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SPATIAL ASSESSMENT OF FLOOD-PRONE AREAS IN MELAKA TENGAH, MALAYSIA, USING THE ANALYTIC HIERARCHY PROCESS AND GIS

**Nur Haidah Binti Jaafar¹, Zakiah Ponrahono², Aisyah Abu Bakar³,
Fatiah Abdul Aziz⁴, Kamil Muhammad Kafi⁵**

*^{1,2,3} Department of Environmental Management,
FACULTY OF FORESTRY AND ENVIRONMENT,
UNIVERSITI PUTRA MALAYSIA*

*⁴ Faculty of Industrial Management,
UNIVERSITI MALAYSIA PAHANG AL-SULTAN ABDULLAH*

*⁵ Department of Urban and Regional Planning,
Faculty of Earth and Environmental Sciences,
BAYERO UNIVERSITY KANO*

Abstract

Driven by population growth and tourism, urban expansion in Melaka Tengah has converted natural landscapes into built-up areas, escalating regional flood risks. This study evaluates flood susceptibility using a Geographic Information System (GIS) -based Analytic Hierarchy Process (AHP), assessing five core factors: land-use change, rainfall, drainage density, slope, and elevation. Results indicate a 6% increase in built-up areas from 2014 to 2023, with rainfall identified as the primary risk driver (31% weight). Cross-referenced with local 2035 planning blueprints, this spatial framework offers empirical insights for sustainable risk mitigation and municipal urban governance.

Keywords: Land Use Changes, Flood-Prone Areas, Analytic Hierarchy Process (AHP), Geographic Information System (GIS)

² Corresponding author. Email: zakh@upm.edu.my

INTRODUCTION

Melaka City, a UNESCO World Heritage Site and popular tourist destination, is vulnerable to heavy rainfall and flash floods in dense built-up regions (Bahari et al., 2023; Khairi, 2021). The Smart Melaka Blueprint 2035 predicts an 86.5% urbanisation rate and a 40% population increase to 1.54 million by 2035 (State Government of Melaka & Malaysian Industry Government Group for High Technology, 2024). This progressive expansion of impervious surfaces alters catchment hydrology by reducing soil infiltration, disrupting natural runoff pathways, accelerating peak discharge, and overwhelming existing drainage networks (Abdulkareem et al., 2018; Ahmed et al., 2024). The Department of Irrigation and Drainage (JPS) empirical records show that past flood hotspots are in low-lying, intensively developed metropolitan areas. GIS-based multi-criteria flood susceptibility mapping is widely used worldwide, but existing frameworks categorise land use broadly and rarely bridge the empirical gap between tourism-driven land dynamics and watershed-scale hydrological models. (Giofandi et al., 2024; Widaningrum et al., 2020). Tourism-driven urban growth and GIS-AHP flood mapping have been reported in Melaka Tengah, but no integrated spatial tool has been developed to predict how this land conversion will interact with monsoonal rainfall regimes to change flood limits and influence local spatial planning (Giofandi et al., 2024).

LITERATURE REVIEW

Characteristics and Causative Factors of Flooding

In Malaysia, flooding reflects the interaction of seasonal monsoon rainfall, catchment characteristics, land-use change, and drainage capacity. Monsoon floods are prolonged and predictable during the Northeast Monsoon, while flash floods occur rapidly in heavily developed areas and are associated with sharp water-level rise, high flow velocity, and substantial debris loads (Rosmadi et al., 2024, 2023). In urban settings, flood behaviour is further intensified by rapid urbanisation, poor drainage, land clearance, and climate-linked increases in rainfall intensity, which tend to increase both flood frequency and inundation extent (Ibrahim et al., 2024a; Mahmoud & Gan, 2018; Saad et al., 2024). Malaysian flood-susceptibility studies therefore commonly use variables such as rainfall, slope, drainage network or density, land use, soil type, elevation, TWI, and flow accumulation because these capture the main hydrological and terrain controls on where flooding occurs (Elsheikh et al., 2015a; Ibrahim et al., 2024b).

