

## Enhancing Urban Flood Vulnerability Mapping with Multi-Criteria Decision Analysis

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### ABSTRACT

*Urbanization, climate change, and hydrological variability have significantly heightened flood risks in metropolitan areas, particularly in low-lying and highly developed regions. The increasing frequency and severity of urban floods necessitate advanced spatial decision-making techniques for effective flood vulnerability mapping. This study applies Multi-Criteria Decision Analysis (MCDA) integrated with Geographic Information Systems (GIS) to assess urban flood susceptibility in Taman Sri Muda, Shah Alam, Malaysia, an area frequently affected by flash floods. The study aims to identify key factors contributing to urban flooding, develop a spatial flood hazard model, and propose mitigation strategies. Six critical parameters including land use and land cover, distance from the main channel, drainage density, rainfall distribution, elevation and slope were reclassified and assigned weights. The weighted overlay technique was employed to generate the flood vulnerability map, which was validated using historical flood records. The results indicate that 37.8% of the study area is classified as high flood risk, while 24.8% falls under moderate risk, 27.6% under low risk, and 9.8% under very low risk. The findings provide valuable insights for urban planners, emergency response teams, and policymakers in developing flood mitigation strategies, improving drainage infrastructure, and enhancing flood resilience. This study underscores the necessity for integrating real-time hydrological data and machine learning models to further improve flood prediction accuracy in future research.*

*Keywords: Urban flooding; MCDA; geospatial; vulnerability mapping*

### INTRODUCTION

Natural disasters arise from the interaction between natural hazards (e.g., earthquakes, floods) and human activities. Weaknesses in natural disaster management lead to

financial, structural, and human losses. Natural disasters such as earthquakes can result in tsunamis, droughts can lead to famine and disease, and floods can cause property damage and loss of life, among other consequences (Mohd et al. 2006; Sadeka et al. 2023).

Furthermore, climate change, which has shown an increase in the frequency of extreme rainfall, is also one of the major factors exacerbating the flooding issue (Pandey et al. 2010; Gao et al. 2023). Unpredictable flood events have adverse effects on road infrastructure, especially in low-lying areas (Doocy et al. 2013; Maranzoni et al. 2023). Floods and flash floods in Malaysia often happen during periods of continuous heavy rainfall (Table 1). Floods during the monsoon season frequently occur in the East Coast states of Peninsular Malaysia such as Kelantan, Terengganu, and Pahang, as well as in West Sarawak (Buslima et al. 2018; Maqtan et al. 2022).

Floods are a major global disaster, frequently affecting Malaysia and other countries. It is an unavoidable phenomenon that occurs periodically in all rivers and natural drainage systems. Flood events adversely impact both natural and human systems by degrading environmental resources, disrupting ecological functions, and triggering substantial economic costs, infrastructure damage, and

public health risks. According to the Intergovernmental Panel on Climate Change (IPCC) (2007), there are many factors that contribute to the occurrence of flood disasters besides the rise in sea levels and increased development in flood plains.

In response to these multidimensional challenges, spatial decision-support techniques such as Multi-Criteria Decision Analysis (MCDA) have emerged as effective tools for flood risk assessment. MCDA enables the systematic evaluation of complex environmental conditions by integrating diverse spatial parameters, such as land use/land cover (LULC), topography, rainfall intensity, and hydrological features, into a composite vulnerability index. When embedded within Geographic Information Systems (GIS), MCDA enhances the capacity to visualize and prioritize risk zones in urban landscapes. This integrative framework is especially valuable for flood-prone urban areas like Taman Sri Muda, where decisions must consider both physical terrain and human settlement patterns.

TABLE 1. Flood history in Malaysia

No.	Year	Flood Event	Impact and Consequences
1	1996	Severe flooding due to Tropical Storm Greg in Keningau, Sabah.	<ul style="list-style-type: none"> <li>• 241 casualties.</li> <li>• Infrastructure and property damages exceeding USD 97.8 million.</li> <li>• Thousands of homes were destroyed.</li> </ul>
2	2000	Flooding induced by heavy rainfall frequently affects Kelantan, Terengganu and the northern regions of Peninsular Malaysia.	<ul style="list-style-type: none"> <li>• 15 fatalities in Kelantan and Terengganu.</li> <li>• Over 10,000 individuals were displaced across northern Peninsular Malaysia.</li> </ul>
3	2001	Tropical Storm Vamei triggered floods in eastern Malaysia.	<ul style="list-style-type: none"> <li>• Flooding and landslides impacted the region.</li> <li>• Five casualties were recorded.</li> <li>• Estimated damages worth USD 3.6 million.</li> </ul>
4	April & Oct 2002	Flash flooding in Kuala Lumpur	<ul style="list-style-type: none"> <li>• Severe flash floods affected Kuala Lumpur.</li> </ul>
5	Oct 2003	Widespread flooding in northwestern Peninsular Malaysia	<ul style="list-style-type: none"> <li>• Extensive flood damage was reported across Kedah, Penang, and northern Perak.</li> </ul>
6	Dec 2006 & Jan 2007	Major flooding event in Johor	<ul style="list-style-type: none"> <li>• 18 lives lost.</li> <li>• Economic losses estimated at USD 489 million.</li> </ul>
7	2008	Recurring flood event in Johor due to monsoon rainfall	<ul style="list-style-type: none"> <li>• 28 casualties recorded.</li> <li>• Infrastructure and economic damages amounting to USD 21.19 million.</li> </ul>
8	2010	Severe flooding in Kedah and Perlis	<ul style="list-style-type: none"> <li>• Four fatalities.</li> <li>• 45,000 hectares of agricultural land affected.</li> <li>• More than 50,000 residents displaced</li> </ul>
9	2013	Flash flood in Cameron Highlands due to dam water release	<ul style="list-style-type: none"> <li>• Three lives lost.</li> <li>• 80 houses and 100 vehicles damaged.</li> </ul>
10	Dec 2014 & Jan 2015	Catastrophic flood event affecting multiple states in Peninsular Malaysia	<ul style="list-style-type: none"> <li>• Kelantan, Terengganu, Pahang, Perak, Sabah, Negeri Sembilan, Johor, Perlis, Kedah, and Sarawak were impacted</li> <li>• Over 200,000 people were affected with 21 casualties.</li> <li>• Estimated damages surpassing RM 1 billion.</li> </ul>
11	May 2016	Flash floods occurred in Kuala Lumpur and Selangor	<ul style="list-style-type: none"> <li>• Severe flooding disrupted four major roads in Kuala Lumpur.</li> <li>• 15 cars submerged and hundreds of vehicles stranded.</li> <li>• Over 300 evacuees affected in Dengkil, Selangor.</li> </ul>

