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INTEGRATING ANALYTICAL HIERARCHICAL PROCESS AND QUADRANT MATRIX ANALYSIS IN A DECISION ANALYTICS FRAMEWORK FOR FLOOD MANAGEMENT PLANNING

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ABSTRACT

Flood management planning (FMP) requires decision analytics approaches that can prioritize multiple criteria while accounting for uncertainty in expert judgment and data availability. This study presents a decision analytics framework that integrates the Analytic Hierarchy Process (AHP) and Quadrant Matrix Analysis (QMA) to identify key flood and trade-off criteria, and to develop a structural plan to support FMP decision making. Using the PESTEL framework, a refined set of 40 criteria was assessed through structured elicitation involving 10 experts from diverse disciplines. AHP was applied to find the relative importance of each criterion, while QMA mapped the criteria by both importance and certainty. The AHP results indicate that the Political, Legal, and Economic domains were the main driving criteria for FMP. At the criterion level, P1: Fair distribution of resources was ranked first (0.1917), followed by L1: Land ownership for flood protection (0.0739) and L4: International constitutional standards and guidelines (0.0543). QMA, in contrast, identified 25 “Must-Have” criteria, primarily within the Environmental, Social, and Technological domains. A comparison of AHP and QMA outputs reveals that criterion certainty significantly affects practical applicability, even for criteria

that are highly ranked in importance. By jointly considering importance and certainty, EC7: Economic loss, EC5: Financial budget, and L3: Flood Disaster Institutional emerged as "Very Highly Ranked" and "Must-Have". The framework also incorporates a structured criterion-reflection stage, informed by the Weather Model, to refine expert evaluations. Overall, the proposed decision analytics framework enhances clarity and consistency in the selection of criteria and offers practical guidance for FMP in Malaysia and other planning contexts.

Keywords: AHP, criteria analysis, decision making, flood management planning, quadrant matrix analysis.

INTRODUCTION

Floods are among the most frequent and devastating natural hazards, exerting profound impacts on socio-economic systems and environmental sustainability. Beyond causing extensive damage to infrastructure and property, floods disrupt economic activities and pose significant risks to human life. From 1992 to 2022, 4,578 flood disasters were documented globally, affecting over 2.9 billion people and causing approximately 210,250 deaths (CRED, 2023; Liu et al., 2024). The scale and persistence of these impacts highlight the critical importance of developing data-driven approaches to flood risk assessment and management. The growing escalation in the frequency and severity of flood occurrences in recent decades has highlighted the critical need for evidence-based flood management planning (FMP). The development of such plans necessitates a comprehensive evaluation of criteria across both macro and micro domains.

An effective FMP is essential for reducing the impact of floods, and its effectiveness is influenced by the factors and criteria used to formulate it. The criteria analysis for FMP is a multifaceted and challenging task that requires meticulous consideration of various aspects. Relying exclusively on a single perspective would obscure the overall picture and thus undermine the effectiveness of decisions. Various methodologies have been employed to support the criteria analysis for FMP, such as the Analytical Hierarchy Process (AHP) and Quadrant Matrix Analysis (QMA). These tools involve analyzing multiple criteria to make informed decisions about intricate FMPs. The AHP and QMA methodologies entail subjective assessments and evaluations that necessitate expert review to ensure that the analyses and resulting decisions are sound. An expert review can help to identify potential biases or gaps in the analysis, provide guidance on the relative importance of different criteria, and ensure that the methods are being used appropriately and that the weights assigned to each criterion are reasonable and accurate. This can help to prevent errors and biases that can impact the quality of the analysis and the resulting decisions.

The main objective of the current study is to enhance FMP decision-making by systematically prioritizing flood-related criteria that drive effective FMP. This study advances the existing body of knowledge by providing empirical insights into the relative importance of critical flood management factors, as well as the degree of certainty associated with their evaluation. Furthermore, it identifies potential limitations inherent in the AHP and QMA approaches and proposes methodological refinements to strengthen their applicability in flood management contexts. Specifically, the study pursues three interrelated objectives. First, it applies the AHP technique to rank and evaluate flood management criteria at both local and global levels. Second, it employs QMA to map these criteria according to their relative importance and certainty. Third, it proposes a macro domain criteria analysis framework to support a more systematic and evidence-based FMP.

The significance of this study stems from its structured, integrative analytical approach to evaluating the criteria underpinning effective flood management policies and strategies. By combining multi-criteria decision analysis with quadrant-based mapping, the proposed framework provides a basis for informed decision-making and strategic prioritization to mitigate flood impacts. This paper is organized as follows: Section 2 presents the study's background, Section 3 outlines the methodological framework, and Section 4 reports the results and analysis. The findings are discussed in Section 5, and Section 6 concludes the study by outlining key implications for practice and avenues for future research.

