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Spatial–Temporal Assessment of Urban Flood Vulnerability using GIS and AHP in Klang River Basin

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Abstract
Urban flooding poses a critical challenge in rapidly urbanising river basin areas. Taman Sri Muda, located in the Klang River Basin, Malaysia, has experienced recurrent flooding driven by intense rainfall, rising water levels, and urban development. This study assesses the spatial–temporal evolution of flood vulnerability in 2016, 2020, and 2024 using a GIS-based multi-criteria decision analysis approach. Rainfall, water level, elevation, slope, and land use were integrated using the Analytic Hierarchy Process and weighted overlay analysis. Results show increased flood vulnerability between 2016 and 2020, with modest improvement by 2024, providing insights for evidence-based urban planning and flood management.

Keywords: Urban Flood Vulnerability, Environment–Behaviour Interaction, Spatial–Temporal GIS, Urbanisation, Flood Exposure

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1.0 Introduction

Urban flooding in rapidly urbanising river basins has increasingly shifted from an episodic hazard to a structurally embedded urban condition shaped by the interaction between climatic intensity, topographical constraints, and land-use transformation. In monsoon-dominated Southeast Asia, intensified rainfall interacts with expanding impervious surfaces, dense settlement patterns, and constrained drainage systems, resulting in spatially concentrated and persistent flood exposure (Biswash et al., 2026). Beyond physical inundation, such events disrupt mobility, residential stability, and risk perception, highlighting the relevance of an environment–behaviour perspective in understanding flood vulnerability as both a spatial and social condition (Kosova et al., 2024).

Within the Klang River Basin, Taman Sri Muda represents a particularly relevant case due to its low elevation, minimal slope gradients, and proximity to major river channels. Although GIS-based flood assessments have been widely applied to identify flood-prone areas, much of the existing literature remains temporally static, with emphasis placed on single-period susceptibility mapping rather than on longitudinal analysis of vulnerability change (Leeonis et al., 2024; Sulaiman et al., 2025). This limitation restricts understanding of how hydrological drivers and urban morphology interact cumulatively over time, particularly in rapidly urbanising river-basin environments. A spatial–temporal framework is therefore needed to capture the evolving character of urban flood vulnerability and to provide a stronger basis for adaptive flood governance.

The aim of this study is to assess the spatial–temporal evolution of urban flood vulnerability in Taman Sri Muda for 2016, 2020, and 2024 using a GIS–AHP approach. The objectives of this study are: (1) to identify the key parameters influencing flood vulnerability; (2) to determine the relative weights of these parameters using the Analytic Hierarchy Process (AHP); (3) to assess the spatial distribution of flood vulnerability using GIS-based weighted overlay analysis; and (4) to establish the spatial–temporal trends of flood vulnerability across the selected years.

2.0 Literature Review

Urban flooding is widely recognised as a multidimensional process shaped by the interaction of hydrological variability, topographical constraints, and rapid urbanisation. Recent studies consistently identify rainfall intensity and river water levels as major hydrological triggers in monsoon-influenced regions, where extreme precipitation increases runoff volume, drainage overload, and overflow frequency (Guo et al., 2025; Leeonis et al., 2024). However, these drivers operate within topographical settings in which elevation and slope regulate runoff concentration, flow velocity, and water accumulation, thereby influencing the spatial concentration of flood risk (Bhuiyan et al., 2022; Yin et al., 2026). At the same time, land use and land cover (LULC) transformation, particularly the expansion of impervious surfaces, has reduced infiltration capacity and increased peak discharge, further intensifying urban flood vulnerability (Afreen et al., 2022; Tang et al., 2024). Taken together, these studies suggest that a single factor does not drive flooding, the cumulative interaction among climatic intensity, terrain characteristics, and urban development processes drives it.

Methodologically, GIS-based approaches integrated with Multi-Criteria Decision Analysis (MCDA), particularly the Analytic Hierarchy Process (AHP), have become widely used in flood susceptibility and vulnerability assessment because they provide a transparent framework for integrating heterogeneous spatial variables and assigning relative importance to each factor (Ali & Nelson, 2025; Imani et al., 2025). Previous studies have shown that GIS–AHP is effective for combining rainfall, water level, elevation, slope, and land-use variables to identify flood-prone areas and support spatial planning decisions (Berrezel et al., 2025; Ardiansyah, 2023). The strength of this approach lies in its analytical transparency, reproducibility, and ability to incorporate expert judgement into structured spatial decision-making.

Nevertheless, much of the existing literature remains temporally static, with emphasis on single-period or event-based flood-susceptibility mapping rather than on the longitudinal assessment of vulnerability change. These limits understanding of how repeated hydrological stress and continuing urban expansion interact over time to reshape flood vulnerability patterns. From an environment–behaviour perspective, static assessments also provide limited insight into how recurrent flood exposure progressively influences spatial practices, settlement vulnerability, and risk perception (Feng et al., 2021; Liu et al., 2025). A longitudinal spatial–temporal framework is therefore necessary to capture the cumulative interaction between hydrological intensity and urban morphology over time.

To address this gap, the present study applies an integrated GIS–AHP approach to assess the spatial–temporal evolution of urban flood vulnerability in Taman Sri Muda across 2016, 2020, and 2024. By moving beyond static susceptibility mapping, the study offers a comparative multi-year perspective on how flood vulnerability is produced and reconfigured within a rapidly urbanising river basin.