Methodological Framework: GIS and the Analytic Hierarchy Process (AHP)

In practice, GIS is widely used to delineate flood-prone areas using factors such as Land Use and Land Cover (LULC), drainage density, geology,

geomorphology, soil, normalised difference vegetation index (NDVI), slope and topography witness index (TWI) (Blakime et al., 2024; Bokhari et al., 2024; Subraelu et al., 2023). In flood studies, AHP is frequently combined with GIS because it enables the transparent, replicable weighting and integration of multiple spatial factors into composite flood susceptibility maps (Zhran et al., 2024). In Malaysia, GIS-AHP approaches have proven effective in different settings: for example, Rasu et al., (2023) mapped flood risk in Maran, Pahang, using a limited set of parameters (digital elevation model, soil type, land use, topography and rainfall) and showed that low slopes, clay-rich soils, sparse vegetation and high rainfall substantially increase flood susceptibility.

Research Significance and Objectives

Multi-criteria, GIS-based flood susceptibility models incorporating expert-derived weights are widely utilised to synthesise rainfall, drainage density, slope, elevation, and land use into composite risk maps across diverse physical and urban landscapes (Dano et al., 2019a; Lin et al., 2019; Sahraei et al., 2023). Many modern economic or environmental assessments of localised flood impacts use descriptive statistics or micro-scale hydrodynamic simulations instead of integrating multiple physical and anthropogenic drivers into a spatial decision-making matrix (Ibrahim et al., 2024c; Ouma & Omai, 2023). Despite the development of expert-weighted multi-criteria GIS models, tourism-driven built-up expansion and watershed-based flood susceptibility in Melaka Tengah have not been explicitly linked, despite similar approaches being used in other regions for land-use planning and risk zoning (Dano et al., 2019b; Ibrahim et al., 2024b; Mariappan et al., 2019). Five factors were selected because they capture Malaysia's main flood controls, while other variables were omitted because the literature treats them as secondary, context-specific, or data-dependent refinements rather than core drivers, with rainfall repeatedly identified as the main trigger, drainage density as a runoff concentrator, slope and elevation as controls on flow and ponding, and land use as a proxy for urbanisation and infiltration loss (Ashfaq et al., 2025; Elsheikh et al., 2015b; Imani et al., 2025a). Thus, this research identify, evaluate, and map flood-prone areas in Melaka Tengah, Malaysia, by integrating the AHP and GIS based on selected flood-conditioning factors.

RESEARCH METHODOLOGY

Study area and description

The study was conducted in Melaka Tengah District on the southwest coast of Peninsular Malaysia, one of three districts in the state alongside Alor Gajah and Jasin. The district comprises a heterogeneous mix of dense urban fabric,

residential suburbs, industrial zones, tourism facilities and remnant agricultural and vegetated areas.

Materials and data sources

This work examines five flood-conditioning parameters, LULC change, monsoonal rainfall, drainage density, topographic slope, and elevation, to maintain model parsimony and eliminate multicollinearity. The homogenous soil structure in Melaka Tengah's coastal plain precluded secondary factors like lithology and soil capacity. Instead, the chosen elements capture the crucial connections between monsoonal weather cycles, topography restrictions, and rapid, tourism-driven urban surface alterations. **Table 1** summarises the datasets, processing steps and roles of each component in the flood susceptibility analysis.

Table 1: Materials and data sources for flood-conditioning factors in Melaka Tengah

Component	Description
Flood-conditioning framework	Five factors were used: land use and land cover, elevation, slope, rainfall and drainage density, combining geospatial, hydrometeorological and planning data for Melaka Tengah.
Terrain and drainage	A 30 m United States Geological Survey (USGS) DEM was processed (reprojected, clipped, sink-filled) to derive elevation (five classes, -14 to 181 m), slope (very gentle to very steep) and drainage density (total stream length per unit area).
Rainfall	Station data in and around Melaka were converted to multi-year average monthly values and interpolated with Inverse Distance Weighting (IDW) to produce a 30 m rainfall surface.
Land use and land cover	Landsat 8 imagery (2014, 2018, 2023) was classified (maximum likelihood) into water, barren land, vegetation, and built-up, resampled to 30 m, clipped to Melaka Tengah, and validated against plans and high-resolution imagery.
Contextual documents	Strategic plans and national statistics informed the selection of factors and the interpretation of flood-susceptibility results.