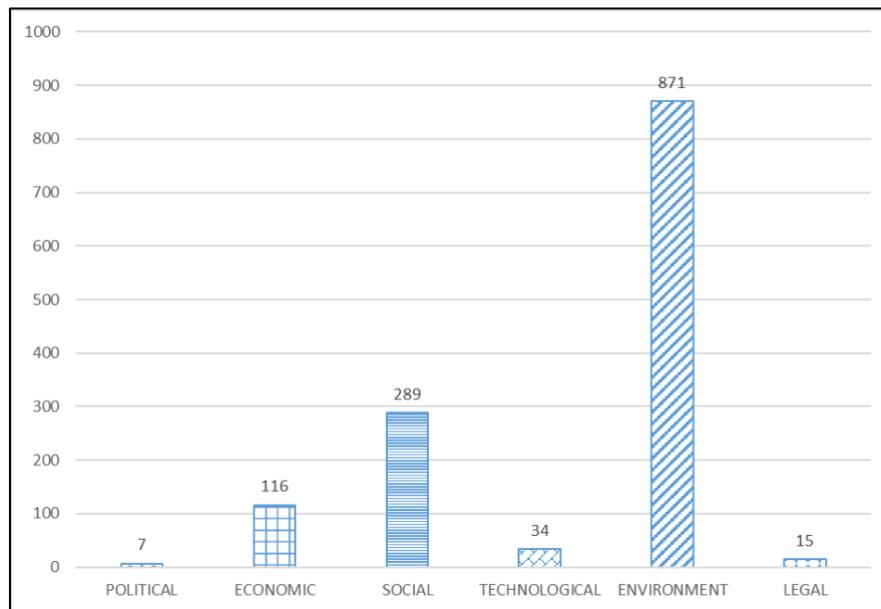
LITERATURE REVIEW

The development of effective flood management planning (FMP) has become increasingly critical amid the rising frequency and intensity of flood events in recent years. Climate change has further amplified flood risks, exacerbating both their severity and spatial extent. Despite ongoing efforts in preparedness, planning, and mitigation, existing flood management measures remain inadequate to address the growing complexity and scale of flood impacts. In the Malaysian context, where flood disasters pose substantial socio-economic and environmental challenges, the need for systematic and evidence-based decision-making frameworks is particularly pronounced. By integrating the Analytical Hierarchy Process (AHP) and Quadrant Matrix Analysis (QMA) with expert-driven evaluation, this study provides a structured approach to enhancing the FMP decision-making process. The findings offer practical and methodological insights that can support Malaysian stakeholders in prioritizing critical criteria and strengthening strategic flood management interventions.

Previous studies (Abdullah et al., 2021; Khiavi et al., 2024) highlight the importance of analyzing various criteria for different flood measures to aid in decision-making for FMP for various Disaster Management Plan (DMP) phases based on the MCDA technique. Further analysis of FMP criteria within the PESTEL macro domain framework (Political, Economic, Social, Technological, Environmental, and Legal) indicated a pronounced dominance of Environmental domain criteria over the other domains, followed by the Social and Economic domains, as evidenced in Figure 1 (Abdullah et al., 2022). Moreover, the results revealed that a substantial proportion of existing studies concentrated on single-domain perspectives, particularly within the Environmental domain (see Table 1). These findings highlight the underlying rationale of FMP, which aims to mitigate the adverse impacts of flooding across economic, social, and environmental dimensions. However, the observed domain imbalance suggests that current FMP approaches may overlook the multidimensional nature of flood risk and management. Consequently, future FMP decision-making frameworks should incorporate a broader, more integrated set of criteria across multiple macro domains to enhance analytical feasibility and support more comprehensive, informed decision-making.

Figure 1

Criteria Distribution based on PESTEL Macro Domain



Source: Abdullah et al., 2022

Table 1

Distribution of Macro Domain Criteria

No	Macro Domain	Number of Study	No	Macro Domain	Number of Study
1.	EN	68	11.	EC + S	2
2.	EC + S + EN	19	12.	EC + S + EN + L	1
3.	S + EN	11	13.	EC + T + EN	1
4.	EC + S + T + EN	6	14.	EC + T + L	1
5.	EC + S + T + EN + L	4	15.	P + EC + S + EN	1
6.	P + EC + S + T + EN	3	16.	P + S + EC	1
7.	S	3	17.	S + EN + L	1
8.	S + T + EN	3	18.	S + T	1
9.	EC	2	19.	T + EN	1
10.	EC + EN	2			

P: Political, E: Economic, S: Social, T: Technological, EN: Environmental, L: Legal

Source: Abdullah et al., 2022

Previous studies have demonstrated a significant increase in the compounding domains for FMP. Yang, Xu, Lian, Ma, and Bin (2018) employed a set of 12 criteria spanning the economic, social, technological, and environmental domains. In a similar vein, Zahmatkesh and Karamouz (2017) assessed 54 criteria drawn from the economic, social, technological, environmental, and legal domains. The identification, prioritization, and ranking of criteria across multiple macro domains were conducted prior to their application to various flood measures, with both studies focusing on flood vulnerability. While this approach has demonstrated efficacy, it may not necessarily yield all-encompassing FMP

strategies that adequately address all macro domains. This underscores the necessity for a more equitable approach to FMP strategies, considering that the other domains are equally important.