Source: Buslima et al. (2018)

The Malaysian Medical Relief Society (MERCY) states that rapid urbanization in floodplains, including Kuala Lumpur, Penang and Sarawak, along with upstream development in hilly areas, has increased the exposure of many regions to hazardous flash floods (MERCY 2014). When an urbanised area's natural and drainage systems are unable to handle the amount of precipitation and runoff discharge, urban flooding results (Wan Mohtar et al. 2020).

Flood incidents in the Klang Valley area, especially in Selangor, are considered unexpected, with most areas being inundated and main roads being closed (Othman et al. 2024). Therefore, Taman Sri Muda, Shah Alam, was selected as the case study due to its severe flash flood disaster in December 2021, which resulted in widespread property damage, displacement, and loss of life. Despite repeated flooding episodes, this area remains underrepresented in high-resolution spatial flood risk assessments, particularly those integrating GIS-based MCDA. Most existing studies on urban flooding in Malaysia focus on broader river basins or regional flood models, often overlooking localized urban flash flood dynamics in highly developed townships such as Taman Sri Muda. This reveals a critical knowledge gap in understanding how compound geospatial variables interact to shape vulnerability at the sub-district level. Hence, this study aims to fill that gap by providing a spatially explicit flood vulnerability map using an MCDA approach tailored to the unique geomorphological and infrastructural context of Taman Sri Muda.

## FLOOD AT SHAH ALAM

Shah Alam, the capital of Selangor, is among Malaysia's fastest-growing cities (Khailani et al. 2013; Sukereman et al. 2024). Shah Alam, situated downstream in the Klang River Basin, faces significant environmental challenges such as air and water pollution, environmental degradation, and the encroachment of human settlements into river floodplains. Despite being a relatively well-planned and organized city, rapid industrialization has intensified pressure on the Klang River Basin, which encompasses Kuala Lumpur, Shah Alam, Petaling Jaya, and Klang-Malaysia's most densely populated region (Khailani et al. 2013).

Since 1971, Shah Alam has experienced several major floods, with the 2007 flood causing substantial economic losses estimated at USD 28.6 million. The city receives an annual rainfall of 2,500–4,000 mm (Leeonis et al. 2024),

primarily during the northeast monsoon season (November to March) and the southwest monsoon season (late May to September). The northeast monsoon serves as the primary rainy season, during which convective thunderstorms are prevalent (Leeonis et al. 2024). These storms produce short but intense rainfall, overwhelming the drainage system and contributing to flash flood occurrences.

Flash floods can be classified as floods caused by local heavy forest, floods caused by upper river flow, and floods caused by high tides associated with storm surges. Intense rainfall within a short period, i.e., less than 6 hours, can trigger flash floods (Suparta et al. 2014; Wan Mohtar et al. 2020). Floods due to heavy rainfall in urban areas are caused by inadequate or poor drainage. Floods caused by upper river flow are due to high runoff from upstream and the effects of high tides at river mouths.

This case study focuses on urban areas experiencing flash flood disasters and aims to demonstrate the capability of GIS analysis in identifying topographic factors and land cover related to floods, floodplain mapping, mitigation, and flood control in Malaysia. The purpose of this study is also to explain the use of GIS in flood management efforts for preparedness, mitigation, and disaster response, and to formulate ongoing efforts to develop GIS-based decision support systems for the Klang Valley area, specifically in Taman Sri Muda, Shah Alam.

## STUDY AREA

This case study was conducted in Taman Sri Muda, Shah Alam (Figure 1). Taman Sri Muda, a major township in Section 25, Shah Alam, has witnessed multiple flood events, notably the severe 2021 flash flood. With over 9,000 residential units spanning 58,475 hectares (Muhamad Azizi & Teriman, 2023), its low-lying topography and proximity to the Klang River exacerbate flood risks. This makes it a critical case study for flood vulnerability assessment.

Among the buildings and educational institutions found in this area are Apartment Andorra, Pangsapuri Taman Damai, Tabika Kemas Sri Kilat, and Sekolah Kebangsaan Taman Sri Muda. This location is situated near the Klang River and experienced floods on December 25, 1995. A total of 38,812 residents were affected by the severe flooding that hit the area. At the end of the year 2021, this area was struck by flash floods, resulting in significant damage and causing substantial losses (Othman & Abdul Tharim, 2023).