Data Processing and Accuracy Assessment of the Flood Susceptibility Model

All values were resampled to 30 m resolution and reprojected to the Kertau Rectified Skew Orthomorphic (RSO) Malaya Meter system (EPSG: 3168) for GIS modelling in ArcGIS Pro using the Spatial Analyst extension. Line Density was used to compute drainage density from Department of Irrigation and Drainage stream vectors, while slope (degrees) was derived from a pre-processed 30 m DEM. Inverse Distance Weighting was used to create continuous precipitation surfaces from point data. Human effect was captured by classifying Landsat 8 data (2014, 2018, 2023) into built-up, vegetation, water, and barren land inputs. Using a confusion (error) matrix, stratified random reference points for each land-cover class were validated against high-resolution reference imagery and ground-truth data to calculate the overall accuracy, Kappa coefficient, and producer and user accuracy. The classification accuracy of 87.5%

and Kappa coefficient of 0.83 supported the reliability of the land-use inputs for flood susceptibility modelling.

The resulting flood susceptibility map was then validated against two independent reference datasets: historical flood records from the DID and official evacuation records for the study area. Using a spatial overlay procedure in ArcGIS Pro, documented past flood events from the DID registers were converted into point features, overlaid onto the classified susceptibility map, and intersected with the underlying risk classes. The majority of these points fell within the "High" and "Very High" risk corridors, confirming that the model correctly identified genuinely flood-prone locations. The same procedure was applied to the official evacuation records. Because evacuations occur only during severe flooding, these locations serve as on-the-ground indicators of significant flood impact, and they, too, aligned predominantly with the high-risk zones. This strong spatial agreement confirms that the map reliably reflects the actual pattern of chronic inundation within the study area.

Analytic Hierarchy Process

To establish objective priority weights for the five flood-conditioning factors, the Analytic Hierarchy Process (AHP) was utilised, drawing on input from a panel of seven local experts in urban planning, hydrology, and municipal infrastructure management. Their pairwise comparisons were grounded in historical municipal flood records and extensive professional field experience across Melaka, ensuring contextually accurate and robust model weighting. The AHP was introduced by Saaty (1987) and was used to derive weights for the five flood-conditioning factors, land use and land cover, rainfall, elevation, slope, and drainage density, based on their relative influence on flood susceptibility in Melaka Tengah. In AHP, expert judgements on the importance of each factor are expressed through pairwise comparisons and assembled in a square comparison matrix $A = [a_{ij}]$, where a_{ij} denotes the importance of factor i relative to factor j on Saaty's 1–9 scale (1 = equal importance, 9 = extreme importance; Saaty, 1980, 2008). The consolidated pairwise comparison matrix derived from the expert panel is presented below:

Table 2: Pairwise Comparison Matrix (A)

Criteria	Rainfall	Drainage Density	LULC	Slope	Elevation
Rainfall	1	1	3	2	2
Drainage Density	1	1	2	1	1
LULC	1/3	1/2	1	1	1
Slope	1/2	1	1	1	1
Elevation	1/2	1	1	1	1

The priority weight vector $w = (w_1, \dots, w_n)^T$ is obtained as the normalised principal eigenvector of A , satisfying $Aw = \lambda_{max}w$, where λ_{max} is the maximum eigenvalue. This yielded the following weights: rainfall (0.31), drainage density (0.22), elevation (0.17), slope (0.17), and land use/land cover (0.13). Consistency of the judgements was evaluated using the Consistency Index $CI = (\lambda_{max} - n)/(n - 1)$ and the Consistency Ratio $CR = CI/RI$, where n is the number of factors and RI is the Random Index. For $n = 5$ ($RI = 1.12$), the analysis produced $\lambda_{max} = 5.25$, $CI = 0.063$, and $CR = 0.056$. As $CR < 0.10$, the criterion for acceptable consistency was satisfied in the present study. Each factor was represented as a 30 m raster layer in a common projection and reclassified into ordered susceptibility classes. The final AHP-derived weights were integrated into a Geographic Information System using a weighted linear combination $S = \sum_{i=1}^5 w_i F_i$, where F_i are the standardised factor maps, to produce a continuous flood susceptibility index that was subsequently classified into five classes (very low, low, moderate, high, and very high) for mapping and interpretation.