The effectiveness of a decision-making process depends not only on the integration of relevant criteria but also on the extent to which such criteria are available, accessible, and clearly defined. Addressing ambiguity or uncertainty within the criteria is essential to ensure methodological rigor and enhance the reliability of the resulting decisions. Consistent with the analytical approach advanced by Iacovidou et al. (2017), this study evaluates each criterion along two dimensions: relative importance and level of certainty. Relative importance refers to the degree to which a criterion influences FMP decisions in comparison with other identified criteria. Certainty, on the other hand, reflects the extent to which a criterion is inherently sufficient and free from ambiguity. Assessing both dimensions enables a more systematic and transparent evaluation of the criteria, thereby contributing to the formulation of more effective FMP strategies.

Recent research on multi-criteria decision analysis (MCDA) in flood disaster management has incorporated broad, macro-level criteria; however, these selections often lack a comprehensive justification, and discussions on criteria certainty remain limited. Such omissions may introduce complexity and reduce the feasibility of FMP decision processes. To address this gap, the present study employs expert judgment to assess both the importance and certainty of criteria, subsequently positioning them within a two-dimensional quadrant for clearer interpretation. Expert elicitation plays a critical role in enhancing the accuracy and credibility of the analysis, particularly within the integrated framework that combines the AHP and QMA.

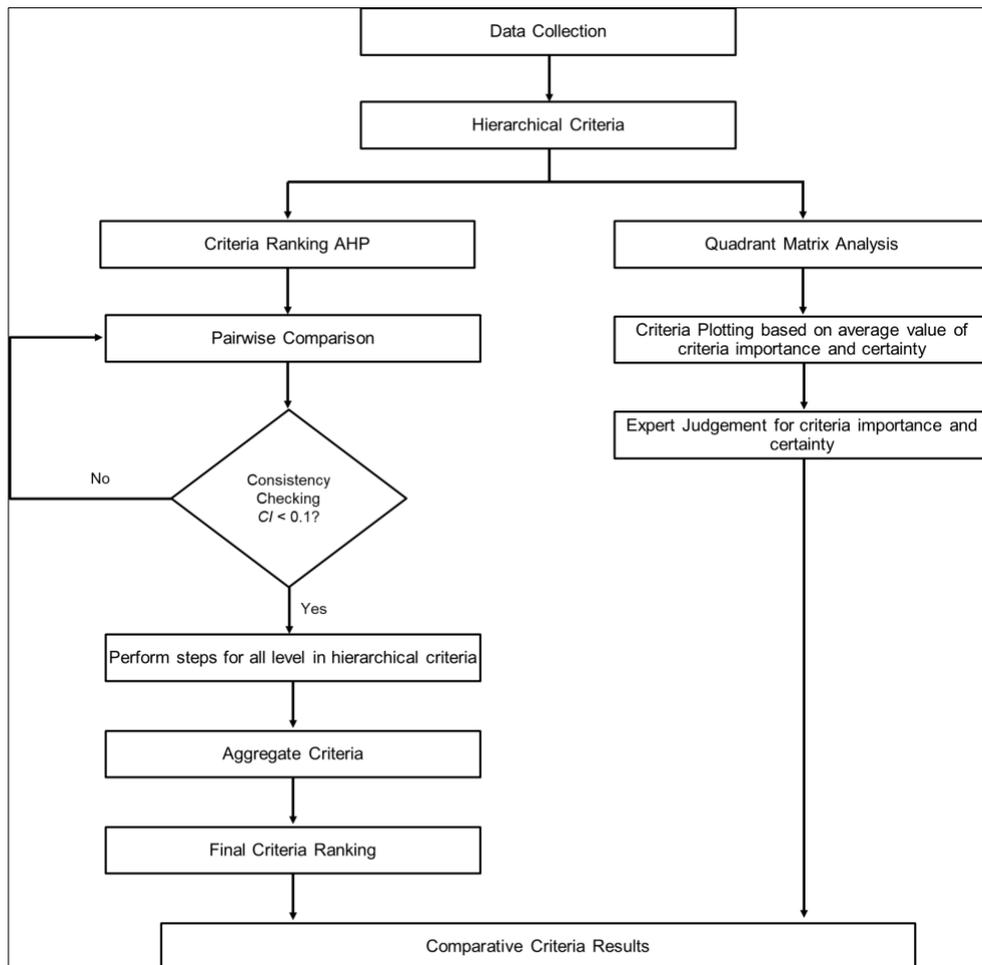
METHODOLOGY

This study engaged in a critically informed and methodologically rigorous analysis of the previously identified PESTEL macro domain criteria. This evaluation was conducted through expert elicitation, which involved prioritizing and ranking the criteria and examining their relative importance and degree of certainty. The same panel of experts participated in both stages of assessment to ensure methodological consistency and reliability. To operationalize this evaluation, the AHP was employed to establish hierarchical rankings and prioritize the criteria. In contrast, the QMA was applied to assess the relative importance and associated certainty of the criteria.