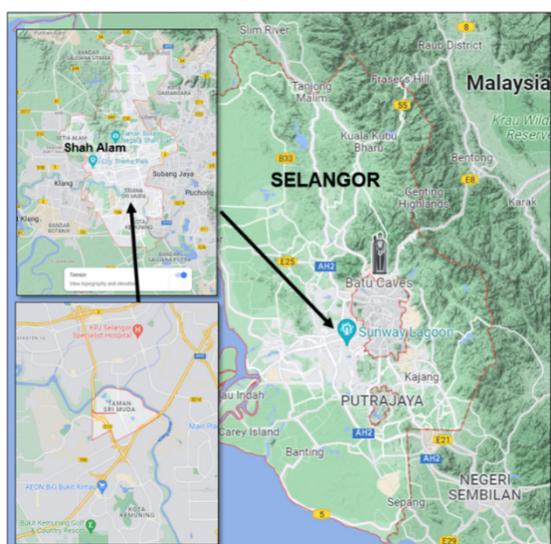


FIGURE 1. Map of Taman Sri Muda, Selangor

## METHODOLOGY

This study utilizes data from government institutions, research publications, and library archives. It is including secondary data, including LULC information, distance from the channel, drainage density, rainfall distribution, elevation and slope from different time periods. Rainfall data were obtained from the Department of Irrigation and Drainage (JPS) for the years 2016 to 2021, covering key events including the December 2021 flash flood. The Inverse Distance Weighting (IDW) method was used to interpolate these data for spatial analysis. LULC data were based on the imagery from Department of Survey and Mapping Malaysia (JUPEM) from year 2020, reflecting the most recent urban patterns before the flood event. The Digital Elevation Model (DEM), with a 0.5-meter resolution, was also sourced from JUPEM and derived from Interferometric Synthetic Aperture Radar (IfSAR) data collected in 2020, allowing for detailed terrain analysis. For validation, historical flood extent data up to 2023 were used, including overlays from official records and remote sensing outputs to assess model accuracy.

Land use and topography data were processed using ArcGIS and Global Mapper. Thematic maps were generated through raster reclassification and vector overlays. The Inverse Distance Weighting (IDW) method was applied for rainfall interpolation, while the stream network was delineated using the Hydrology Toolbox in ArcGIS. A DEM was utilized to extract slope and elevation data, ensuring high accuracy in terrain representation. Furthermore, MCDA was utilized for this analysis, and the Taman Sri Muda area was categorized into four classes according to flood vulnerability: “High”, “Moderate”,

“Low”, and “Very Low”. Figure 2 illustrates the flowchart of the study process implemented to fulfil the stated objectives.

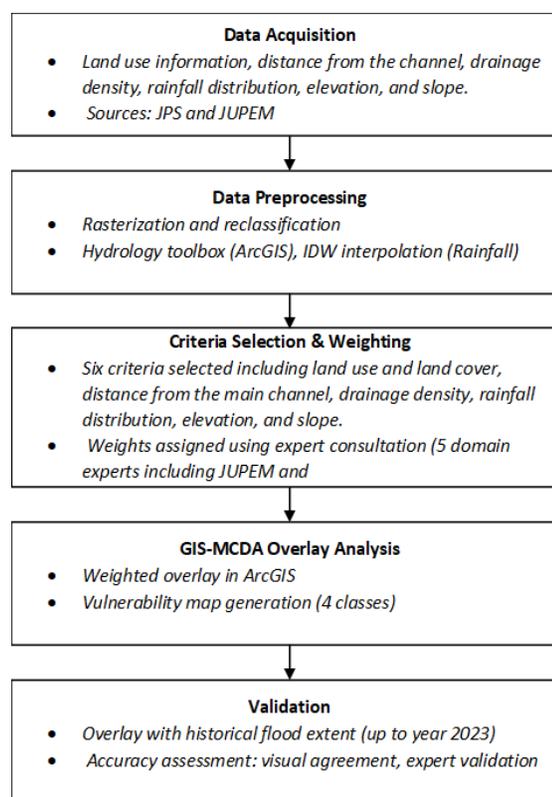


FIGURE 2. Flowchart of the study process implemented to fulfil the stated objectives.

The validation process involved a panel of five subject-matter experts, comprising three academic hydrologists from Universiti Kebangsaan Malaysia, one from Universiti Kuala Lumpur and one from JUPEM. These experts reviewed the weighted criteria, the classified vulnerability map, and provided feedback during a structured validation session. Historical flood data until the December 2023 event was overlaid to assess spatial agreement with the vulnerability zones. While quantitative metrics such as kappa statistics were not applied, spatial agreement was observed to be high in known flood-affected zones, supporting the model’s predictive validity.

## IMAGE CLASSIFICATION

The study utilized SPOT 7 satellite imagery, which provides a spatial resolution of 1.5 meters in panchromatic mode and 6 meters in multispectral mode. These resolutions allowed for relatively detailed land cover classification, particularly in distinguishing urban, vegetation, and water bodies. This image classification technique relies on

spectral reflectance values, assuming that the training data follow a normal distribution (Behanzin et al. 2015). The hybrid image classification approach effectively incorporates additional information into the classification process. The images will be categorized into four classes: agricultural land and shrubs, built-up areas, fallow land, and rivers and lakes.

## MULTI-CRITERIA DECISION ANALYSIS (MCDA)

According to Abo-Taha et al. (2022), GIS-MCDA is a combination of geographic data and the transformation of various preference (value judgements) to obtain essential information for decision-making. When making decisions to assess climate change and disaster vulnerability, parametric techniques are useful. Although parametric approaches have existed for several decades, MCDA has been strongly linked with these approaches. There are many uncertainties in the indicators for assessing flood vulnerability in social, economic, and environmental aspects. Clear output is produced by systematically reducing subjective uncertainty through expert-informed weighting in the MCDA process.

Meyer et al. (2009) developed a multi-criteria method for flood risk assessment that considers all aspects of ecological, social, and economic vulnerability (Li et al. 2022). When evaluating economic losses and analyzing flood disasters, the multi-criteria approach is highly recommended, especially in metropolitan areas, due to factors such as high population density, diverse economic activities, valuable properties, and infrastructure (Kubal et al. 2009; Moreira et al. 2021).

