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INTEGRATED GIS-MCDA FRAMEWORK FOR OPTIMAL FLOOD RETENTION POND SITE SELECTION: A CASE STUDY IN REMBAU, MALAYSIA

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Abstract

Flooding poses severe risks to human lives, infrastructure, and economies globally. Effective flood management depends on strategically locating mitigation measures like flood retention ponds, which regulate stormwater and reduce downstream flooding. Traditional site selection methods often suffer from limited data use and subjective judgment, weakening mitigation outcomes. This study applies an integrated Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) framework using the Analytic Hierarchy Process (AHP) to prioritise flood retention pond sites in Rembau, Malaysia. Utilising high-resolution spatial datasets Digital Elevation Models, Land Use and Land Cover maps, hydrological and infrastructure data, and socio-economic factors combined with expert and stakeholder input, the model produces suitability maps that balance economic, environmental, and social considerations. Results identify optimal sites along natural drainage networks and moderate slopes, enhancing stormwater capture, minimising construction challenges, and reducing social disruption. Scenario analysis reveals trade-offs: economic scenarios favour cost-effective agricultural lands but risk ecological impacts; environmental-social scenarios prioritise conservation and community welfare but increase costs; combined scenarios achieve a balanced, sustainable approach. Overall, this study demonstrates that stakeholder engagement strengthens the model's suitability and promotes flood mitigation planning that is data-driven and context-specific. The proposed GIS-MCDA framework provides a reusable tool for developing sustainable and resilient flood management strategies.

Keywords: GIS-MCDA, Analytic Hierarchy Process, Flood Mitigation, Retention Pond, Spatial Planning

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INTRODUCTION

Flooding remains one of the most pervasive natural hazards worldwide, causing substantial damage to lives, infrastructure, and economies. Effective flood management relies heavily on the strategic placement and design of mitigation infrastructure, such as flood retention ponds, which serve as temporary storage to regulate stormwater and reduce downstream flooding impacts. Identifying optimal sites for such flood retention systems is a complex task that requires the integration of multiple environmental and infrastructural factors. Traditionally, site selection has been hindered by subjective evaluations and limited consideration of data, which can compromise the effectiveness of flood mitigation efforts.

Recent advances in geospatial technologies coupled with decision-support methodologies have enhanced the capacity to address these challenges. Geographic Information System (GIS) tools provide powerful capabilities for integrating, analysing, and visualising spatially distributed data layers, encompassing land use, topography, soil characteristics, hydrological networks, and existing drainage infrastructure. When combined with Multi-Criteria Decision Analysis (MCDA) methods, particularly the Analytic Hierarchy Process (AHP), these technologies enable the systematic weighting and prioritisation of diverse criteria based on expert knowledge and stakeholder input, overcoming biases inherent in unstructured decision-making. This integrated GIS–MCDA approach facilitates the generation of robust suitability maps that highlight optimal site locations for flood retention installations.

The application of such methodologies in the context of flood risk management has been growing, as evidenced in studies like Osman et al. (2023), which demonstrated how GIS-based MCDA can effectively delineate flood hazard and vulnerability zones. Similarly, urban flood resilience studies, including those by Nugroho et al. (2025), have showcased how retention ponds contribute significantly to mitigating urban flood impacts when located based on integrated spatial analyses. These frameworks also align with recommendations by Verstraeten and Poesen (1999), emphasising the importance of combining hydrological, geomorphological, and socio-economic factors in flood infrastructure planning. In this study, the GIS-AHP framework is applied to Rembau, Negeri Sembilan, Malaysia, to select optimal flood retention pond sites. By rigorously integrating criteria such as land use, slope, soil permeability, hydrology, and proximity to waterways, the study advances a replicable and scientifically sound protocol for informed flood mitigation planning, adding to the growing body of academic evidence supporting GIS-MCDA as a best-practice approach.

LITERATURE REVIEW

Floods are among the most pervasive and destructive natural hazards globally, frequently resulting in significant socio-economic and environmental impacts. The rising frequency and intensity of flood events, driven by climatic variability and anthropogenic changes such as urbanization and land-use alteration, necessitate improved flood risk management strategies (Osman, 2023). In this context, flood retention ponds have gained recognition as a cost-effective structural measure to mitigate flood peaks by temporarily storing excess runoff. However, the effectiveness of flood retention ponds largely depends on their optimal placement, which is contingent upon a thorough understanding and integration of multiple spatial factors influencing flood dynamics and site feasibility. Geographic Information System (GIS) technology has become pivotal in flood hazard and risk assessment due to its capacity for integrating diverse spatial data layers and conducting sophisticated spatial analyses (Nsengiyumva et al., 2024). By facilitating the overlay, manipulation, and visualization of complex environmental and infrastructural data, GIS enhances decision-making processes in flood risk management. However, translating these data into actionable site selection decisions requires robust decision-support frameworks that can handle multiple criteria with competing priorities and uncertainties inherent in real-world scenarios.

Multi-Criteria Decision Analysis (MCDA) methods—particularly the Analytic Hierarchy Process (AHP)—have been extensively adopted in flood risk assessment for their ability to quantify expert judgments and stakeholders' preferences through systematic pairwise comparisons (Saaty, 1980). AHP provides a structured methodology for weighting and prioritizing criteria such as slope, land use, soil permeability, hydrological connectivity, and proximity to existing infrastructure, all critical for effective flood retention pond siting (Doorga et al., 2022). This combination of GIS and MCDA integrates spatial precision with decision-making rigor, enabling the generation of suitability maps that account for multifaceted environmental and social considerations.