ANALYSIS AND DISCUSSION

Land Use Change

Between 2014 and 2023, built-up areas in Melaka Tengah expanded from 64.33% to 70.33% (199.81–218.48 km²). This growth displaced water bodies (declining from 2.45% to 1.21%), barren land (3.40% to 1.06%), and vegetation (29.64% to 27.41%). Concentrated around rapidly urbanizing mukims like Bandar Melaka, Batu Berendam, and Bukit Katil, these transitions mirror trends in growing global cities where population growth drives green space loss and heightened flood exposure (Handayani et al., 2020; Rendana et al., 2025a; Weday et al., 2023).

Flood Causative Factors

Between 2014 and 2023, built-up areas in Melaka Tengah expanded from 64.33% to 70.33% (199.81–218.48 km²), displacing water bodies (2.45% to 1.21%), barren land (3.40% to 1.06%), and vegetation (29.64% to 27.41%). Concentrated in rapidly developing mukims such as Bandar Melaka, Batu Berendam, and Bukit Katil, these infrastructure and residential conversions mirror broader global trends in which urban population growth drives green space degradation and heightened flood exposure (Kafi & Ponrahono, 2026). The selection of causative factors is justified by the region's physical and developmental characteristics, where intense monsoonal rainfall, low-lying terrain, gentle slopes, expanding built-up areas, and modified drainage systems collectively drive localised flooding. Integrating these parameters effectively captures the hydrological, topographic, and human-induced dynamics essential for comprehensive risk assessment (see Figure 1 to Figure 4), as they determine spatial risk patterns and

improve identification accuracy (Kafi et al., 2025). This approach helps identify and delineate risk-prone zones in Melaka.

Causative Factors Influencing Flood Risk

Figure 5 presents the AHP weights derived from expert consensus, which prioritize rainfall (31%) as the primary driver of flood risk in Melaka, followed by drainage density (22%) due to its control over runoff concentration. Reflecting Melaka's flat terrain, elevation (17%) and slope (17%) exert moderate influence, while land use (13%) contributes the least through impervious surfaces. Compared to regional GIS-AHP benchmarks, such as Kota Setar and Padang Terap (land use: 21%) or Batu Pahat (land cover: 11%), Melaka's land-use weight occupies the lower end of the regional literature spectrum, emphasizing regional precipitation and drainage networks over surface characteristics (Imani et al., 2025b; Zainudin et al., 2026).