The multi-criteria approach has the potential to reduce costs and time (Siddique et al. Ologunorisa, 2004; Moreira et al. 2021). Therefore, this study employs a GIS-based MCDA approach specifically tailored to assess flash flood vulnerability, which is prevalent in the study area. Flash floods are typically characterized by short-duration, high-intensity rainfall events, compounded by rapid runoff, minimal infiltration, and poor urban drainage. The selected criteria, slope, LULC, drainage density, rainfall distribution, distance from the main channel, and elevation, are particularly relevant in flash flood contexts where terrain steepness, impervious surfaces, and proximity to channels critically influence the speed and volume of surface water accumulation (Heywood et al. 1993; Moreira et al. 2021).

While some of these criteria may overlap with those used in riverine or coastal flood assessments, their relative weights and influence would differ due to the distinct temporal and spatial dynamics of other flood types. Hence, this study's criteria set and weight assignments are uniquely justified for flash flood modeling in rapidly urbanizing, low-lying environments such as Taman Sri Muda.

## CRITERIA FOR FLOOD VULNERABILITY

Previous studies have consistently identified six critical criteria for flood vulnerability mapping: LULC, distance from the main channel, drainage density, rainfall distribution, elevation, and slope (Heywood et al. 1993; Bapulu & Sinha, 2006; Moreira et al. 2021; Hagos et al. 2022). These parameters collectively capture both topographic and hydrological characteristics that influence flood susceptibility across diverse geographic settings.

### LAND USE / LAND COVER (LULC)

LULC maps are important parameters for flood vulnerability mapping (Rashidiyan & Rahimzadegan, 2024). The impact of land use on debris flow, infiltration rates, and the interaction between surface and groundwater is significant (Osman et al. 2023). Shrubland and vegetated areas have higher absorption rates, whereas developed environments and swampy areas exhibit higher surface runoff rates.

LULC is a crucial factor that significantly affects the quantity of surface runoff and recharge events. For example, urban and industrial areas have more impermeable surfaces compared to agricultural area. On the other hand, agricultural areas are less vulnerable to flooding (Rashidiyan & Rahimzadegan, 2024).

A substantial part of the study area is comprised of built-up areas, while fallow land is dispersed throughout. Water bodies occupy a minimal portion, primarily in the form of a reservoir located in the northern part of the town. The LULC map for Taman Sri Muda was reclassified into three categories: (i) canals, rivers and lakes, (ii) built-up areas and (iii) vacant land. These categories were assigned weights of 3 (moderate), 2 (low) and 1 (very low), respectively (Figure 3).

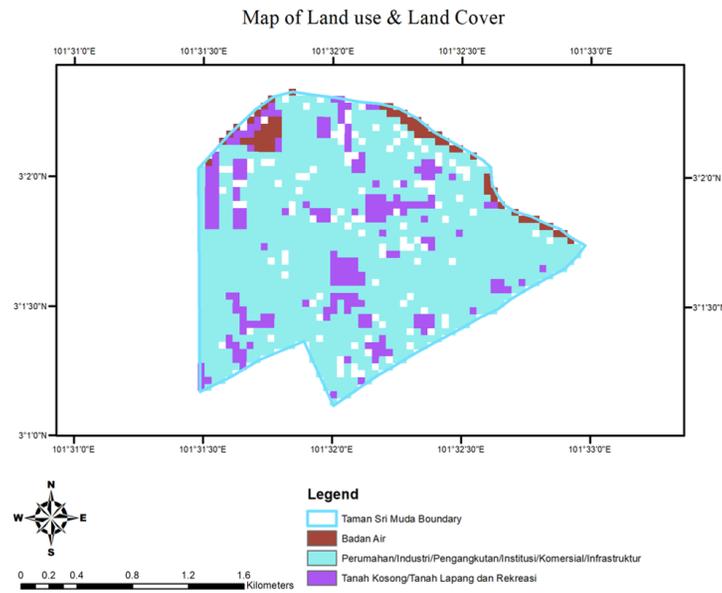


FIGURE 3. Reclassified map: LULC

### DISTANCE FROM MAIN CHANNEL

Flood risk is higher in areas adjacent to the main river channels and decreases with increasing distance (Kiss et al. 2021). Areas around the river are more severely affected during floods. This criterion involves measuring the linear distance from a specific location to the main river channel or watercourse. Proximity to the main channel is a key factor in flood vulnerability. Areas close to the main channel are more likely to experience flooding during periods of increased water flow, such as heavy rain or snowmelt. GIS performs buffer analysis to determine zones based on the distance from the main channel. Buffers are

created around the main channels, and the distance from these buffers is used as a criterion to assess flood vulnerability.

The Klang River is the main river in this study area. It flows from the north and has a few tributaries in the western part of the area. The Klang River has been mapped using satellite images and topographic maps. Multiple ring buffers have been created based on the distance from the river channel, and these buffers have been divided into three classes: high (distance less than 500m), moderate (distance less than 1000m), and very low (distance exceeding 1500m) (Figure 4).