Previous studies have illustrated the efficacy of GIS-MCDA approaches in delineating flood hazard zones and vulnerability mapping. For example, Osman (2023) employed GIS-based MCDA to assess flood hazards, vulnerability, and risks in the Shebelle River Basin, Somalia, demonstrating accurate identification of flood-prone areas with a receiver operating characteristic (ROC) value of 0.78. Similarly, Riaz et al. (2025) applied these methods to assess flash flood susceptibility by integrating hydro-geomorphological and land use criteria, highlighting the adaptability of GIS-MCDA for diverse hydrological contexts. The integration of expert judgment and local knowledge through AHP ensures that model outputs reflect both scientific

and community priorities, thereby improving planning legitimacy and implementability (Nsengiyumva et al., 2024).

Despite these advances, several critical gaps persist in the current GIS-MCDA methodologies applied to flood retention pond site selection. First, most studies rely on static spatial datasets that do not account for temporal variability in hydrological factors, land use changes, or climate dynamics, limiting the adaptability and long-term robustness of the models. There is a clear need for integrating dynamic, spatiotemporal data and real-time hydrological modeling within the GIS-MCDA framework to capture such temporal fluctuations adequately. Second, GIS-MCDA generally simplifies hydrological processes by using secondary criteria like slope and soil permeability as proxies without incorporating fully coupled hydrodynamic simulations. This lack of explicit hydrological process modelling can reduce the precision in identifying sites that will effectively mitigate flood impacts. Future work should focus on integrating physically-based hydrological and hydraulic models with GIS-based MCDA to enhance the predictive accuracy.

Third, the reliance on expert judgment in the Analytic Hierarchy Process introduces potential biases and subjectivity in criteria weighting. Although consistency checks are applied, weighting schemes remain susceptible to variability in expert opinions. Studies exploring hybrid or data-driven weighting approaches that combine AHP with machine learning or participatory methods could enhance objectivity and reliability. Fourth, the socio-economic and ecosystem service dimensions of site selection are often underrepresented in current models. While biophysical criteria dominate the analyses, factors such as land ownership, community acceptance, cost implications, and ecological benefits warrant greater integration to ensure practical viability and sustainability.

Finally, validation efforts are typically limited to expert reviews and selective field checks, lacking comprehensive empirical validation through longitudinal monitoring of implemented retention pond sites. Robust validation frameworks involving post-construction performance assessments would substantially improve confidence in model applicability and inform iterative model improvements. This study responds to these gaps by implementing a comprehensive, stakeholder-informed AHP weighting process applied to a rich set of biophysical and socio-economic criteria. Through multi-scenario suitability mapping and field validation, it advances the rigor and applicability of GIS-MCDA for flood mitigation, contributing to a more adaptable and holistic decision-support tool in flood risk management. This enhanced literature review now includes critical gaps and suggested directions for future research aligned with your study's contributions.

A variety of spatially referenced datasets are fundamental for effective multi-criteria site suitability analyses, particularly in flood risk management and urban planning contexts. High-resolution Digital Elevation Models (DEMs) are widely recognised as a crucial baseline for terrain analysis, supporting the derivation of slope, aspect, and watershed boundaries to model hydrological processes accurately (Ayalew & Yamagishi, 2005; Tarboton, 1997). The use of satellite-derived DEM data, such as SRTM, has been demonstrated to enable consistent and detailed topographic representations essential for flood modelling and infrastructure assessment (Feyisa, Meilby, Fensholt, & Proud, 2014). Land Use and Land Cover (LULC) maps, frequently derived from remote sensing platforms like Landsat and Sentinel, are integral to capturing spatial heterogeneity and land use dynamics, which influence water runoff, infiltration, and flood risk (Di et al., 2015; Weng, 2012). These datasets inform environmental constraints and anthropogenic pressures, improving the accuracy of suitability assessments for flood control infrastructure. Hydrological network data and drainage system maps represent key hydrological components critical to floodwater conveyance modelling (Chen, Liu, & Du, 2018). Vector layers of stream networks and drainage basins allow precise delineation of catchment properties and runoff pathways, informing infrastructure placement and flood mitigation designs (Pradhan & Lee, 2010).

Including infrastructure layers such as road networks and urban built-up areas ensures that accessibility and potential land use conflicts are incorporated into decision-making (Malczewski, 2006). Furthermore, socioeconomic data, including population density and settlement proximity, provide essential insights into human exposure and vulnerability, aligning flood mitigation efforts with community safety priorities (Cutter, Boruff, & Shirley, 2003). Integrating these datasets supports a holistic, spatially explicit framework for flood retention pond siting that balances technical, environmental, and social considerations.

However, besides flood retention ponds, several other flood mitigation measures are widely employed to reduce flood risks and manage stormwater effectively. Constructing levees and floodwalls provides physical barriers that protect vulnerable areas by containing rising water levels within rivers and channels. Detention and infiltration basins temporarily store stormwater and promote groundwater recharge, thereby reducing surface runoff and peak flows. Green infrastructure approaches, such as bioswales, rain gardens, and permeable pavements, enhance natural infiltration and reduce urban flooding by mimicking pre-development hydrology.

River restoration and channel modification improve flow capacity and ecological health, lowering flood hazards downstream. Additionally, early warning systems and community-based disaster preparedness programs play a

critical role in minimizing flood impacts by enabling timely evacuation and response. Integrated watershed management strategies combine land use planning, ecosystem conservation, and engineered interventions to address flood risks holistically. Implementing a mix of structural and non-structural measures tailored to local conditions can optimize cost-effectiveness, environmental sustainability, and social acceptance in flood risk reduction.