The integrated application of these two methodological approaches, illustrated in Figure 2, provides a structured, evidence-driven analytical framework for examining criteria relevant to FMP. This combined approach enhances the transparency and comprehensiveness of the assessment process.

Figure 2

A Flow Diagram of the Detailed Study Process



Data Collection

This study evaluated the PESTEL-based criteria by drawing on the earlier work of Abdullah et al. (2021), which investigated the application of multi-criteria decision analysis (MCDA) in water-related disaster contexts. The PESTEL strategic analysis framework was employed as a structured, systematic lens for assessing the criteria (Dockalikova & Klozikova, 2014). This framework facilitates the identification and examination of macro domain factors that influence both the operational and strategic dimensions of flood FMP. Considering these domains enables decision-makers to incorporate a broader contextual understanding and to integrate both macro- and micro-level considerations, thereby supporting more informed and comprehensive FMP decisions.

A systematic and extensive literature review was undertaken, comprising 131 research articles. From this review, 1,332 criteria were extracted and subsequently categorized within the PESTEL framework. Through a multi-stage refinement process, a final set of 40 criteria was selected for inclusion in this study (see Table 2). The criteria mapping process involved four key steps: (1) mapping the extracted criteria to the PESTEL macro domains; (2) eliminating duplicates; (3) clustering similar or overlapping criteria; and (4) renaming and standardizing the criteria to ensure conceptual clarity and analytical coherence.

Table 2

PESTEL Macro Domain Criteria

Domain	Sub-criteria
Political (P)	Fair distribution of resources (P1) and Government capacity & capability (P2)
Economic (EC)	Damage & Loss to Building (EC1), Damage & Loss in Infrastructure (EC2), Damage & Loss in Economic Activities (EC3), Investment Cost (EC4), Financial Budget (EC5), Economic Density (EC6), and Economic Loss (EC7)
Social (S)	Quality of Life & Human Needs (S1), Transportation Access(S2), Telecommunication Capacity (S3), Religious, Cultural & Heritage (S4), Personal Loss (S5), Town planning (S6), Health, Safety, Welfare & Lifestyle (S7), and Education & Awareness (S8)
Technological (T)	Flood Early Warning System (T1), Data collection and analyses (T2), Flood System/Modelling (T3), Education & Awareness (T4), Flood Structure & Control (T5), Communication (T6), and Financial Budget (T7)
Environmental (EN)	Water Quality (EN1), Land use & Planning (EN2), Hydrology (EN3), Topographic/Physical Data (EN4), Protection of wildlife habit (EN5), Protection & improvement of natural landscape (EN6), Water Supply Quantity (EN7), Flood risk management plan (EN8), Water infrastructure for Flood Protection (EN9), Damage in land use and land cover (EN10), Flood Mitigation Plan (EN11), and Biodiversity (EN12)
Legal (L)	Land ownership for flood protection (L1), Government Law & Policy Regulation (L2), Flood Disaster Institutional (L3), and International Constitutional & Standard, Guidelines (L4)

A criteria scoring session was conducted with the participation of ten experts, based on a set of 40 criteria. The experts involved in the project possessed varied backgrounds in research, technical, and management domains, comprising a gender distribution of six females and four males. Their collective experience spanned 10 to 20 years. The experts were tasked with assessing the criteria for both methodologies.

Analytical Hierarchical Process (AHP) for Criteria Prioritization

The AHP was employed to rank the criteria by eliciting expert judgments of their relative importance. The use of AHP ensured that the prioritization process was conducted systematically, allowing expert evaluations to be incorporated in a transparent, structured, and methodologically defensible manner.

Originally developed by Saaty (1980), AHP is a semi-quantitative decision-making methodology that organizes complex problems into a hierarchical structure comprising multiple levels, namely, the overarching goal, relevant criteria, potential sub-criteria, and available alternatives (Saaty & Vargas, 1998). Within this framework, the criteria are presumed to be mutually independent and do not exert reciprocal influence on the alternatives, which are likewise considered independent of one another. A key component of AHP is the pairwise comparison procedure, through which experts compare criteria in pairs to determine their relative weights for prioritization (Triantaphyllou & Mann, 1995). These comparisons are operationalized using Saaty’s fundamental scale (see Table 3), which assigns numerical values ranging from 1 to 9 to express the degree of importance of one criterion relative to another. This quantitative scale enables the systematic conversion of qualitative expert judgments into numerical weights, supporting consistent prioritization.