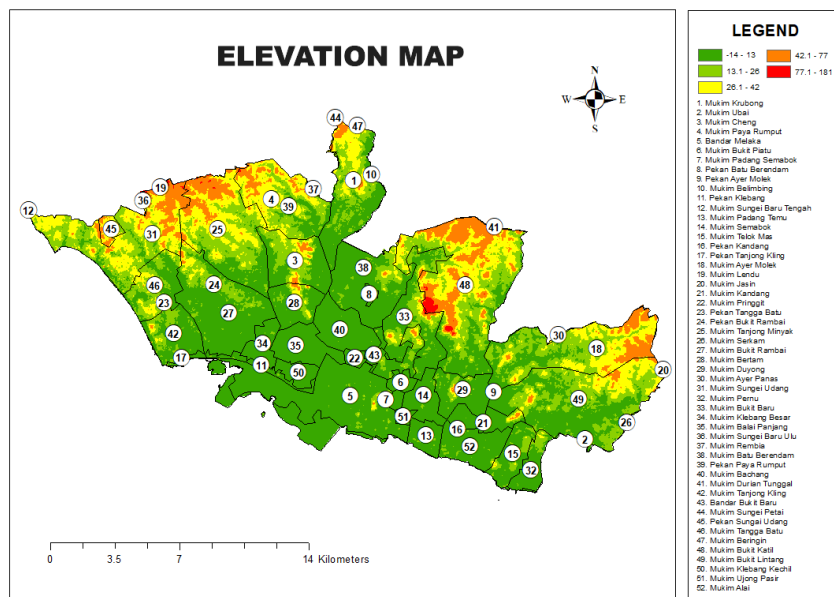


Figure 1: Elevation Map

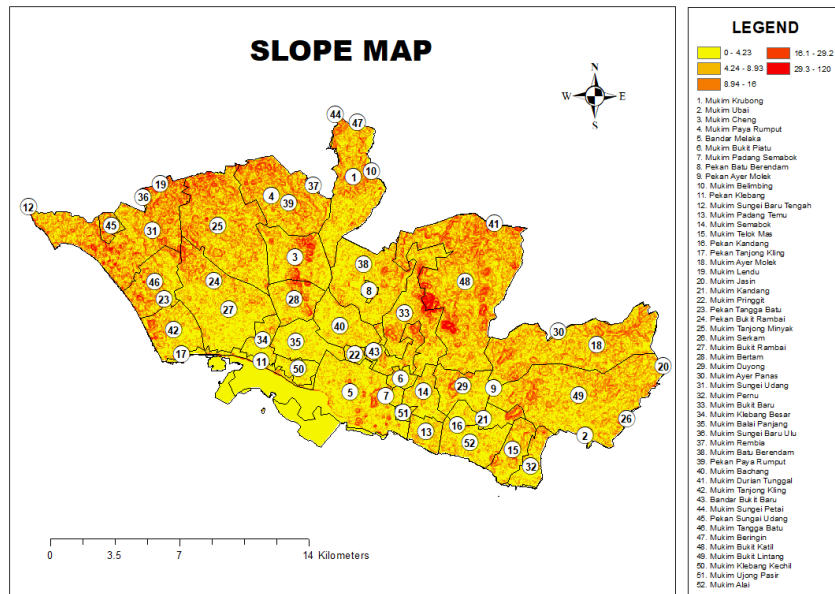


Figure 2: Slope Map

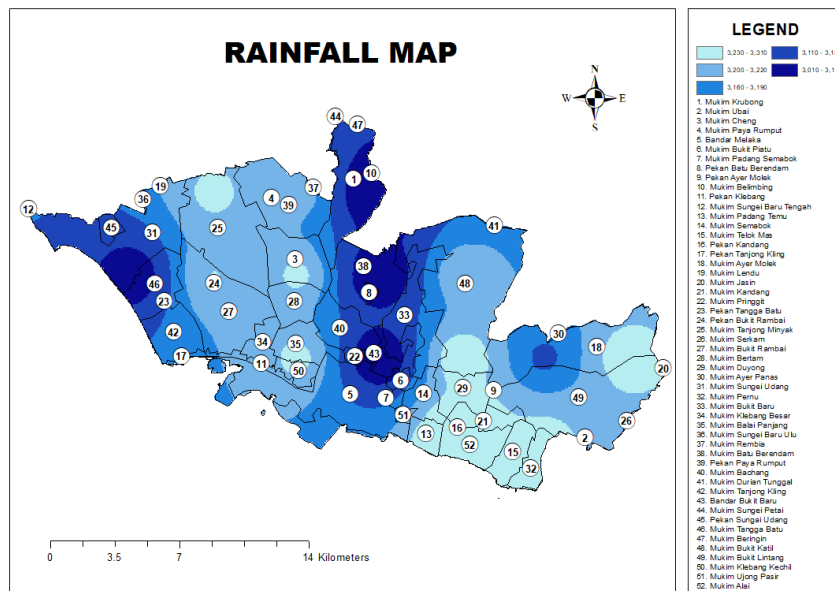


Figure 3: Rainfall Map

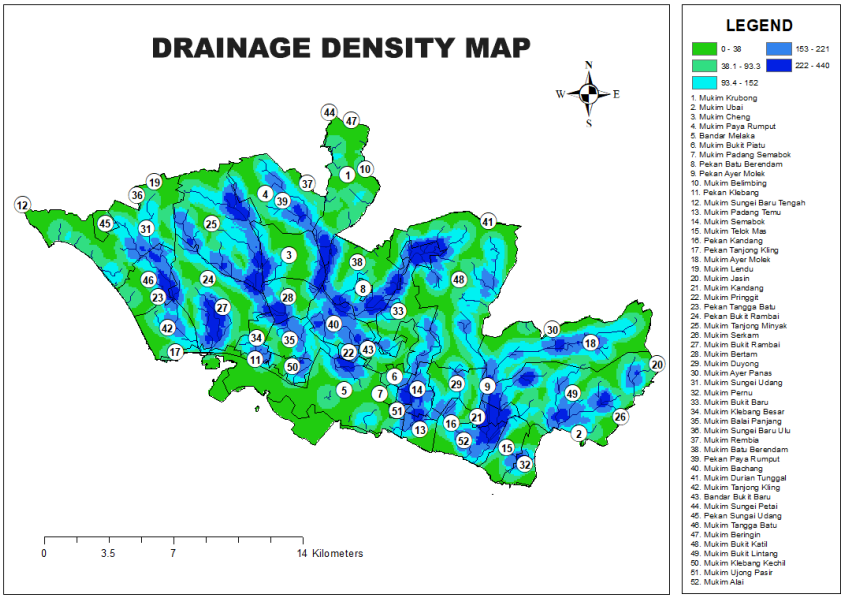


Figure 4: Drainage Density Map