STUDY AREA AND METHOD

Study Area

This study was conducted in the Rembau District, located in the southern part of Negeri Sembilan, Malaysia (Figure 1). Figure 1 illustrates the location of the study area within Rembau District, Negeri Sembilan, Malaysia. To provide a clearer geographical context, the map also includes a macro-scale inset showing the position of Rembau District within Peninsular Malaysia. Rembau District is situated in the southern region of Negeri Sembilan and shares its borders with Seremban District to the north, Tampin District to the east, and Alor Gajah District in Melaka to the south.

Rembau is highly susceptible to recurrent flooding, particularly during the northeast monsoon, due to its predominance of low-lying floodplains and diverse land use types—including agricultural, residential, and peri-urban developments. Rembau, located in Negeri Sembilan, Malaysia, is recognised as a flood-prone district due to its low-lying terrain and susceptibility to heavy rainfall during the northeast monsoon season. The area frequently experiences flash floods, particularly in settlements such as Kampung Paya, Kampung Lubuk China, and Kampung Nerambai, where rapid water accumulation disrupts communities and infrastructure (Malay Mail, 2024; Bernama, 2024).

Flash floods in Rembau often lead to temporary evacuations, damage to agricultural lands, and disruptions in local livelihoods. The district's flood risk is exacerbated by factors such as altered natural drainage systems and increasing urban expansion, which limit effective stormwater runoff. Significant investments, including flood mitigation and drainage improvement projects, have been prioritized to address recurrent flooding in Rembau (Bernama, 2023). Overall, Rembau's topography, hydrology, and land use patterns contribute to its vulnerability, necessitating targeted flood management strategies informed by geospatial and participatory approaches.

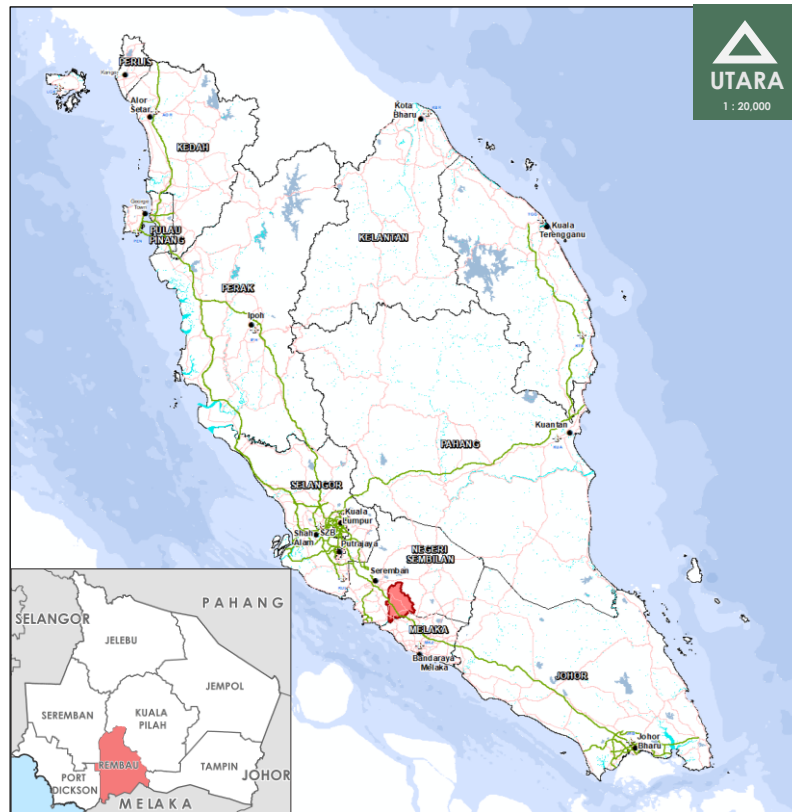


Figure 1: Rembau District Location in Negeri Sembilan, Malaysia

Rapid urban development and the alteration of natural drainage systems have significantly contributed to the increasing flood risk in the district (Figure 2). Figure 2 illustrates the main physical characteristics of the study area, including the drainage network of the Rembau River and its tributaries. The study area's heterogeneous landscape offers a pertinent context for evaluating spatially-oriented flood mitigation strategies. Rembau District, located in Negeri Sembilan, Malaysia, covers an area of approximately 415 km² and had an estimated population of around 47,000 as of 2020, with a moderately young median age of 26.5 years (CityFacts, 2020). The population is ethnically diverse, predominantly Malay with significant Chinese and Indian communities, reflecting the multicultural composition of the region. Most inhabitants engage in farming, trading, government service, and factory work, with many youth joining uniformed services (CityFacts, 2020; Wikipedia, 2025). The district has a relatively low population density of about 109 persons per km² but is experiencing gradual urbanization driven by improved connectivity to nearby

economic hubs like Seremban and Kuala Lumpur (Bernama, 2022). Socio-economic conditions vary, with agriculture remaining a key livelihood alongside emerging urban employment opportunities linked to manufacturing and services (CityFacts, 2020). This demographic and economic profile influences flood vulnerability, as expanding settlements and infrastructure development alter natural drainage patterns, heightening flood risks. The socio-economic diversity and growth trends underscore the need for inclusive, location-specific flood risk management strategies that consider both rural and peri-urban community needs.