Table 3

Saaty's Scale Table

Intensity of Importance	Definition	Intensity of Importance	Definition
1	Equal Importance	7	Very Strong Importance
3	Moderate Importance	9	Extremely Strong Importance
5	Strong Importance	2,4,6,8	Intermediate Values (for compromise between the above values)

Source: Saaty, 1997

The AHP was applied in the current research for its inherent advantages, in particular, its structured decision-making scaffold, its consistency-enhancing capability, and its capacity to accommodate numerous criteria and sub-criteria. Furthermore, the methodology allows the evaluation of both quantitative and qualitative factors (Wedley, 1990). The steps involved in AHP are:

Step 1: Define the decision goal and develop a hierarchical structure of criteria (see Figure 4),

Step 2: Construct pairwise comparison matrices,

Let $A = (a_{ij})[a_{ij}]_{n \times n}$ denote the pairwise comparison matrix, where a_{ij} represents the relative importance of criterion i over criterion j , and $a_{ji} = \frac{1}{a_{ij}}, a_{ii} = 1$

Step 3: Calculate the criteria weights $\mathbf{w} = w_1, w_2, \dots, w_n$ as in Equation 1,

$$A_{\mathbf{w}} = \lambda_{\max} \mathbf{w}, \tag{1}$$

Where λ_{\max} is the maximum eigenvalue of A . The normalized weight of each criterion is given by Equation 2:

$$w_i = \frac{w_i}{\sum_{i=1}^n w_i}, i = 1, \dots, n. \tag{2}$$

Step 4: Calculate the consistency ratio,

where the consistency of judgments is evaluated first using the Consistency Index (CI), as in Equation 3:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

Then, calculate the Consistency Ratio (CR) as in Equation 4:

$$CR = \frac{CI}{RI} \tag{4}$$

where RI is the Random Index. A comparison matrix is considered consistent if $CR < 0.10$.

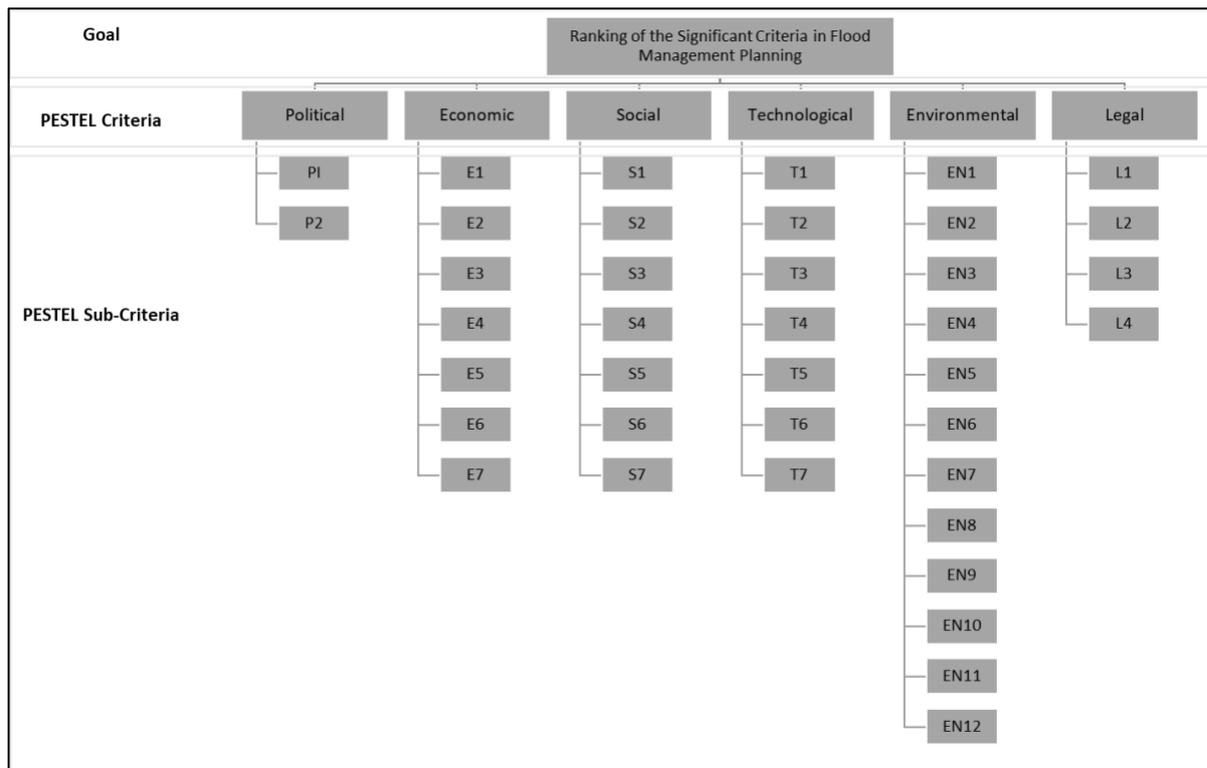
Step 5: Calculate the overall scores as in Equation 5.