3.0 Methodology

This study adopts a longitudinal spatial–temporal design integrating Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) within a Multi-Criteria Decision Analysis (MCDA) framework (Fig.1). GIS provides the spatial platform for collecting, managing, analysing, and visualising flood-related factors. At the same time, AHP is used to assign relative importance to each factor through systematic pairwise comparison. MCDA then combines these weighted criteria to produce an overall flood risk map.

The integration of these techniques improves the analytical transparency and reproducibility of the study. GIS ensures that all variables are spatially referenced and comparable, AHP provides a logical and consistent weighting procedure, and MCDA enables the aggregation of diverse criteria into a single decision-support model. This configuration is also theoretically aligned with the environment–behaviour perspective, which views vulnerability as a dynamic condition shaped by cumulative environmental change, urban growth, and human settlement patterns rather than as a static phenomenon (Akhter et al., 2025; Sukri et al., 2025).

3.1 Research Design and Temporal Framework

A comparative multi-year design was employed using three benchmark years, 2016, 2020, and 2024, to capture pre-peak, peak, and post-peak flood conditions associated with rainfall variability and urban expansion. These three years were deliberately chosen to reflect important stages in the temporal evolution of flood vulnerability within the study area. The year 2016 represents the pre-intense flood-related changes, 2020 captures the peak period of observed flood susceptibility, and 2024 reflects the more recent, post-peak situation in which the spatial effects of urban development and hydrological variation can be evaluated.

Rather than relying on single-year susceptibility mapping, the longitudinal configuration enables identification of structural shifts in vulnerability trajectories. This approach addresses limitations of temporally static modelling and supports the interpretation of progressive spatial transformation.

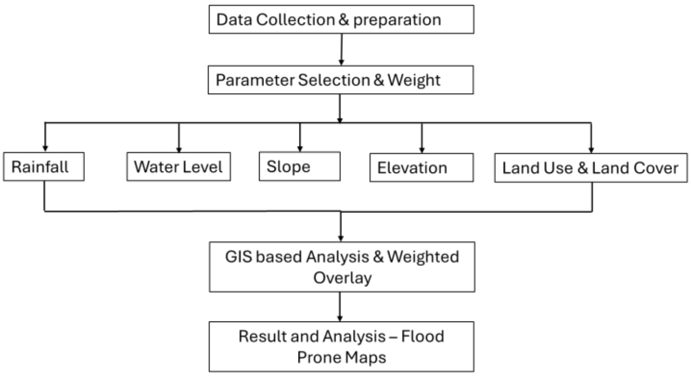


Fig.1: Workflow for Flood Risk Assessment

3.2 Study Area

Taman Sri Muda, located within the low-lying floodplain of the Klang River Basin (Fig.2), was selected due to its documented history of recurrent flooding and geomorphological susceptibility (Amir Abdullah et al., 2023; Tufail et al., 2025). Elevation values predominantly below 5 m, minimal slope gradients, and proximity to the Klang River create hydrological conditions conducive to water accumulation during extreme rainfall events. The area provides a suitable empirical setting for examining interaction effects between climatic intensity and urban morphology.

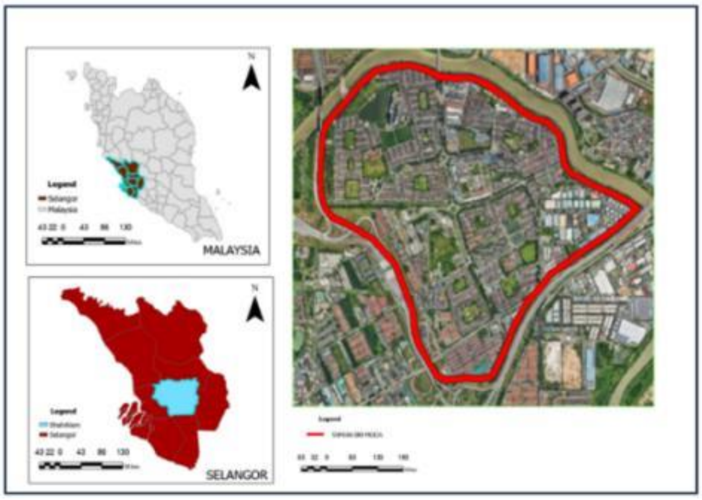


Fig. 2: The location of Taman Sri Muda, Seksyen 25, Shah Alam

3.3 Data Collection and Preparation

Five parameters, such as rainfall, water level, elevation, slope, and land use/land cover (LULC), were selected based on empirical evidence of their relevance in contemporary flood vulnerability modelling (Kaya et al., 2023; Zhang et al., 2020). Datasets were harmonised through projection standardisation, spatial resolution matching, and raster resampling to ensure cross-year comparability. All layers were reclassified into five standardised vulnerability classes (very low to very high) using consistent threshold criteria to minimise classification bias (Abdo et al., 2024) (Table 1).