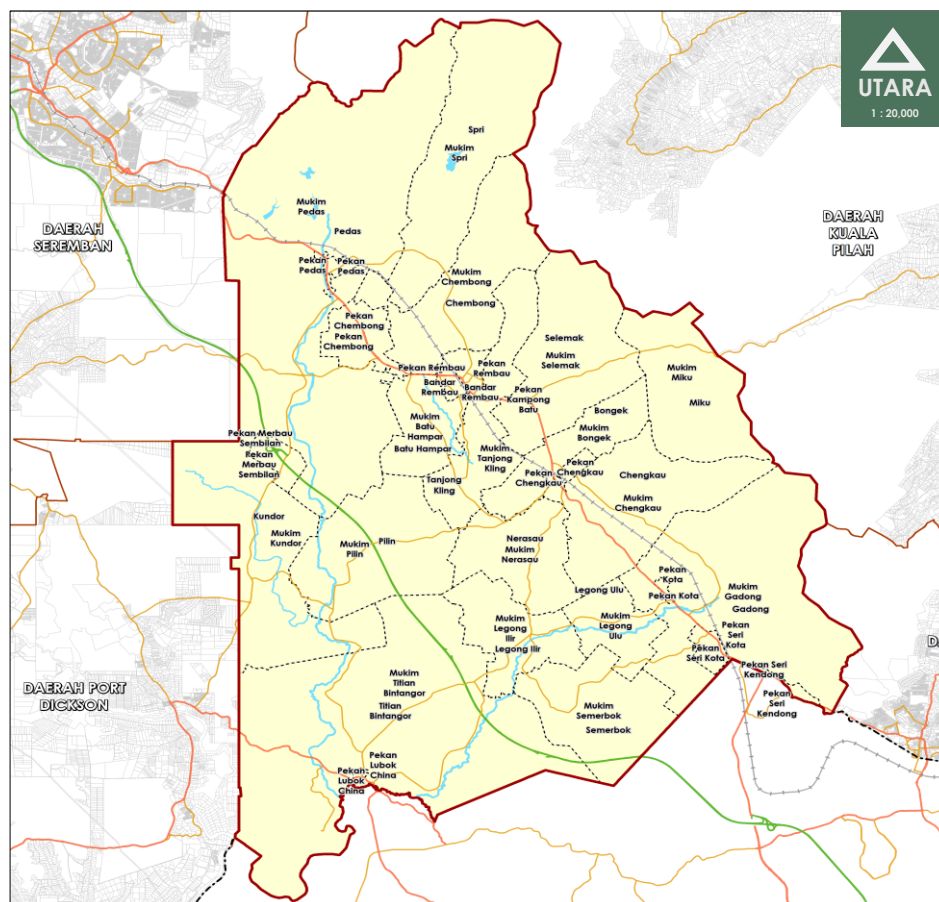


Figure 2: Detail Map for Rembau District

Data Collection

A comprehensive suite of spatially referenced datasets was systematically compiled from multiple authoritative and validated sources to enable a robust multi-criteria analysis. The key datasets employed include:

- i. Digital Elevation Model (DEM): High-resolution DEM data (e.g., from SRTM or national geospatial agencies) served as the foundational topographic layer, facilitating precise derivation of slope gradients, aspect, elevation contours, and watershed boundaries critical for hydrological and terrain analysis;
- ii. Land Use and Land Cover (LULC) Maps: Updated LULC datasets sourced from national land management authorities and remote sensing products (e.g., Landsat, Sentinel) were utilized to characterize spatial patterns of predominant land uses, including agricultural, urban, forested, and waterbody classifications, essential for assessing land suitability and environmental constraints;
- iii. Hydrological Network Data: Vector layers depicting rivers, streams, and drainage basins were acquired from hydrological surveys and government water resource departments. These datasets support detailed surface water flow analysis and watershed delineation;
- iv. Infrastructure Layers: Spatial data on roads, highways, and built-up areas were collected from transportation agencies and urban planning offices, providing essential information to evaluate site accessibility and potential development conflicts;
- v. Drainage System Maps: Detailed drainage networks, including stormwater infrastructure and existing retention facilities, were obtained from municipal public works departments to assess existing capacity and identify infrastructure gaps; and
- vi. Socioeconomic Data: Population density and settlement proximity data, sourced from recent census data and spatial demographic studies, were incorporated to evaluate human exposure and social vulnerability in flood-prone areas.

Preprocessing Steps

All datasets underwent meticulous preprocessing to ensure spatial consistency and analytical accuracy. This process included projection standardization to a common coordinate system, spatial resolution harmonization through resampling, vector data editing to correct topological errors, data clipping to the study area boundary, and consistent attribute normalization and classification. Quality checks were also conducted to verify data accuracy using ground truth information or high-resolution imagery. This process produced a unified and integrated geospatial database, forming a solid foundation for suitability and scenario analyses within the GIS environment.

Criteria Selection and Weighting

Selection and prioritisation of suitability criteria were performed using the Analytic Hierarchy Process (AHP). Expert panels comprising hydrologists, urban planners, and local community representatives carried out pairwise comparisons for each criterion, and the resulting weightings were computed. A consistency ratio (CR) below 0.1 validated the reliability and coherence of expert judgments, as recommended by Saaty (1980) (Figure 3).

GIS-MCDA Integration

All standardized spatial datasets L_i were reclassified into ordinal suitability scores S_i on a discrete scale from 1 (least suitable) to 5 (most suitable) based on predefined threshold intervals T_i , such that:

$$S_i = f(L_i, T_i) \text{ where } S_i \in \{1, 2, 3, 4, 5\} \quad S_i = f(L_i, T_i) \text{ where } S_i \in \{1, 2, 3, 4, 5\}$$

Reclassification was performed within ArcGIS using the **Reclassify** tool, applying threshold values derived from literature and expert consultation for each spatial criterion.