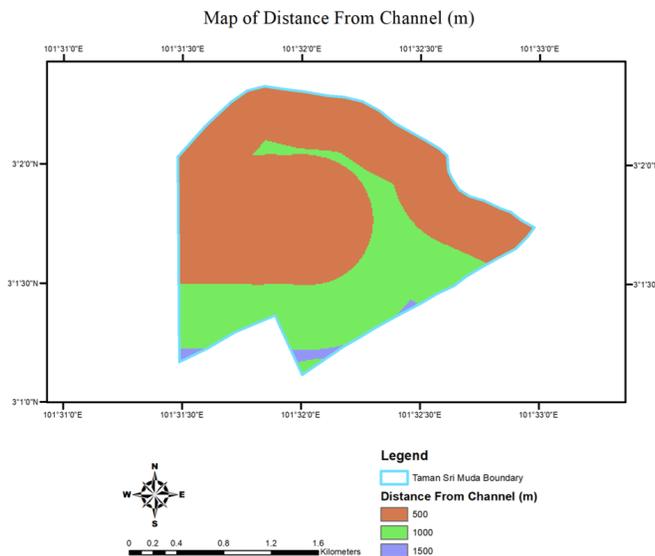


FIGURE 4. Reclassified map: Distance from main channel

## DRAINAGE DENSITY

Drainage density is a measure of the spacing between rivers (Osman & Das et al. 2023). Drainage density reflects the geology and climate of the basin. Basins underlain by permeable material have low drainage density, whereas basins underlain by weak and impermeable materials have high drainage density (Nnaji et al. 2024). For similar geology and slope angles, humid areas tend to have low density due to thick vegetation growth that promotes infiltration. Dry areas will have higher densities in the same geology.

Higher drainage density values indicate a high concentration of rivers. High drainage density often signifies an efficient drainage system, facilitating the movement of water from the area. This can reduce the likelihood of flooding during heavy rain or other precipitation events. In GIS, data on the spacing between rivers, river flow, and artificial drainage channels are combined with other relevant layers such as land use, soil type, slope, and rainfall data. This integration enables a comprehensive assessment of flood vulnerability.

The drainage density map in Taman Sri Muda town is classified into four categories based on flood hazard guidelines as follows: very low (0-0.71), low (0.72-1.4), moderate (1.5-2.1), and high (2.2-2.8), with respective weights assigned as 1, 2, 3, and 4. This map was generated from spatial analysis within ArcGIS. The analysis used is line density analysis for the river areas (Figure 5).

The classification thresholds for each criterion were determined through a combination of literature review and expert validation. For drainage density, class intervals were adapted from Behanzin et al. (2015) and modified based on local hydrological characteristics in Taman Sri Muda. Slope classification followed guidelines from Moreira et al. (2021), where urban flood susceptibility was highest in areas with slopes below 2%. Rainfall, elevation, and land use classes were reclassified to match hydrologically relevant thresholds validated by five domain experts from JUPEM and academic hydrology institutions. This ensured that all inputs used in the weighted overlay maintained both theoretical relevance and site-specific applicability.

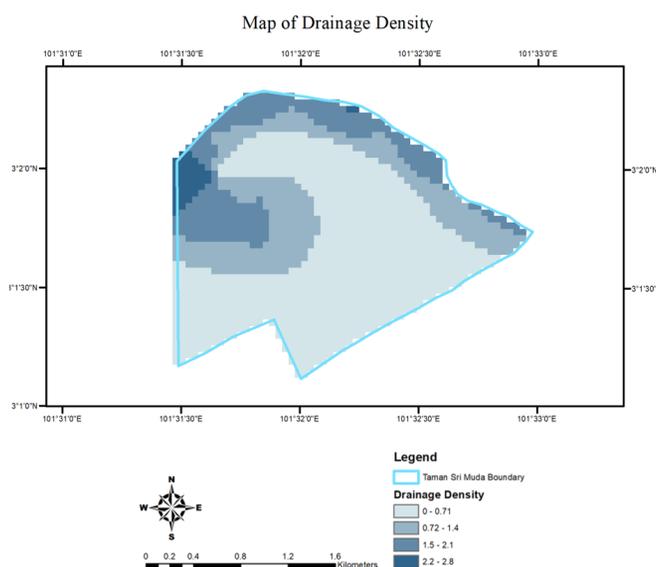


FIGURE 5. Reclassified map: Drainage density

## RAINFALL DISTRIBUTION

Rainfall is a critical factor in triggering floods. Flood events occur when increased surface runoff, driven by escalating rainfall, exceeds the capacity of river channels to accommodate the additional water load (Wei et al. 2024). GIS integrates historical spatial data and current rainfall patterns obtained from meteorological stations or remote sensing. This data is essential for understanding precipitation patterns in the study area. Rainfall data is analyzed over

time to identify patterns and changes. Temporal analysis helps assess rainy seasons and detect periods of increased flood risk. GIS tools aid in analyzing the spatial distribution of rainfall.

Some areas may be more vulnerable to heavy rainfall due to local topography or geographical features. This spatial information contributes to identifying areas with higher flood vulnerability. GIS enables scenario analysis by allowing decision-makers to simulate the effects of different rainfall scenarios on flood vulnerability. This aids

in planning adaptation strategies to reduce flood risk. Essentially, rainfall in MCDA based on GIS for flood vulnerability involves the integration, analysis, and visualization of spatial rainfall data along with other relevant criteria.

Rainfall in the study area increases towards the southwest. Rainfall data was collected from three rainfall stations located in Sri Muda, Kampung Jawa, and Taman Desa Kemuning. This rainfall map was prepared using spatial interpolation IDW in ArcGIS software. The rainfall map was categorized into four classes: very low rainfall (1,101–1,195 mm), low rainfall (1,196–1,289 mm), moderate rainfall (1,290–1,382 mm), and high rainfall (1,383–1,476 mm). The very low rainfall category was assigned the lowest weight of 1, while the high rainfall category received the highest weight of 4. The maximum rainfall is observed in the southwest part of Taman Sri Muda (Figure 6).