Table 1. Data types, descriptions, and sources used

Data Type	Description	Source
Satellite Imagery	High-resolution images to capture land use, vegetation, and urban development in the study area (Jung et al., 2025).	Commercial satellite providers, Google Earth Engine
Digital Elevation Model (DEM)	Elevation data to assess topography, slope, and potential water flow dynamics	USGS, local mapping agencies
Hydrological Data	Rainfall and water level data to evaluate flood-prone areas based on precipitation patterns.	Meteorological and hydrological stations, local weather data providers
Land Use/Land Cover (LULC)	Classification of the land surface, highlighting urbanisation, vegetation, and water bodies.	Remote sensing data, local urban planning datasets

3.3 Parameter Selection

The Analytic Hierarchy Process (AHP) was applied to derive parameter weights through structured pairwise comparison using the Saaty scale (Idris et al., 2025). Each parameter was compared with the others using a Saaty scale to assess its relative influence on flood occurrence. These parameters represent both environmental and anthropogenic drivers of urban flooding and are summarised in Table 2.

Table 2. Flood Risk Factors

Flood Risk Factor	Description	Significance of Flood Risk
Rainfall	Precipitation that contributes to water accumulation in urban areas	High: Excessive rainfall leads to surface runoff and flooding
Water Level	The height of water in rivers or drains	High: Elevated water levels during rainstorms increase flooding risk
Slope	The steepness of the land surface	Moderate: Low slopes result in water pooling, while steep slopes lead to rapid runoff.
Elevation	The height above sea level	Moderate: Low-lying areas are more prone to flooding
Land Use and Land Cover (LULC)	The type of land use (urban, agricultural, forest) and its coverage	High: Urbanisation increases impermeable surfaces, exacerbating flooding

The eigenvector method was used to compute relative weights, and the Consistency Ratio (CR) (Equation 1) was calculated to assess the logical coherence of the expert judgments. A CR value below 0.10 confirmed acceptable internal consistency. This procedure enhances methodological rigour by reducing subjective bias while preserving expert-informed prioritisation. Sensitivity testing was conducted to confirm that minor weight variations did not significantly alter spatial vulnerability patterns.

$$CR = \frac{CI}{RI}$$

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

Equation 1

3.4 GIS-Based Analysis and Weighted Overlay

Reclassified raster layers were integrated using weighted overlay analysis, whereby each layer was multiplied by its corresponding AHP-derived weight and aggregated to produce a composite Flood Vulnerability Index (FVI) (Akindele et al., 2023). The index was subsequently categorised into five vulnerability levels to facilitate spatial interpretation and cross-temporal comparison. This integrative modelling approach enables systematic representation of spatial heterogeneity while supporting evidence-based urban flood governance.

By linking hydrological, topographical, and land-use parameters within a temporal framework, the methodology aligns with an environment–behaviour perspective that recognises how environmental processes and urban development trajectories shape exposure patterns over time. The combined approach supports spatially informed decision-making and provides an evidence-based foundation for adaptive urban flood management strategies in rapidly urbanising river basin environments (Aslan et al.,2023).

3.5 Importance of GIS and Weighted Overlay in Flood Risk Assessment

The integration of GIS and weighted overlay analysis provides a robust framework for urban flood risk assessment, particularly in rapidly urbanising environments such as Taman Sri Muda. GIS facilitates the integration of hydrological, topographical, and land-use datasets, enabling a spatially explicit evaluation of flood vulnerability across multiple scales (Aslan, 2023).

The weighted overlay method enhances analytical transparency by explicitly incorporating the relative importance of each parameter into the flood risk assessment. When combined with AHP, this approach ensures that expert judgment and local contextual knowledge are systematically embedded within the analysis. Importantly, the GIS-based weighted overlay approach enables the identification of high-risk zones and supports spatially informed decision-making for urban planning and flood mitigation (Idris, R.,2025). By visualising how flood risk varies spatially and temporally, this methodology provides policymakers and planners with valuable insights for designing effective and sustainable flood management strategies.

3.7 Robustness and Sensitivity Analysis

To enhance methodological robustness, a sensitivity analysis was conducted to evaluate the stability of the Flood Vulnerability Index (FVI) under variations in parameter weights. Incremental adjustments were applied to the highest-weighted parameter (rainfall) and redistributed proportionally among remaining variables to examine shifts in spatial vulnerability classification.