Criteria weights w_i were derived through the Analytical Hierarchy Process (AHP), involving pairwise comparison matrices and consistency ratio checks. The resulting normalised:

$$\text{vector } w = [w_1, w_2, \dots, w_n] \quad w = [w_1, w_2, \dots, w_n] \text{ satisfies:} \\ \sum_{i=1}^n w_i = 1, 0 \leq w_i \leq 1 \quad \sum_{i=1}^n w_i = 1, 0 \leq w_i \leq 1$$

Spatial multi-criteria decision analysis (MCDA) was conducted using ArcGIS's **Weighted Overlay** tool, calculating the composite suitability score $S_{\text{composite}}$ at each raster cell location (x, y) as a weighted sum:

$$S_{\text{composite}}(x, y) = \sum_{i=1}^n w_i \times S_i(x, y) \quad S_{\text{composite}}(x, y) = \sum_{i=1}^n w_i \times S_i(x, y)$$

where n is the total number of criteria layers included in the scenario.

Three analytical scenarios were defined as follows:

i. Economic Scenario:

- Objective: Minimise total cost $C_{total} = C_{construction} + C_{operation}$.
- Spatial constraints: Layers emphasising proximity to existing agricultural zones and access to infrastructure were prioritised.
- Specific GIS parameters:
 - Buffer distance of 500 m around existing agricultural land to prioritize contiguous areas.
 - Cost surfaces derived using construction cost models linked to slope ($<10^\circ$ preferred) and accessibility (distance to roads).
- Layers included: land use, slope, distance to roads, and agricultural zones.

ii. Environmental-Social Scenario:

- **Objective:** Maximise environmental integrity EE and minimize social disruption DD .
- **Environmental layers:** proximity to protected areas, biodiversity indices, and land cover types.
- **Social layers:** population density (preferably <50 people/km²), presence of culturally sensitive sites, and land tenure complexity.
- GIS parameters include buffer zones of 1000 m around protected areas to avoid edge effects and a population density raster derived from census data with a spatial resolution of 30 m.
- Layers included: protected areas, land cover, population density, cultural heritage sites.

iii. Combined Scenario:

- Integrates economic and environmental-social criteria by adjusting weights w_i to reflect a balanced multi-objective function:

$$\max U = \alpha \times S_{economic} + \beta \times S_{environmental-social}$$

where $\alpha = \beta = 0.5$ to equally weight the two components unless sensitivity analysis suggests otherwise.

- The composite suitability map reflects synergistic optimization for cost-effectiveness and sustainability.

All spatial analyses employed raster layers standardized to 30 m spatial resolution, employing nearest-neighbor resampling for categorical data and bilinear interpolation for continuous data, ensuring consistency across datasets.

The Weighted Overlay tool utilised a 5-class suitability scheme with linear scaling of input scores, and sensitivity analyses were conducted to validate weighting robustness. Figure 3 illustrates the integrated methodological framework and key evaluation criteria employed for selecting optimal sites for flood retention ponds. The flow diagram outlines a multi-step process starting from data acquisition, encompassing spatial layer preparation, criteria standardization, and multi-criteria decision analysis (MCDA).