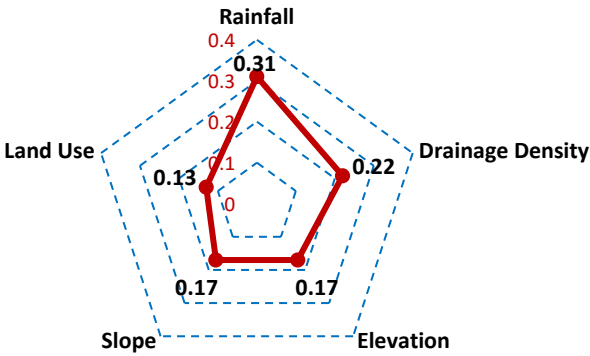


Figure 5: Assigned weights of flood causative factors used in determining flood risk zones

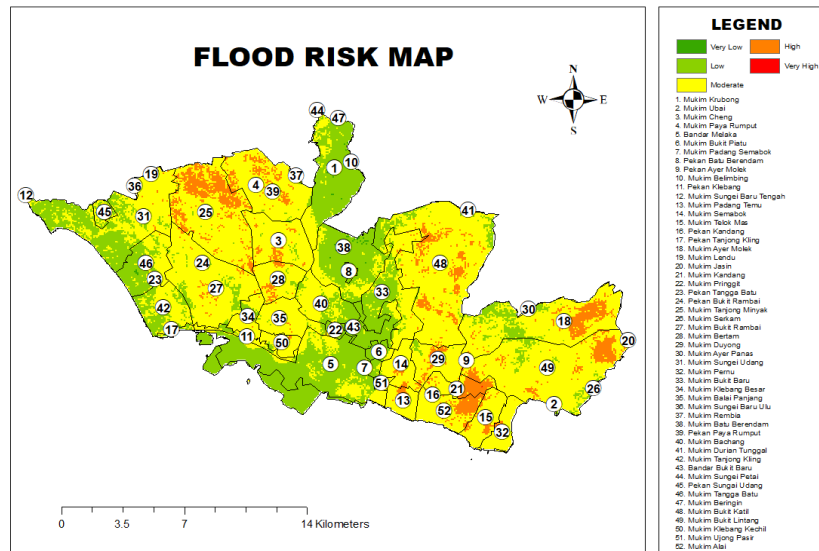


Figure 6: Flood risk maps derived from AHP analysis: (a) distribution of all risk levels (very low to very high)