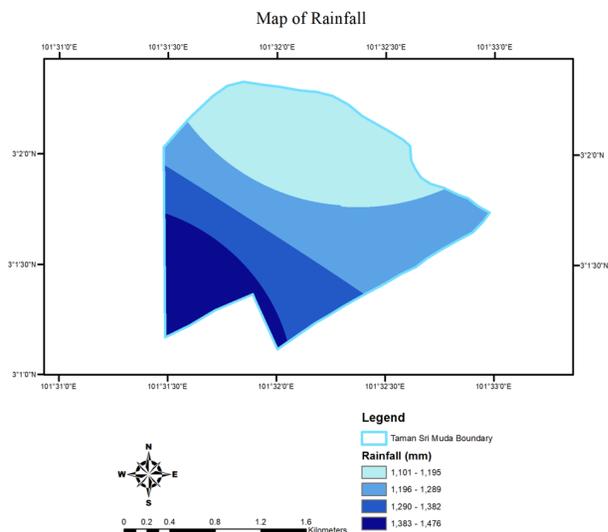


FIGURE 6. Reclassified map: Rainfall

### ELEVATION

Height criteria are crucial in identifying flood-prone areas as they control the direction of runoff and water level depth (Leta & Adugna, 2023). Elevation also influences flood conditions. There is continuous surface water flow from high-elevation areas to low-elevation areas. Low-lying flat areas are more prone to severe flooding compared to high-elevation areas. GIS incorporates elevation data to understand the topography of an area. DEM or other elevation datasets can be used to represent varying elevations across the landscape.

Elevation data aids in long-term planning by considering potential changes in sea levels and landscape

changes. Elevation in MCDA based on GIS for flood vulnerability involves the integration and analysis of elevation data to assess topographic features and identify areas at different risk levels. This information is crucial for making informed decisions in flood risk management.

This area has a nearly uniform (flat) elevation. There are only a few elevated areas in the southwest part of the study area. The elevation map was created using IfSAR. Based on flood hazard guidelines, the elevation map was reclassified into four classes: high (less than 5m), moderate (6-7m), low (8-10m), and very low (20-200m). Areas with low elevation are assigned the highest weight of 4 (most prone to flooding), while areas with high elevation are assigned the lowest weight (Figure 7).

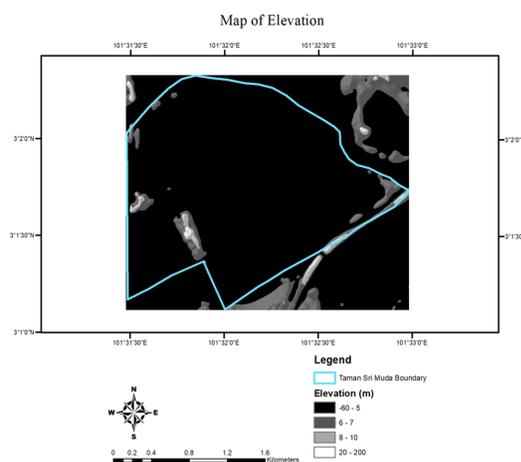


FIGURE 7. Reclassified map: Elevation

### SLOPE

The slope criterion, indicating the rate and duration of rainfall runoff, has a significant impact on flood mapping. Flat surfaces are more prone to flood zones than steep surfaces because water flows more slowly on low (flat) slope surfaces. Steeper slopes generally contribute to faster runoff and can affect flood vulnerability. According to Karir et al. (2022), slope datasets can be expressed as percentages or as slope degrees. In ArcGIS, slope maps are generated using contour lines. GIS can be used to obtain flow accumulation models based on slope data. This helps identify areas where water may accumulate and potentially cause floods.

Topographic indices, often derived from slope analysis and contributing areas, are used in GIS to assess how topography influences water movement. Areas with higher topographic indices are more susceptible to surface runoff and may be prone to flooding. Slope analysis is often combined with land use data in GIS. Urban areas on steep

slopes may experience increased runoff, leading to higher flood vulnerability. This combination enhances flood risk assessment.

Lower slope values indicate flat areas, while higher slope values indicate steeper areas. The slope dataset is labelled in degree values. The slope map is generated based on IfSAR data and analyzed using slope surface analysis methods. Almost the entire city is flat, with only a few areas in the southwest having hilly topography. Most of the study area, estimated at 90%, has slopes less than 1.4°. Low-degree slopes are given the highest weight, while high-degree slopes are given the lowest weight (Figure 8).

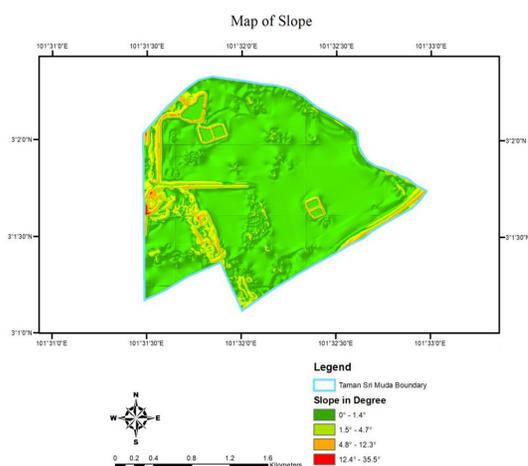


FIGURE 8. Reclassified map: Slope

## RESULT AND DISCUSSION

This section will explain the findings and decisions from the analysis conducted in the Taman Sri Muda area using the MCDA approach in ArcGIS software. The MCDA approach enables a comprehensive assessment of various criteria affecting flood risk, including slope, LULC, stream density, rainfall distribution, distance from main channels, and elevation.

By assigning weights to each criterion based on its importance, this analysis aims to identify areas prone to flood risk. The results of the MCDA analysis assist in visualizing different risk zones, providing precise and relevant information for flood risk management and more effective urban planning. Maps resulting from this analysis can aid local authorities in framing and making decisions for disaster preparedness tailored to reduce the impact of floods in the Taman Sri Muda area, Shah Alam.