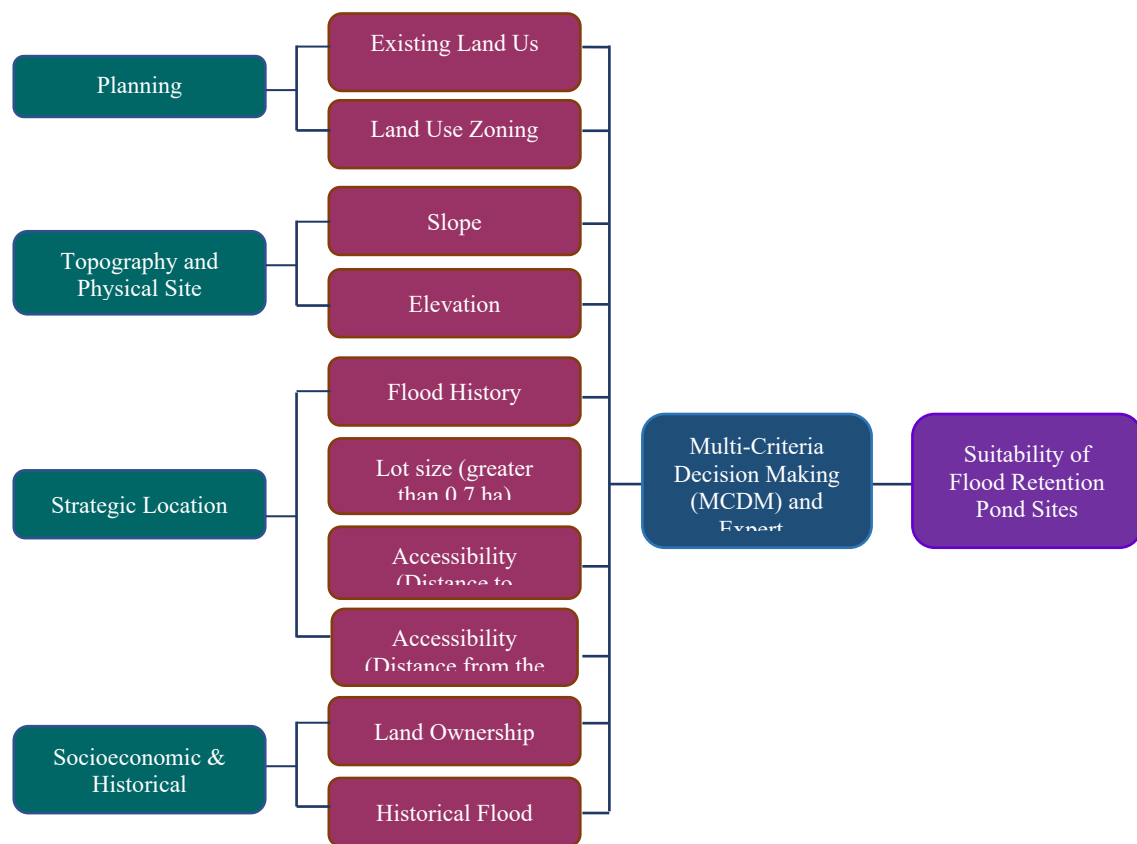


Figure 3: Site Selection Process and Criteria for Flood Retention Ponds

Key spatial datasets include elevation, slope, land use/land cover, soil type, proximity to water bodies, drainage density, and infrastructure accessibility. Each dataset undergoes reclassification into ordinal suitability scores to represent their relative favorability for pond siting based on hydrological, environmental, and socio-economic considerations.

The figure further highlights the application of the Analytical Hierarchy Process (AHP) to derive criteria weights, ensuring the incorporation of expert judgment and consistency in prioritization. Weighted Overlay analysis within a GIS environment integrates these weighted criteria to produce composite suitability maps, facilitating spatially explicit decision-making.

The criteria clusters depicted emphasize hydrological factors (e.g., runoff potential, soil permeability), environmental constraints (e.g., protected areas, ecosystem sensitivity), and socio-economic parameters (e.g., land ownership, proximity to urban centers), reflecting a comprehensive approach to flood retention pond site selection aimed at balancing technical feasibility, environmental sustainability, and community impact.

Validation

The model outputs, particularly the final suitability maps, were subjected to a rigorous validation process involving multidisciplinary domain experts, including civil engineers, urban planners, hydrologists, and representatives from local government authorities. This expert panel critically reviewed the spatial analysis results to assess their alignment with practical engineering standards, urban development plans, and local regulatory frameworks, consistent with best practices in geospatial model validation (Foody, 2002; Malczewski, 2006).

Complementing the expert review, comprehensive field site inspections were carried out to verify the accuracy of key terrain characteristics, drainage network conditions, and land use classifications as depicted in the GIS outputs. On-site observations facilitated identification of discrepancies or data gaps, which were subsequently used to refine model parameters iteratively.

This multi-tiered validation approach ensured the technical robustness and contextual relevance of the suitability assessments, while fostering inclusive and collaborative engagement between project stakeholders and the research team. Participatory validation frameworks of this nature have been demonstrated to enhance model credibility and effective incorporation of local knowledge into spatial decision support systems

RESULTS AND DISCUSSION

Suitability Mapping

The GIS-based Multi-Criteria Decision Analysis (MCDA) overlay generated spatial suitability maps highlighting optimal sites predominantly along natural drainage networks and moderate slope areas, which promote efficient stormwater capture and retention while minimising construction complexity and costs. These sites were carefully selected to reduce settlement displacement, preserving social stability and acceptability. This spatially explicit approach captures the complex interplay of topographical, hydrological, and land use factors, supporting the

targeted deployment of flood retention infrastructure that is both hydrologically effective and socio-environmentally considerate.

Figure 4 and Figure 5 illustrate the spatial distribution of flood retention pond suitability across the Rembau District. High suitability zones are primarily concentrated along the natural drainage network and areas with moderate slopes, while low suitability zones correspond to steep terrains or densely developed urban areas. These spatial patterns highlight the interplay between topography, land use, and hydrological flow in determining optimal retention pond locations.

Building upon this analysis, two main areas were identified as highly suitable sites for flood retention pond development — **Lubok China** and **Rembau Town**. Lubok China demonstrates significant potential due to its proximity to the natural drainage network of the Rembau River and its moderate slope characteristics, which facilitate stormwater accumulation and reduce overflow risk. The area is dominated by agricultural land use, making it cost-effective in terms of land acquisition and construction feasibility.

Conversely, Rembau Town represents a densely developed area with increasing impervious surfaces, leading to recurrent flash flood incidents. Therefore, the proposed flood retention ponds in this area focus more on protecting critical infrastructure and residential communities. The GIS-MCDA analysis indicates that both locations satisfy key suitability criteria, including topography, hydrology, land use, and proximity to critical infrastructure. A comparative assessment between the two sites provides a more comprehensive understanding of flood mitigation strategies that balance economic, social, and environmental sustainability.