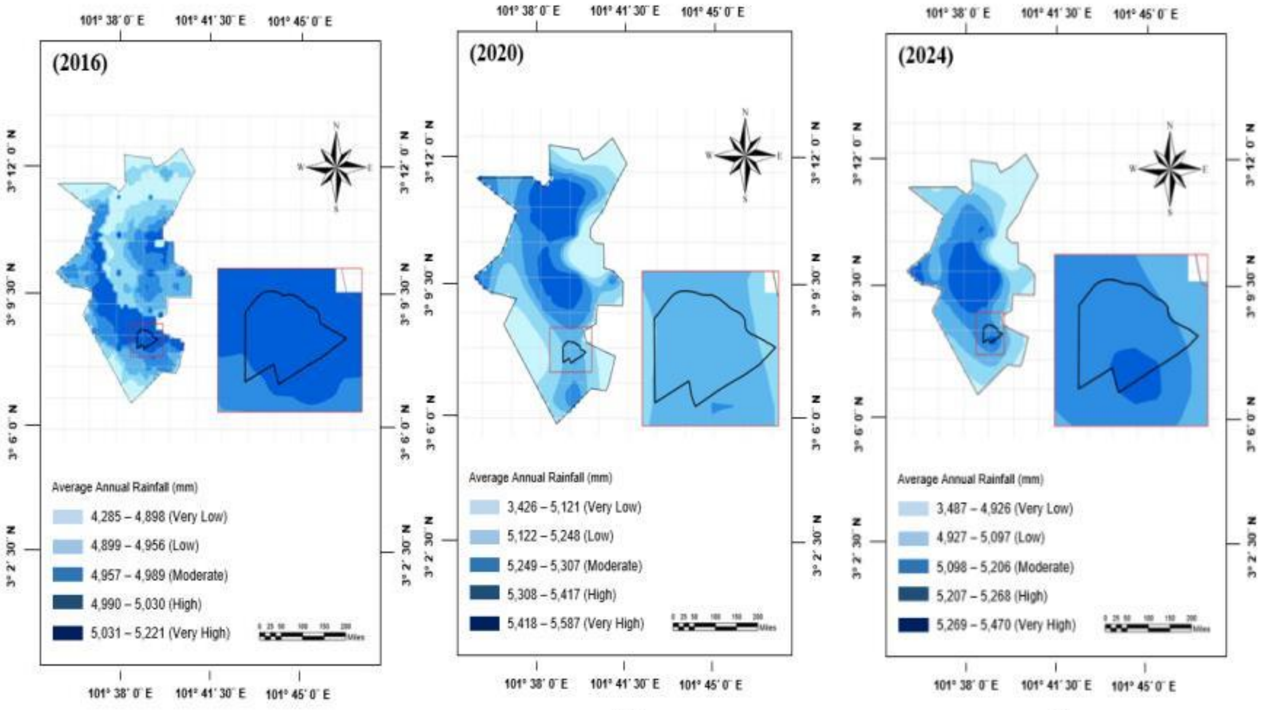
The results demonstrated minimal variation in the overall spatial pattern of high - very high vulnerability zones, indicating model stability and limited sensitivity to moderate changes in weighting. This procedure strengthens confidence in the reliability of the AHP-derived prioritisation and mitigates concerns regarding subjectivity inherent in expert-based weighting. By incorporating sensitivity testing, the modelling framework moves beyond deterministic overlay integration toward a more analytically resilient spatial assessment (Tierolf et al., 2021).

4.0 Findings

This section presents the empirical results of the spatial–temporal flood vulnerability assessment in direct alignment with the four research objectives. The findings are derived from GIS-based weighted overlay modelling and AHP parameter weighting for the benchmark years 2016, 2020, and 2024. The analysis highlights parameter influence, quantified weighting outcomes, spatial distribution patterns, and temporal evolution trends.

4.1 Identification of Key Flood Vulnerability Parameters

Environmental and anthropogenic drivers were identified as primary determinants influencing flood vulnerability in Taman Sri Muda. Five parameters were examined: rainfall, water level, elevation, slope, and land use/land cover (LULC) (Rashidiyan et al., 2024). Rainfall data show pronounced interannual variability (Fig. 3). The most pronounced increase occurred in 2020, when average annual precipitation reached 5,418 mm. This peak coincided with the most extensive expansion of high- and very high-vulnerability zones (Aidinidou et al., 2023; Burayu et al., 2023). In comparison, 2016 recorded lower rainfall levels, associated with more spatially confined high-risk areas. Although rainfall in 2024 declined marginally from the 2020 peak, vulnerability levels remained elevated relative to 2016 (Zhou et al., 2021).



(a) (b) (c)

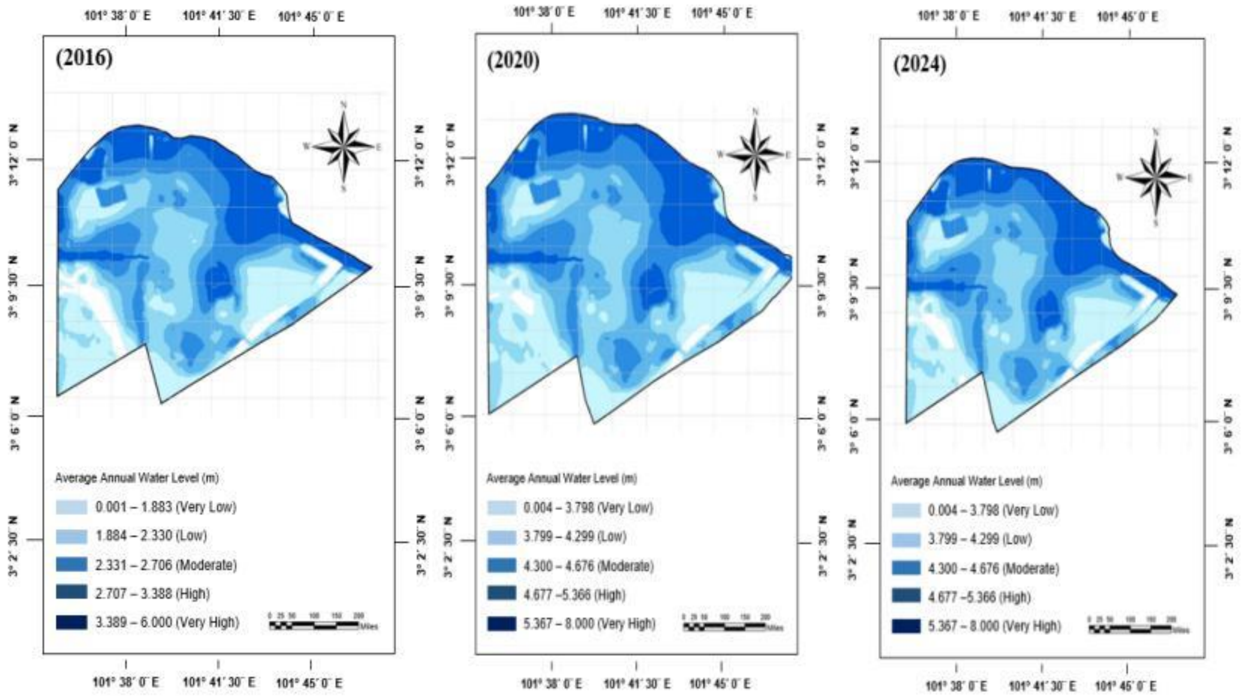
Fig. 3: (a) Rainfall distribution across Selangor in 2016, (b) 2020, (c) 2024