## WEIGHTAGE FOR EACH CRITERIA

The flood vulnerability map is developed by integrating thematic layers, including LULC, distance from the main channel, stream density, rainfall distribution, elevation and slope. The factors influencing flood-prone areas and their respective weights are determined based on expert opinions and previous case studies. The weights for each criterion were determined using a direct rating method, where five experts independently scored the importance of each factor based on its contribution to flood risk. These experts included hydrologists from local universities and officers from JUPEM with experience in urban flood issues. The final weights were calculated by averaging their scores. This method is commonly used in MCDA studies because it is straightforward and effective for expert-based decisions (Malczewski, 2006; Behanzin et al. 2015). While more advanced methods like AHP could be explored in future studies, the direct rating method was suitable for this localized flood assessment.

A summary of the weight allocation for all selected criteria is presented in Table 2. The flood risk levels are categorized as follows: Level 1 represents the lowest flood risk, Level 2 indicates low flood risk, Level 3 signifies moderate flood risk and Level 4 corresponds to the highest flood risk.

TABLE 2. Assigning weights for criterion

Criteria	Weight	Sub-Criteria	Ranking
Rainfall Distribution (mm)	0.26	1,101 - 1,195	1
		1,196 - 1,289	2
		1,290 - 1,382	3
		1,383 - 1,476	4
Distance from Channel (m)	0.21	500	3
		1,000	2
		1,500	1
Drainage Density	0.16	0 - 0.71	1
		0.72 - 1.4	2

*continue ...*

... cont.

		1.5 - 2.1	3
		2.2 - 2.8	4
Elevation (m)	0.16	-60 - 5	4
		6 - 7	3
		8 - 10	2
		20 - 200	1
		Vacant Land / Open Space and Recreation	1
LULC	0.11	Built-up Area	2
		Water Body	3
		Slope	0.1
		1.5° - 4.7°	3
		4.8° - 12.3°	2
		12.4° - 35.5°	1

### FLOOD VULNERABILITY MAPPING

Urban flood vulnerability is categorized into four classes, very low, low, moderate, and high, based on the classification of cumulative vulnerability scores. Approximately 9.8% of the total urban area of Taman Sri Muda has a very low flood vulnerability level. This is due to the higher topography in that area compared to others. As shown in Figure 9, it is found that these high topography areas are in the southwestern part of the study area. There are also areas in the central and southern parts of Taman Sri Muda with low flood vulnerability levels. It was found that these areas consist of residential, open space, and recreational areas (developed areas). This factor also influences the flood vulnerability level in those areas (Muhamad Azizi & Teriman, 2023).

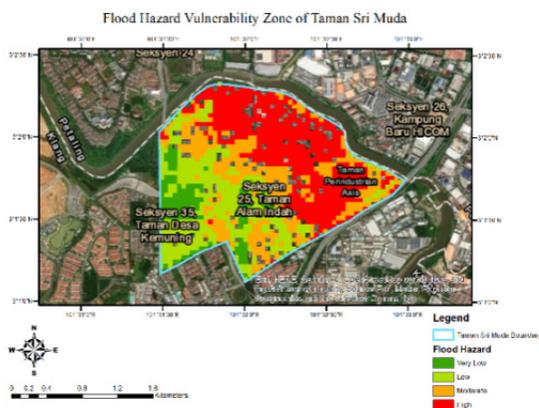


FIGURE 9. Flood hazard vulnerability zones of Taman Sri Muda

The area with a low flood vulnerability rate (27.6%) is concentrated in the central to southern parts of the

township, including Section 25 and Taman Alam Indah. These zones typically consist of structured residential developments and public open spaces. Urban design that incorporates green infrastructure and lower-density zoning has been shown to reduce runoff rates and improve water absorption, as discussed in Rashidiyan and Rahimzadegan (2024). Moreover, the role of land-use regulation in minimizing flood exposure has been supported by Kiss et al. (2021), indicating that built-up zones with regulated drainage and buffer zones experience lower vulnerability when adequately maintained.

Approximately 37.8% of Taman Sri Muda is classified as high-risk, predominantly in low-lying zones adjacent to the Klang River. This spatial pattern is consistent with historical flood records, particularly the December 2021 event. Similar findings have been reported in studies such as Behanzin et al. (2015) and Hagos et al. (2022), which identified river-adjacent urban areas as highly susceptible due to insufficient drainage gradients and impermeable surfaces. The predictive accuracy of the GIS-MCDA model is reinforced by this spatial correspondence, suggesting the methodology's utility in replicating real-world vulnerability patterns, as also evidenced in Kubal et al. (2009) and Osman and Das (2023). The severely affected areas due to flooding are in the northern part (adjacent to the Klang River) and extending to the eastern part (Taman Perindustrian Axis). This demonstrates that areas closer to the river will experience rising water levels first and are more easily affected by flooding, and having flat terrain also contributes to the occurrence of floods in these areas.

The results of this study echo broader findings in the literature that topographic flatness, proximity to water channels, and urban sprawl are critical determinants of flash flood exposure (Wan Mohtar et al. 2020; Leeonis et al. 2024). By applying a GIS-MCDA framework, this research corroborates the efficacy of multi-criteria methods

for urban flood risk zoning and strengthens the case for its adoption in flood-prone Malaysian cities. However, the relative dominance of rainfall and slope weights in this case suggests that future research should prioritize dynamic runoff modeling, consistent with insights from Wei et al. (2024) and Li et al. (2022).

### FACTORS THAT INFLUENCE FLOOD SUSCEPTIBILITY

Flood susceptibility in Taman Sri Muda is shaped by an interplay of topographic, hydrological, and land-use variables. The GIS-MCDA model confirms that each criterion contributes distinctly, with some exerting a greater influence under flash flood scenarios.