$$w_i = \frac{x_{ij}}{\sum_{j=1}^m x_{ij}}, S_j = \sum_{i=1}^n w_i s_{ij}. \tag{5}$$

where w_i denotes the derived criterion weight and s_{ij} represents the normalized performance score of the alternative j under criterion i

Figure 4

Criteria Hierarchical Structure



Quadrant Matrix Analysis (QMA) for Strategic Criteria Analysis

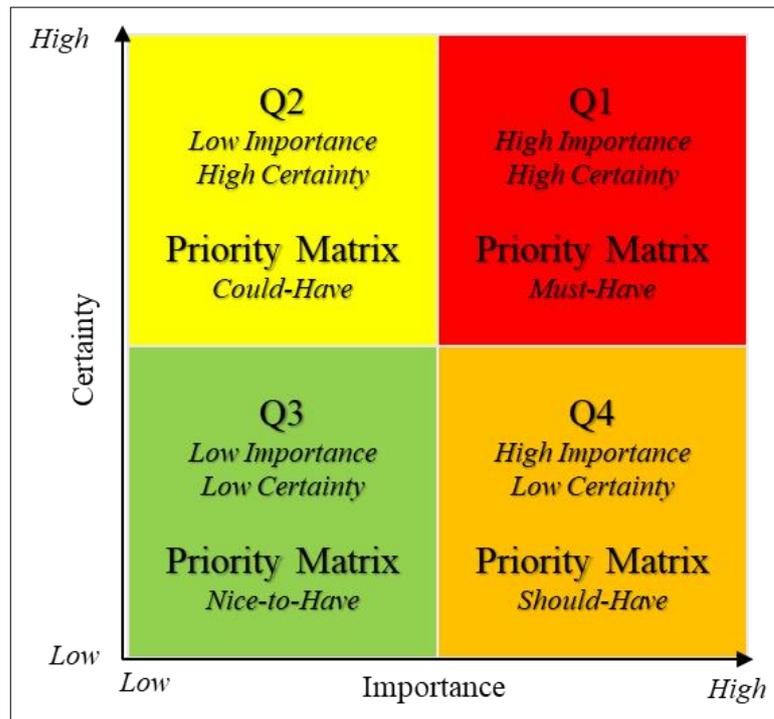
This study further examined the identified criteria using a QMA to assess the interplay between their relative importance and the degree of certainty associated with each criterion. QMA is widely recognized as an analytical tool that supports strategic decision-making by visually mapping two key variables within a four-quadrant matrix, thereby enabling clearer interpretation of complex relationships. This visual representation enhances the communication of analytical outcomes to decision-makers and stakeholders, facilitating a more intuitive understanding of critical issues and supporting the formulation of strategic interventions.

Guided by the methodological procedures outlined by Lynch, Carver Jr., and Virgo (1996), the analysis followed several key steps: (1) define the target of interest-flood decision-maker, (2) specify interest-flood criteria, (3) determine significant and relevant criteria, (4) establish research protocol- expert rate the criteria, (5) narrowing the criteria list, (6) pre-test the list (mock-up test). Some modifications were made to make them fit this study.

As illustrated in Figure 5, the criteria were then positioned within the QMA framework using two principal dimensions. The horizontal axis represents the relative importance of the criteria, while the vertical axis denotes the corresponding level of certainty. The matrix is segmented into four quadrants: Q1, Q2, Q3, and Q4. Each quadrant conveys distinct strategic implications regarding how criteria should be interpreted, prioritized, and acted upon. This structured mapping facilitates a nuanced and evidence-driven evaluation of the criteria, enabling decision-makers to identify priority areas, anticipate potential challenges, and develop more targeted and effective FMP strategies.

Figure 5

Quadrant Matrix Dimension and Matrix Priority



RESULTS AND DISCUSSION

Table 4 presents the results of the AHP consistency assessment for each PESTEL macro domain (Level 2). The consistency ratios obtained fall within the acceptable threshold, indicating that the experts’ pairwise comparisons were logically coherent and their judgments sufficiently reliable for subsequent decision-making analysis. Following this validation, Table 5 summarizes the derived weights and corresponding rankings of the PESTEL macro-domains based on the AHP computation. The results reveal that the Political domain emerged as the most influential criterion (weight = 0.24), followed by the Legal domain (0.21). The Economic (0.17) and Social (0.15) domains occupied intermediate positions, while the Technological and Environmental domains exhibited comparatively lower weights (both 0.11). These results reflect the relative emphasis that experts place on governance-related and regulatory dimensions in shaping effective flood mitigation planning decisions.