Water-level analysis further reinforces the hydrological influence (Fig. 4). During extreme rainfall events in 2020, river water levels reached approximately 8 m, intensifying overflow risk in northern river-adjacent sectors. In 2016, elevated water levels were largely confined to the immediate riverbanks, whereas in 2020, it extended further inland. In 2024, very high water-level zones showed partial reduction but remained concentrated in low-lying northern areas (Ashfaq et al., 2025; Tufail et al., 2025).

Topographical assessment indicates that substantial portions of the study area lie below 5 m above sea level. Elevation values range from approximately 0.001 m to 12.921 m, with extensive low-elevation zones clustered in northern and central sectors. Slope gradients range between 0.001° and 0.088°, reflecting predominantly flat terrain. These minimal gradients constrain natural runoff and promote water stagnation during heavy rainfall (Fig. 5).

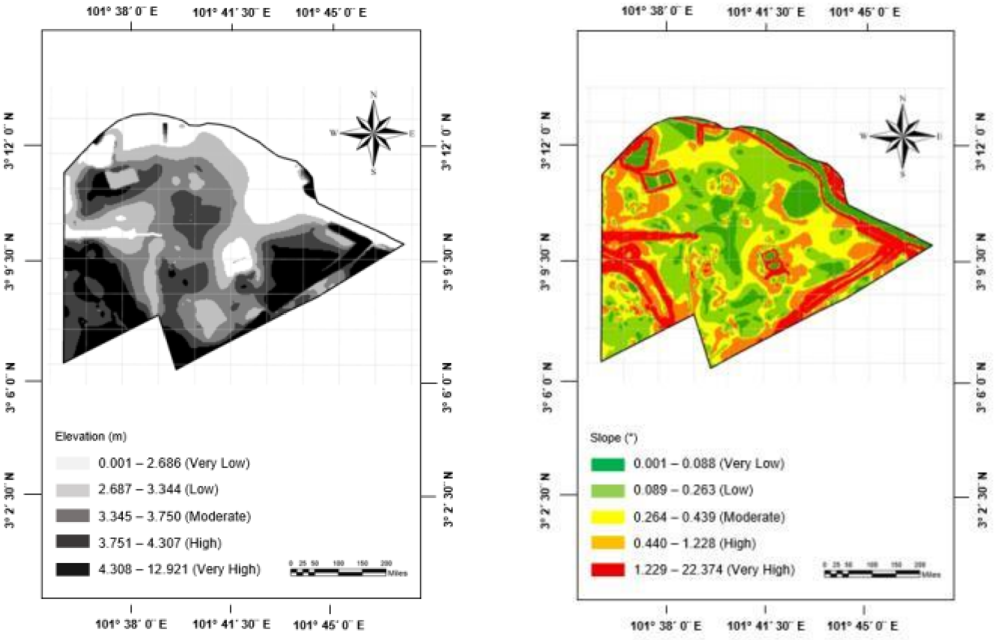
LULC analysis demonstrates the continuous expansion of built-up areas between 2016 and 2024. Vegetated and permeable surfaces declined progressively, particularly in central and northern sectors. The spatial overlap between dense built-up zones and high-flood-vulnerability areas is consistent across all three years. As shown in Fig. 6, built-up areas increased substantially between 2016 and 2024, accompanied by a marked reduction in vegetation and open land that previously facilitated infiltration (Ashfaq et al., 2025).