#### TOPOGRAPHIC CONDITIONS (SLOPE AND ELEVATION)

Slope and elevation significantly influence surface runoff velocity and water accumulation zones. The study area's predominantly flat terrain amplifies flash flood risk, as minimal gradient inhibits natural drainage and prolongs inundation. This observation aligns with Hagos et al. (2022) and Moreira et al. (2021), who found that low-relief urban areas exhibit high susceptibility due to reduced hydraulic gradients. In Taman Sri Muda, areas with near-zero slope consistently overlapped with the very high vulnerability zones, underscoring the terrain's control over flood dynamics.

#### RAINFALL DISTRIBUTION

Intense and spatially concentrated rainfall is a primary trigger of flash floods. The December 2021 event revealed the inability of existing urban infrastructure to cope with high rainfall intensity. Rainfall interpolation using the IDW method highlighted higher precipitation volumes in the northern quadrant, correlating with areas mapped as high vulnerability. These findings support Rashidiyan and Rahimzadegan (2024), who reported similar urban rainfall concentration effects in flash flood modeling.

### HYDROLOGICAL NETWORK: DRAINAGE DENSITY AND PROXIMITY TO MAIN CHANNEL

The density of drainage channels and their proximity to settlements directly influence flood dispersion. In this study, proximity to the Klang River and secondary drains emerged as a critical vulnerability factor. The high-risk zones were tightly clustered around primary drainage corridors, suggesting insufficient channel capacity or maintenance. Kubal et al. (2009) similarly noted that under-designed drainage in urban floodplains exacerbates flash flood outcomes, particularly in rapidly urbanizing contexts.

#### LAND USE / LAND COVER (LULC)

Built-up and impervious surfaces prevent infiltration, intensifying surface runoff. LULC analysis revealed that commercial and high-density residential areas, particularly in the northeast quadrant, correspond with very high vulnerability zones. The lack of vegetated buffers or green infrastructure contributes to poor absorption and delayed runoff dissipation. This supports findings from Behanzin et al. (2015) and Osman and Das (2023), which stressed the importance of urban permeability in moderating flood exposure.

The collective analysis confirms that topographic flatness, intense rainfall, and urban imperviousness act as synergistic drivers of flash flood risk in Taman Sri Muda. The GIS-MCDA model effectively quantifies the spatial impact of each factor, offering a replicable framework for other urban areas facing similar geomorphological and climatic constraints.

#### MITIGATION TO PREVENT FLOODING

Based on the GIS-MCDA analysis, targeted mitigation strategies can be proposed to reduce flash flood risks in Taman Sri Muda. These strategies fall into two broad categories: structural measures, which control water movement, and non-structural measures, which focus on preparedness and resilience. Structural Measures such as upgrading stormwater drainage systems, constructing retention ponds, and maintaining open channels are essential to managing rapid runoff typical of flash flood

events. Studies by Muhamad Azizi and Teriman (2023) emphasize that the efficiency of urban drainage networks significantly reduces flood duration and impact in low-lying Malaysian neighborhoods.

Non-structural Measures include flood forecasting, early warning systems, land-use zoning, and public education. Forecasting systems, when integrated with real-time meteorological and hydrological data, can provide timely alerts that save lives and reduce property damage (Trošelj et al. 2023). Rashidiyan and Rahimzadegan (2024) also advocate the use of probabilistic flood prediction models in conjunction with community-level awareness campaigns to improve response effectiveness. Importantly, GIS-based flood monitoring tools play a dual role in both planning and real-time risk visualization. According to Osman and Das (2023), integrating GIS with remote sensing and weather prediction models enhances spatial decision-making and supports dynamic flood management frameworks.

Additionally, nature-based solutions such as reforestation, green corridors, and wetland preservation are increasingly recognized for their flood buffering potential. These approaches not only reduce peak runoff but also restore ecological balance (Manes et al. 2024). Implementing green infrastructure has shown measurable reductions in urban flood peaks across Southeast Asian cities (Hamel & Tan, 2022). Finally, successful flood mitigation requires a multi-level governance approach, combining the efforts of local communities, municipal planners, and national agencies. This aligns with the Malaysian National Disaster Risk Reduction Policy 2030 that emphasizes shared responsibility and spatial intelligence in urban flood management (Saad et al. 2024).

The findings reinforce that no single intervention is sufficient. A hybrid of infrastructure enhancement, predictive analytics, land-use reform, and community resilience is necessary to address the complex and localized flood dynamics in Taman Sri Muda. These strategies, grounded in both scientific literature and policy frameworks, offer a replicable template for other flood-prone urban areas in Malaysia.

## CONCLUSION

This study demonstrated the effectiveness of GIS-based MCDA for identifying flood vulnerability zones in Taman Sri Muda, using six spatial criteria: LULC, elevation, slope, drainage density, rainfall distribution, and distance from the main channel. The weighted overlay approach produced a vulnerability map that aligned well with known flood extents and expert judgment. However, the study faced several limitations. The land use data used were from 2020

and may not fully capture recent urban developments. In addition, limited access to high-resolution ground truth flood data restricted the application of more rigorous statistical validation methods. The use of expert judgment, while valuable, also introduces subjectivity in weight assignment. Future work should focus on integrating real-time flood monitoring systems, such as IoT-based rainfall and water level sensors, to support dynamic flood forecasting. Improved access to high-resolution, time-stamped flood records will also allow for advanced validation metrics and scenario modelling. Incorporating machine learning techniques and finer-resolution satellite imagery can further enhance flood prediction accuracy. Ultimately, these enhancements will support more proactive, data-driven flood risk management strategies in vulnerable urban areas like Taman Sri Muda.

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## DECLARATION OF COMPETING INTEREST

None.

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