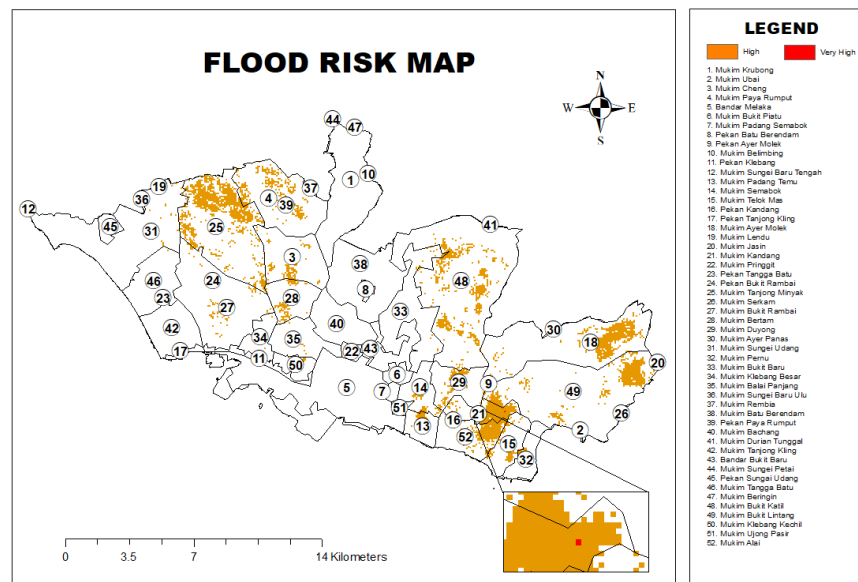


Figure 7: Flood risk maps derived from AHP analysis delineation of high and very high flood risk areas.

Flood risk mapping and Spatial Planning Implications

Flood susceptibility in the research area is primarily moderate-risk, covering 250.32 km² (64.9%) according to the AHP assessment. This means heavy weather might cause flooding across most of the region. The very low-risk class covers only 0.27 km² (0.07%), whereas the very high-risk zone is a minuscule 0.0063 km² (**Figure 6**). In addition, 30.24 km² (7.80%) is identified as high risk, highlighting locations that may require targeted mitigation measures, drainage upgrades and stricter land-use controls (**Figure 7**). This distribution is comparable to other AHP and multicriteria studies where moderate classes dominate, with smaller but critical high-risk pockets that align with historical events (Abdrabo et al., 2020a; Rendana et al., 2025b; Souissi et al., 2020a; Vashist & Singh, 2024).

From a spatial planning perspective, these risk classifications provide an empirical basis for targeted zoning interventions. High and very-high risk zones, typically low-lying, densely drained urban areas adjacent to river corridors, warrant priority allocation for structural enhancements, strict redevelopment constraints, and strategic emergency shelter zoning, mirroring global urban resilience frameworks (Abdrabo et al., 2020b; Rendana et al., 2025c; Rivera & Aguirre, 2025). The selected high-risk zones (30.24 km²) support the enforcement of development and plot-ratio limits in the Historic Melaka City Council Local Plan 2035 (*Rancangan Tempatan MBMB 2035*). The moderate-risk class (64.9%) dominates Melaka Tengah, warranting policy attention given Malaysia's 2,500 mm mean annual precipitation. Very high-risk locations are statistically negligible. (Kia et al., 2012). Due to hydrological extremes, moderate-risk zones require proactive spatial design, structural drainage modifications, community readiness, and early warning frameworks to mitigate flood vulnerabilities (Kafi & Ponrahono, 2025; Tang, 2019), validating the utility of AHP and multicriteria models as reliable tools for baseline risk delineation (Abdrabo et al., 2023; Kafi & Ponrahono, 2024). Translating these findings into practice, high and very-high risk zones warrant restrictive zoning controls, stringent development restrictions, priority drainage upgrading, and dedicated emergency-shelter planning, while the dominant moderate-risk class calls for climate-resilient land-use policy, such as sustainable urban drainage systems and preserved green-blue infrastructure, and low-risk zones can absorb higher-density growth away from vulnerable corridors

Data Limitations, Recommendations, and Regional

The proposed GIS–AHP framework is constrained by its reliance on open-source 30 m DEMs, gridded rainfall, and land-use layers, which may omit fine-scale terrain and urban drainage features, thereby affecting susceptibility precision (Swain et al., 2020; Zhu & Chen, 2024). Lack of hydrological records and flood

inventories limits quantitative validation, making outputs decision-support tools rather than exact predictions. This flexible multi-criteria procedure has been successfully adopted internationally in dry, tropical, and data-scarce catchments by calibrating factor selection and expert weights to local conditions (Kader et al., 2024; Pimenta et al., 2025; Souissi et al., 2020b).

CONCLUSION

By integrating LULC, rainfall, elevation, slope, and drainage density within a GIS-AHP framework, this study demonstrates that Melaka Tengah's flood susceptibility is primarily driven by intense precipitation and high drainage density, with expanding urban impervious surfaces creating significant areas of vulnerability. Despite localised data limitations, these mapped susceptibility patterns strongly align with historical records, providing a practical, scalable decision-support tool to guide climate-resilient, heritage-sensitive urban planning and drainage investments in comparable coastal cities.

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