Collectively, the analyses of rainfall, water level, elevation, slope, and LULC confirm their combined influence as primary determinants of flood vulnerability in Taman Sri Muda. These findings directly address the first objective by empirically validating the selection of key environmental and anthropogenic parameters that shape the spatial flood risk



(a) (b) (c)

Fig. 4: (a) Water level distribution of Taman Sri Muda in 2016, (b) 2020, (c) 2024



(a) (b)

Fig. 5: (a) Elevation and (b) Slope of Taman Sri Muda

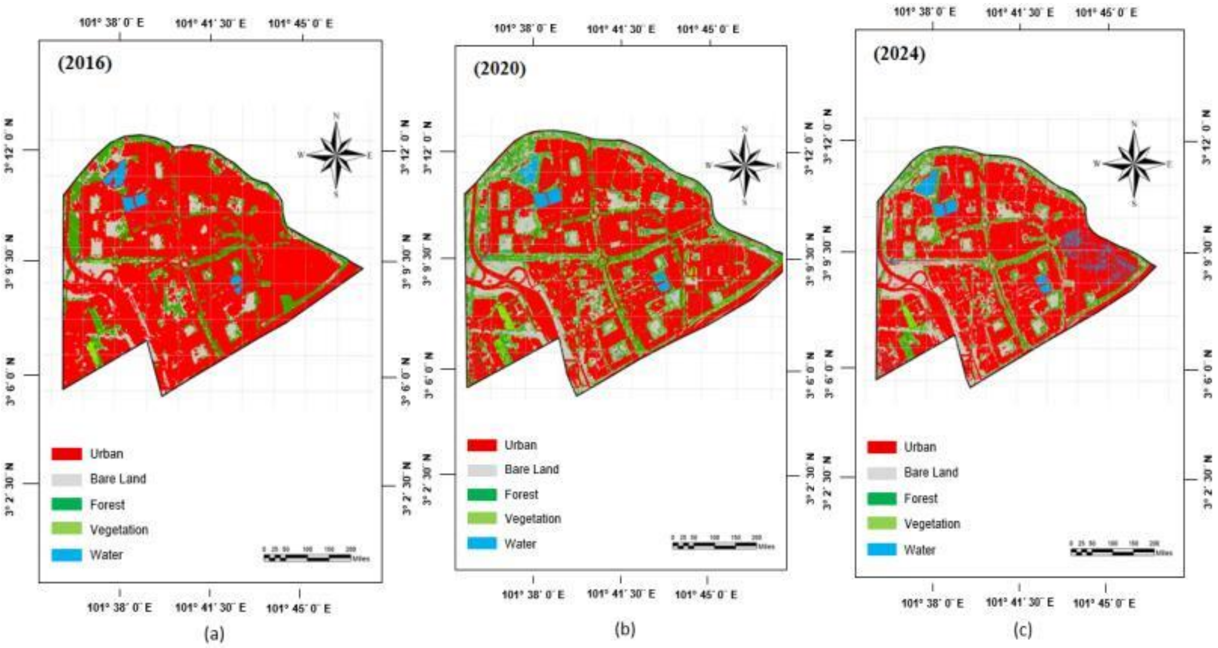


Fig.6: (a) LULC Taman Sri Muda in 2016, (b) 2020, (c) 2024.

4.2 Determining the Weight

The relative importance of rainfall, water level, slope, elevation, and land use/land cover (LULC) was determined using the Analytic Hierarchy Process (AHP), which enables systematic pairwise comparison of parameters based on expert judgment (Pakati et al., 2025). The resulting weights, summarised in Table 4, reflect the perceived significance of each parameter in shaping flood conditions in Taman Sri Muda.

Table 4. AHP weighting table

Parameter	Weight (%)
Rainfall	43.28
Water Level	19.47
Elevation	16.57
LULC	14.59
Slope	11.60

The predominance of rainfall confirms its primary triggering role in annual flood severity. However, the combined contribution of elevation, slope, and LULC (42.76%) demonstrates that the structural characteristics of terrain and urban development collectively exert an influence comparable to that of hydrological drivers. This finding underscores the multidimensional nature of vulnerability.

4.3 Establishment of Spatial–Temporal Trends (2016–2024)

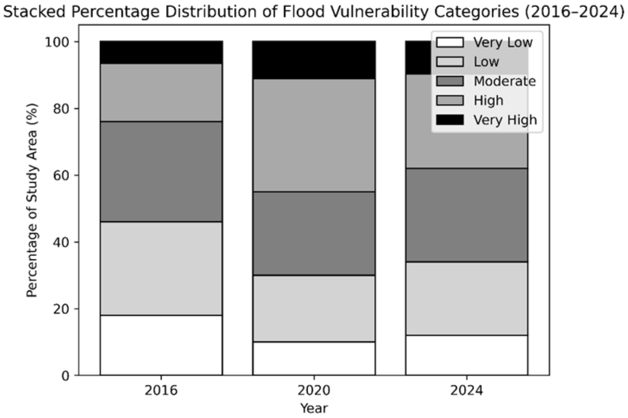


Fig. 7: Percentage of flood risk zones over time (2016,2020,2024)

The temporal trends focused on establishing evolving flood vulnerability trends across the three benchmark years. Comparative analysis of vulnerability categories (Fig. 7) reveals a distinct escalation–stabilisation trajectory.

Between 2016 and 2020, the proportion of very high-risk zones increased significantly, reaching 11.08% of the total study area. This escalation coincides with peak rainfall intensity, elevated water levels, and expanding impervious urban surfaces. The simultaneous amplification of hydrological and anthropogenic drivers contributed to intensified exposure. From 2020 to 2024, a modest decline to 9.76% in very high-risk areas was recorded. Despite this reduction, vulnerability levels in 2024 remained higher than in 2016. High-risk zones continued to cluster in northern and low-elevation sectors, indicating persistent structural susceptibility.