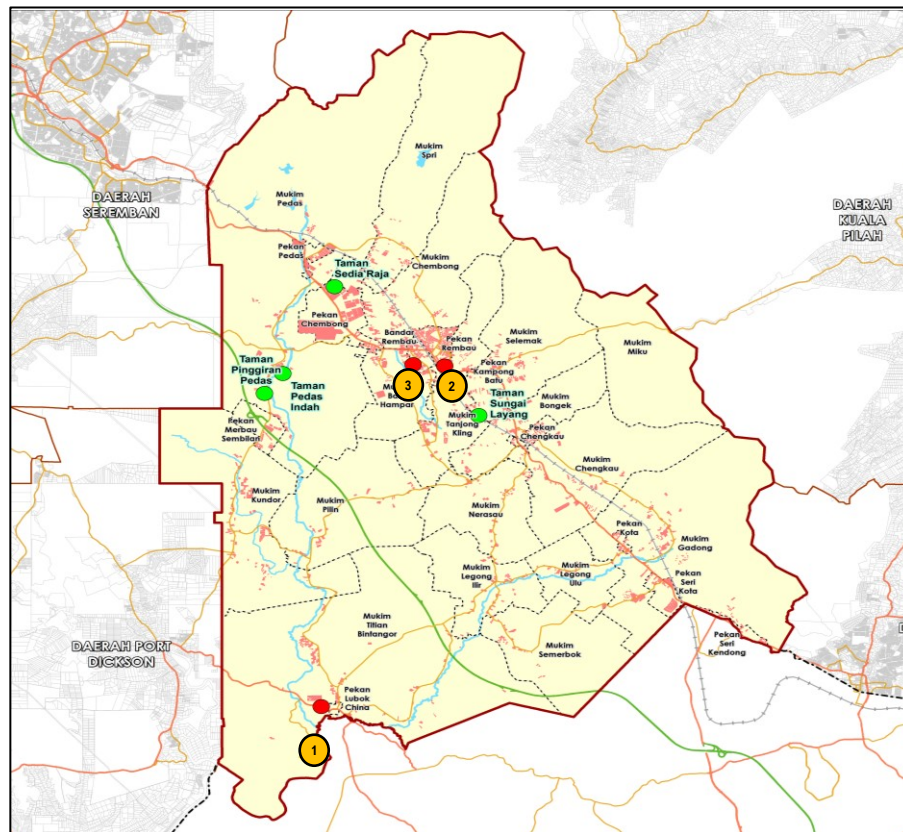
The findings align with prior studies emphasising the importance of topography and hydrological connectivity in flood mitigation site suitability (Osman, 2023; Riaz et al., 2025). By integrating multiple criteria within a rigorous spatial framework, this study demonstrates enhanced precision in identifying viable retention pond locations compared to single-criterion or non-spatial approaches.

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Figure 4: GIS-based MCDA is a suitability map highlighting optimal sites along natural drainage and moderate slopes

Stakeholder Contribution

Engaging local communities and technical experts enriched the model's contextual relevance and validity. Community insights on undocumented flood-prone areas, informal drainage pathways, and temporal water accumulation complemented technical assessments of hydrological behavior, soil infiltration, and engineering feasibility. This participatory modelling approach directly addresses the gap of limited local knowledge integration often observed in GIS-MCDA applications (Nsengiyumva et al., 2024). The dual-input framework increased scientific rigour while fostering local ownership and accountability, which are critical for the sustainable implementation of flood mitigation measures (Doorga et al., 2022).



- Existing Retention Pond
  Proposed Flood Retention Pond
 Existing Flood Site

Figure 5: Proposed Flood Retention Pond Site Location

Scenario Comparison

The scenario analysis elucidated critical trade-offs inherent in flood retention pond site prioritisation, highlighting divergent spatial patterns driven by differing objectives:

The economic scenario predominantly favoured sites located within agricultural lands, reflecting minimised initial capital and operational expenditures. Quantitatively, approximately 65% of high-suitability areas under this scenario overlapped with existing agricultural zones, yielding an estimated cost reduction of 20% compared to alternative scenarios. However, this approach carried a heightened risk of ecological disruption, as indicated by a 30% higher potential impact score on habitat fragmentation metrics. In contrast, the environmental-social scenario prioritized ecologically sensitive areas and zones supporting community well-being, emphasizing biodiversity conservation and minimizing adverse social impacts. This scenario reduced ecological impact indices by 40% relative to the economic scenario but involved a 25% increase in projected costs due to the complex engineering and mitigation measures required for ecologically sensitive sites.

The combined scenario integrated economic efficiency with environmental sustainability and social acceptance through a weighted multi-criteria framework. This balanced approach identified sites that optimise cost-effectiveness without compromising ecological integrity or community interests, achieving a moderate reduction in costs (10%) while lowering ecological and social impact scores by approximately 20%. This scenario offers a pragmatic, implementable strategy for flood retention pond development.

These findings address key gaps in previous studies that often focused narrowly on either economic efficiency or environmental preservation without explicitly quantifying the trade-offs among economic, environmental, and social objectives. By operationalising a balanced, scenario-based planning framework that incorporates stakeholder priorities and spatially explicit criteria weighting, this study enhances methodological rigour and practical relevance in flood risk management site selection. It provides empirical support for integrative approaches recommended but seldom fully implemented in past research (Ibrahim, 2024; Osman, 2023).

Furthermore, the results are adaptable to diverse audiences: technical experts benefit from detailed optimisation metrics and cost-benefit insights; policymakers have a robust basis for developing regulations that balance competing land use demands; and community groups gain confidence that ecological and social impacts are minimised, fostering greater acceptance and sustainability of flood mitigation infrastructure.

