility map categorized the research area into distinct categories of susceptibility, namely: very high, high, moderate, low, and very low. According to the finding of the study, approximately 49% of the study area is classified as highly susceptible to flooding. This is mostly located at flat terrain, low elevation, and heavy rainfall. Based on the data, it can be concluded that Kampung Alor Senjaya and Kampung Alor Gunong are highly vulnerable to future flooding. These two locations are situated in Kota Setar, near the Kedah River.

Conversely, approximately 16% is categorized as having low and extremely low susceptibility levels (Figure 3). The flood susceptibility mapping was validated by comparing it to historical flood marks, and the verification process demonstrated an accuracy of 92%. The validated outcome demonstrated a strong correlation between the historical flood mark and the susceptibility map generated for the area. Hence, the results of this study are confirmed to be applicable for assessing flood risk, implementing measures to reduce it, and guiding future urban development in the region.

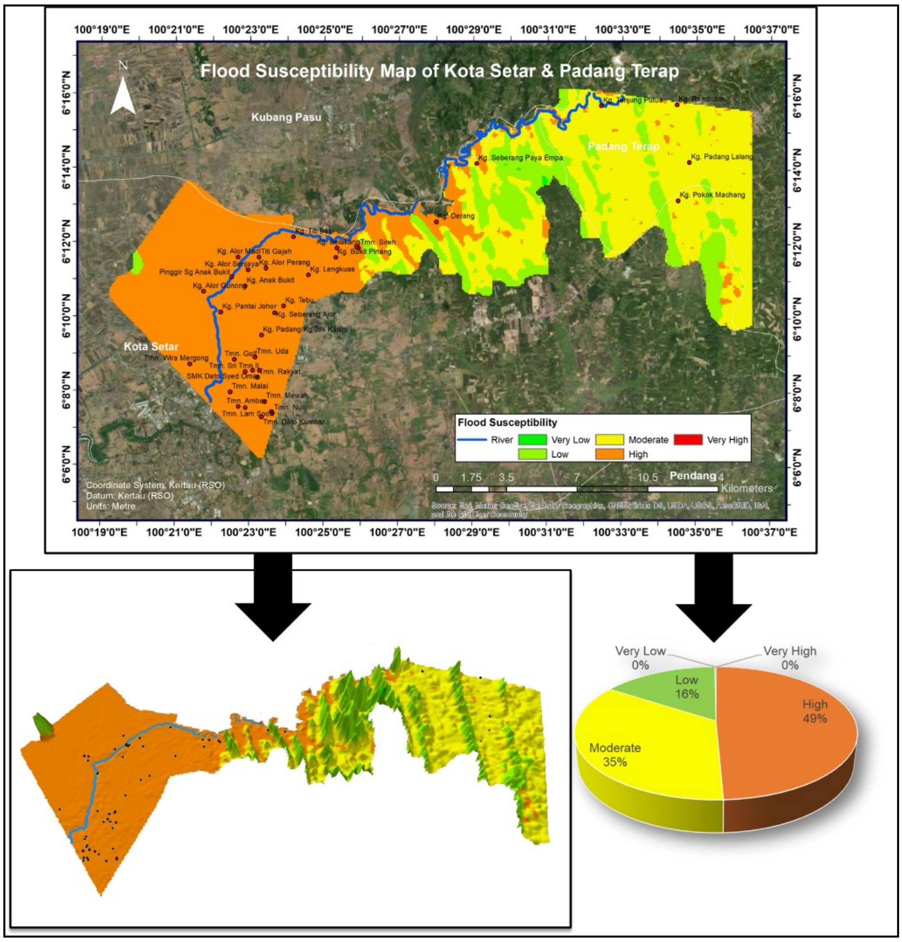

Figure 3: Overall Flood Susceptibility Mapping

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