The temporal pattern, therefore, demonstrates:

i. A moderate baseline condition (2016)
ii. Sharp intensification under combined climatic and developmental pressures (2020)
iii. Partial stabilisation without full vulnerability reversal (2024).

This trajectory confirms that flood vulnerability in Taman Sri Muda is not episodic but progressively shaped by cumulative environmental and urban development processes. The longitudinal comparison establishes clear temporal evolution, thereby fulfilling the fourth research objective.

4.4 Assessment of Spatial Flood Vulnerability Patterns

The assessment of spatial vulnerability distribution for 2016, 2020, and 2024. Weighted overlay integration of the five parameters generated composite flood vulnerability maps classified into five categories: very low, low, moderate, high, and very high (Fig. 8).

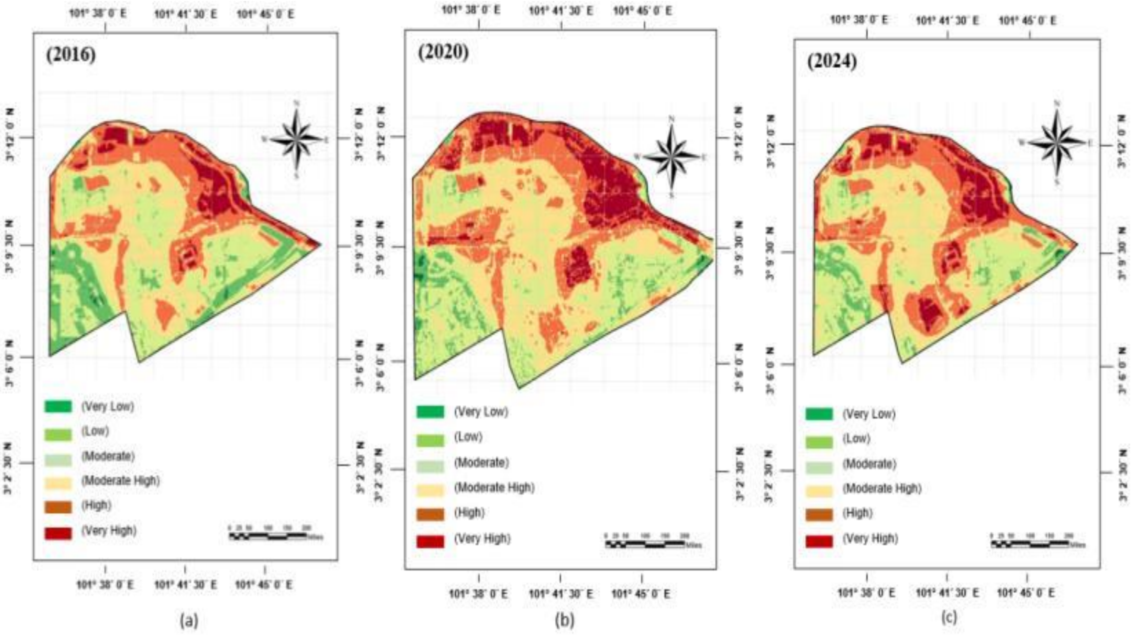


Fig. 8: (a) Flood-prone map of Taman Sri Muda in 2016, (b) 2020, (c) 2024

In 2016, vulnerability was predominantly low to moderate, with high-risk zones concentrated in river-adjacent northern sectors. Very high-risk areas were limited and spatially fragmented. The distribution suggests baseline structural exposure without widespread intensification. By 2020, a substantial expansion of high- and very-high-vulnerability zones occurred. The spatial footprint of very high-risk areas became more continuous, particularly in northern and central low-lying zones characterised by dense built-up coverage. This year represents the most pronounced spatial transformation within the study period.

In 2024, very high vulnerability zones contracted modestly compared to 2020, yet high-risk clusters persisted in northern areas. The spatial gradient consistently shows increasing vulnerability with proximity to the Klang River, lower elevations, and dense urban areas. The spatial outputs clearly delineate vulnerability concentrations and demonstrate the effectiveness of GIS-based weighted overlay analysis in identifying high-risk zones, thereby fulfilling the third research objective.

5.0 Discussion

The findings demonstrate that flood vulnerability in Taman Sri Muda is not merely a consequence of isolated climatic shocks, but rather a structurally embedded condition produced by the cumulative interaction of hydrological intensity, topographical constraints, and urban morphology. While rainfall emerged as the dominant triggering parameter, the substantial combined contribution of elevation, slope, and land use/land cover confirms that vulnerability is spatially conditioned by the landscape's physical and built characteristics rather than distributed randomly (Hamid et al., 2024). This interpretation is consistent with the study's weighting results, which show that rainfall accounted for 43.28% of the influence. At the same time, elevation, slope, and LULC together contributed 42.76%, indicating that terrain and urban development collectively exert an influence comparable to hydrological forcing. Such findings reinforce the argument in prior flood-vulnerability studies that urban flooding is multidimensional and shaped by the interaction of climatic and spatial variables, rather than by precipitation alone.