Table 4

Aggregate Consistency Test Result

Level	Consistency Ratio	Consistency Test
PESTEL Criteria	0.02	Accepted
Political	0.00	Accepted
Economic	0.02	Accepted
Social	0.01	Accepted
Technological	0.01	Accepted
Environmental	0.01	Accepted
Legal	0.04	Accepted

Table 5

Aggregate Criteria Weight

Domain	Weight	Ranking
Political	0.24	1
Economic	0.17	3
Social	0.15	4
Technological	0.11	5
Environmental	0.11	6
Legal	0.21	2

Experts' AHP-based judgements were aggregated and shown in Table 6. For each PESTEL macro domain, the sub-criteria (Level 3) weight and rank were calculated locally and globally. Political and Legal were the top two in global weight and rank. Notably, P1 was determined to be a Very Highly Ranked Criteria (weight 0.1917), followed by L1 and L4, the top three very important sub-criteria. Interestingly, all Legal sub-criteria were deemed very important by experts, placing them among the top ten Very Highly Ranked Criteria. It is noteworthy that over 80% of the sub-criteria for Technological and Environmental were ranked Medium or Low. Even though these, especially Environmental, are related to FMP decisions (Abu El-Magd et al., 2020; Hammami et al., 2019; Khiavi et al., 2024), experts' feedback revealed that other criteria would carry more weight in decision making, potentially altering the decisions. This suggests that experts' experience highlights the need for additional criteria, not just from one perspective. Incorporating more criteria would provide a more thorough understanding, grounded in cohesive criteria recognized as pivotal to the FMP.

From another perspective, based on local rankings of the sub-criteria, the results show which sub-criteria to prioritize within their domains. In cases where the highest-ranked sub-criteria are not applicable or cannot be implemented, the subsequent sub-criteria in the ranking can be adopted as substitutes or used in trade-off analyses. This prioritization structure supports decision-makers in systematically selecting evaluation criteria and facilitates more transparent, informed choices. Consequently, the findings provide policymakers and stakeholders with actionable guidance for designing an FMP that emphasizes the most critical criteria identified in this study.

Table 6

Aggregate Local and Global Weight and Ranking

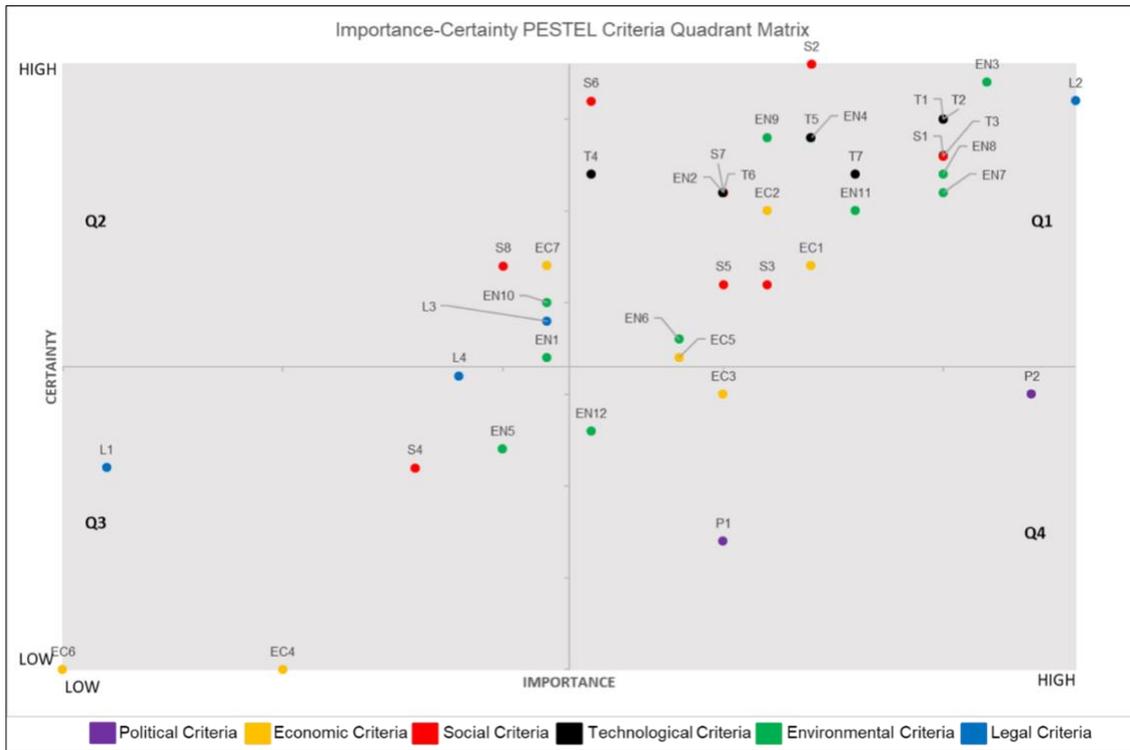
Domain	Domain Weight	Domain Criteria	Local Weight	Ranking	Global Weight	Ranking	Criteria	Domain Weight	Domain Criteria	Local Weight	Ranking	Global Weight	Ranking
Political	0.24	P1	0.7950	1	0.1917	1	Environmental	0.11	EN1	0.0699	10	0.0079	38
		P2	0.2050	2	0.0494	6			EN2	0.0906	3	0.0102	31
Economic	0.17	EC1	0.1858	2	0.0318	8			EN3	0.0824	6	0.0093	34
		EC2	0.1300	4	0.0223	11			EN4	0.0856	4	0.0097	32
		EC3	0.1176	6	0.0202	15			EN5	0.0661	12	0.0075	40
		EC4	0.1150	7	0.0197	16			EN6	0.0705	8	0.0080	36
		EC5	0.1322	3	0.0227	10			EN7	0.0732	7	0.0083	35
		EC6	0.1286	5	0.0220	12			EN8	0.0701	9	0.0079	37
		EC7	0.1907	1	0.0327	7			EN9	0.0915	2	0.0103	30
Social	0.15	S1	0.1390	2	0.0208	13			EN10	0.0691	11	0.0078	39
		S2	0.1222	5	0.0183	19			EN11	0.0828	5	0.0093	33
		S3	0.1254	4	0.0188	18			EN12	0.1481	1	0.0167	21
		S4	0.1373	3	0.0206	14	L1	0.3499	1	0.0739	2		
		S5	0.0929	8	0.0139	25	L2	0.2442	4	0.0516	5		
		S6	0.1162	6	0.0174	20	L3	0.2489	3	0.0526	4		
		S7	0.1042	7	0.0156	23	L4	0.2573	2	0.0543	3		
		S8	0.1668	1	0.0250	9							
Technological	0.11	T1	0.1669	1	0.0189	17	Legal	0.21					
		T2	0.1419	2	0.0161	22							
		T3	0.1287	3	0.0146	24							
		T4	0.1161	4	0.0132	26							
		T5	0.0947	7	0.0107	29							
		T6	0.0978	6	0.0111	28							
		T7	0.0991	5	0.0112	27							