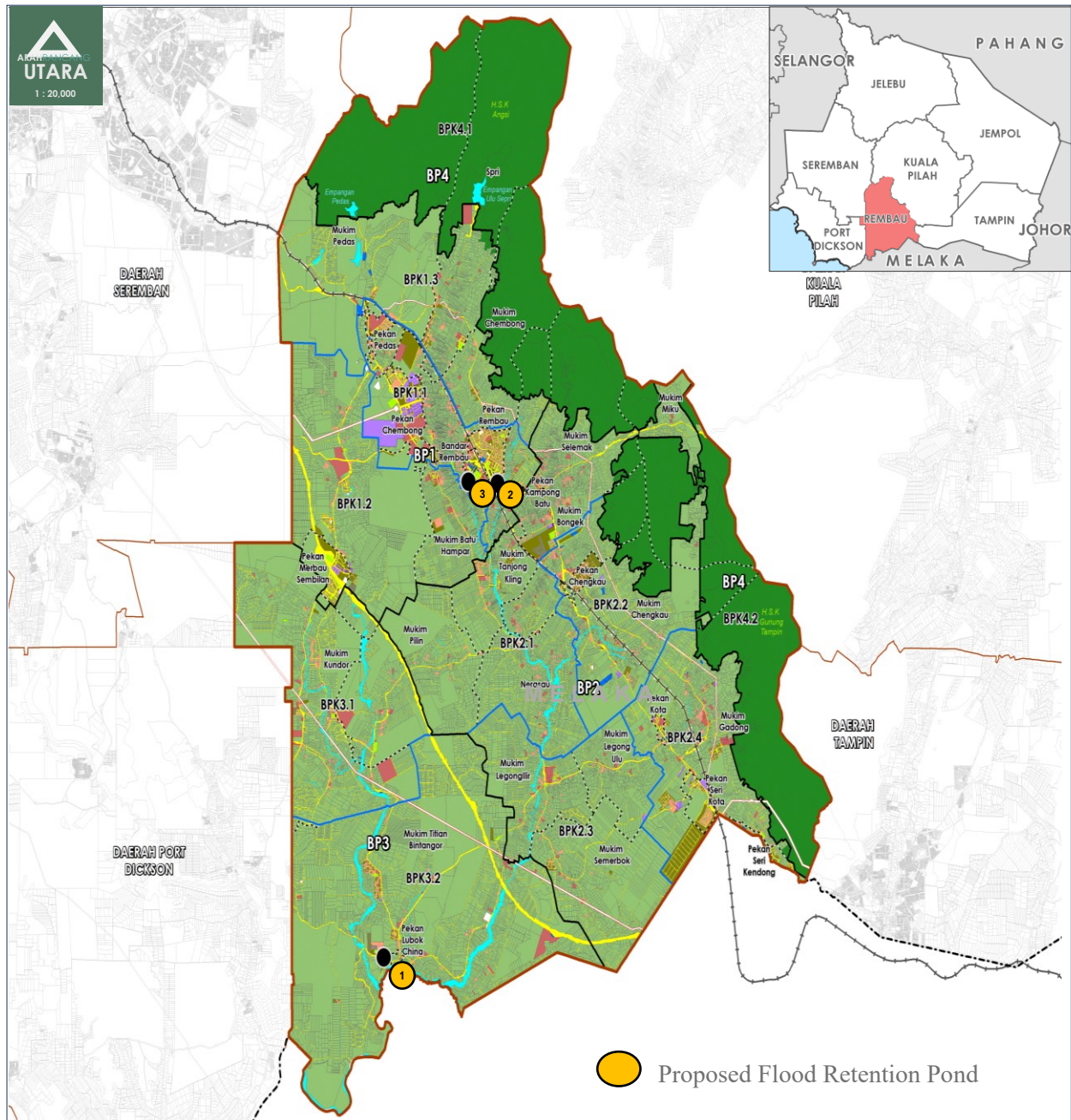


Figure 6: Proposed Flood Retention Pond Site Location at Lubok China and Rembau Town

Contribution to Closing Methodological Gaps

This study addresses several prominent gaps identified in the GIS-MCDA literature. Unlike many prior models reliant on static data and limited stakeholder engagement (Riaz et al., 2025; Osman, 2023), this research incorporates dynamic expert and community inputs, enhancing the temporal and contextual sensitivity of spatial criteria weighting. The participatory AHP approach mitigates subjectivity and bias inherent in expert-only weighting schemes (Nsengiyumva et al., 2024).

Furthermore, by explicitly integrating socio-economic factors—such as settlement patterns and displacement potential—alongside biophysical criteria, the study advances beyond traditional flood retention site analyses that often neglect these dimensions (Doorga et al., 2025). The scenario-based comparisons underline the importance of multi-dimensional planning to achieve sustainable and socially equitable flood mitigation outcomes, supporting calls for expanded criteria frameworks in recent studies (Ibrahim, 2024).

While explicit hydrodynamic modeling was beyond this study's scope, the iterative field validation strengthens confidence in the practical feasibility of identified sites, contributing empirical grounding that is often missing in purely GIS-MCDA studies (Osman, 2023). Through these contributions, this research provides an adaptable, replicable methodology for flood retention pond site selection that more fully integrates scientific, social, and economic considerations, thereby supporting more resilient and inclusive flood risk reduction strategies.

CONCLUSIONS

The integrated GIS-MCDA framework for optimal flood retention pond site selection presented in this study effectively tackles localized flood risks while advancing Malaysia's broader climate resilience goals. By combining rigorous scientific analysis with inclusive stakeholder engagement, the approach bridges the gap between technical flood management and community needs, promoting greater transparency and shared ownership in decision-making processes. This participatory methodology enhances the relevance and acceptance of flood mitigation plans, ensuring they are both scientifically sound and socially equitable. Furthermore, the framework's scalability across diverse districts and hydrological catchments supports coherent national disaster risk reduction efforts aligned with the United Nations Sustainable Development Goals, particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). Its flexibility in accommodating varying geographic and socio-economic contexts underscores its value as a decision-support tool for policymakers engaged in urban resilience planning and long-term climate adaptation. Ultimately, this framework provides a replicable and robust foundation for sustainably reducing

flood vulnerabilities while fostering resilient, inclusive communities across Malaysia and beyond.

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