The temporal pattern observed across 2016, 2020, and 2024 further deepens this interpretation. The substantial escalation of very high-risk zones in 2020 reflects the compound effect of peak rainfall, elevated water levels, and expanded impervious surfaces, while the only partial stabilisation in 2024 suggests that vulnerability did not fully reverse even after hydrological intensity moderated. This indicates that once structurally vulnerable land-use configurations become established, subsequent reductions in climatic extremity do not automatically eliminate risk (Tajuddin et al., 2025). The persistence of high-risk clusters in northern, low-lying, and densely built sectors implies that infrastructural responses alone may reduce exposure only marginally unless accompanied by stronger land-use regulation and spatial restructuring. In this respect, the study shows that urban flood vulnerability is path-dependent, reflecting the cumulative effects of earlier development decisions in flood-prone areas (Ishiwatari et al., 2026).

From an environment–behaviour perspective, recurrent flood exposure should be understood not only as a physical hazard but also as a chronic environmental stressor that progressively shapes everyday spatial behaviour, mobility choices, residential security, and risk perception (Ermagun et al., 2026). By integrating longitudinal GIS-based modelling with AHP weighting, this study advances current scholarship by showing how repeated environmental pressures and urban expansion co-produce evolving patterns of vulnerability over time. This is important because much existing flood mapping remains static or event-based, whereas the present findings demonstrate that vulnerability in river-basin settlements changes through an escalation–stabilisation trajectory rather than remaining fixed (Islam et al., 2025; Destefanis et al., 2025). The discussion, therefore, extends the study beyond technical mapping and supports a more behavioural and relational understanding of urban flood exposure in rapidly urbanising environments (Bernardini et al., 2023).

The implications of these findings extend beyond Taman Sri Muda. In rapidly urbanising river basins, flood governance must move beyond short-term mitigation and embed flood vulnerability assessment into land-use planning, zoning controls, drainage design, and green infrastructure strategies (Oneto & Canepa, 2023). The findings suggest that adaptive spatial planning should prioritise stricter control over development in low-elevation and river-adjacent zones, while also promoting permeable surfaces, retention landscapes, and nature-based interventions that work with rather than against hydrological realities (Griffiths et al., 2024). More broadly, the study contributes to policy discussions on urban resilience by showing that unmanaged urban expansion can progressively entrench structurally embedded flood risk.

6.0 Conclusion and Recommendations

This study demonstrates that urban flood vulnerability in Taman Sri Muda is structurally embedded within the interaction between climatic intensity and cumulative land-use transformation. By adopting a longitudinal GIS–AHP framework, the research moves beyond static susceptibility mapping to reveal an escalation–stabilisation trajectory across 2016, 2020, and 2024. The findings confirm rainfall as the principal triggering factor, while elevation, slope, and LULC collectively condition the spatial persistence and concentration of high-risk zones. Vulnerability, therefore, emerges not as an episodic anomaly but as a path-dependent outcome of spatial planning decisions and hydrological constraints.

The study advances environment–behaviour scholarship by empirically demonstrating how recurrent environmental stressors progressively reshape exposure patterns within dense river basin settlements. The integration of temporal modelling with structured parameter weighting provides a transferable methodological template for rapidly urbanising monsoon cities across Southeast Asia. Several limitations warrant consideration. The analysis focused on five environmental parameters and did not incorporate socio-economic vulnerability indicators such as income distribution, housing resilience, or adaptive capacity. Additionally, benchmark-year modelling may not fully capture short-term climatic variability. Although sensitivity testing confirmed model stability, AHP weighting remains partially reliant on expert judgment.

This study has several limitations. First, the analysis was confined to five environmental parameters and did not incorporate socio-economic variables such as household income, housing resilience, social sensitivity, or adaptive capacity. Second, the benchmark-year approach may not fully capture short-term climatic variability between the selected years. Third, although the consistency ratio indicated acceptable model reliability, the AHP weighting process remains partially dependent on expert judgement. These limitations should be taken into account when interpreting the findings and assessing their broader applicability.

Flood-vulnerability assessment should be more explicitly integrated into land-use governance and urban planning frameworks. Development control needs to be strengthened in low-elevation and river-adjacent areas that consistently exhibit high vulnerability. Urban authorities should also prioritise expanding green and blue infrastructure, including permeable surfaces, retention areas, and improved drainage systems, to reduce runoff concentration and enhance water absorption. In addition, community-based resilience strategies, including local preparedness measures and flood-risk awareness programmes, should be incorporated more systematically into urban flood management.

Future research should extend the present framework by integrating socio-demographic indicators, higher-resolution geospatial datasets, and climate projection scenarios to improve predictive robustness and policy relevance. Comparative application in other rapidly urbanising river basin cities would also help evaluate the framework’s wider transferability. Ultimately, aligning urban growth with hydrological realities is essential to prevent the further entrenchment of structurally embedded flood risk in river basin environments.

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Paper Contribution to the Related Field of Study

This study advances environment–behaviour research in Asia by integrating spatial–temporal GIS–AHP modelling with behavioural interpretation of urban flood vulnerability. It conceptualises flood risk as a progressively embedded condition shaped by monsoon variability and rapid urbanisation rather than an episodic event. The longitudinal framework offers a transferable model for river basin cities across Southeast Asia, supporting adaptive spatial governance, green infrastructure integration, and behaviour-informed urban resilience strategies in high-density monsoon.

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