Very Highly Ranked Criteria (Rank 1-10)
 Highly Ranked Criteria (Rank 11-20)
 Medium Ranked Criteria (Rank 21-30)
 Low Ranked Criteria (Rank 31-40)

Based on the experts' ratings of criterion importance and certainty, average scores per sub-criterion were calculated using QMA. The Figure 6 quadrant matrix analysis identified 25 criteria in Q1 as highly important and highly certain, making them Must-Have criteria for flood decision making. In Q1, Environmental dominated with eight criteria, followed by Social and Technology with six each. Q3 had six low-importance, low-certainty criteria, deemed Nice-to-Have. L1, L4, EC6. S4, EC4, and EN5 were in Q3. Comparing L1 and L4 results, although the AHP ranked both highly, quadrant analysis revealed differences arising from negotiation and compromise among experts, which were not accounted for in the QMA approach.

Figure 6

QMA for PESTEL Criteria Importance and Certainty



Q4 had four criteria, a Should-Have criteria for crucial flood decisions, but with low certainty. Q4 included P1, P2, EC3, and EN12, aligning P1 and P2’s AHP ranks and showing experts’ consistent judgment of their importance. Meanwhile, Q2 had five criteria (L3, EC7, S8, EN1, and EN10), a Could Have criteria for consideration in the decision process. The visual representation of experts' prioritization of criteria importance and certainty can guide the decision making process. It helps identify areas that need improvement and those that are performing well. Criteria that perform well should be maintained, and their certainty ensured. Those needing improvement require efforts, especially if certainty is an issue; addressing it is crucial.

Considering these findings, a comparative analysis was conducted. Since AHP focuses more on the objectivity from one dimension (criteria importance), QMA’s two-dimensional approach (criteria importance and certainty) would supplement AHP’s results. Thus, applying multiple approaches to criteria selection in decision making might be ideal. Different methods can complement and support each other, enhancing the analysis process. Table 7 displays comparative results for the criteria analysis. The ideal criteria to be employed are in “Very Highly Ranked Criteria” and “Must-Have Criteria” groups. The reason behind this situation could be the certainty score, which affects the final distribution of the criteria. This is shown by the certainty scores of the top three ranked criteria (P1, L1, and L4), which were beneath the average. Thus, it could be said that certainty plays a vital part in criterion selection and identification in FMP, where an assumed realistic criterion might not be selected based on its availability for use.

By integrating insights from both AHP and QMA, decision-makers are better positioned to gain a holistic understanding of the criteria and their relative significance in FMP. Such an approach reduces the likelihood of overlooking critical factors or disproportionately emphasizing less influential ones,

thereby enhancing the overall effectiveness and efficiency of FMP decisions. Furthermore, comparative analysis across these methods enables the identification of inconsistencies or divergences in expert assessments, offering an opportunity to reconcile contradictions and strengthen decision reliability.

The comparative results also underscore the importance of accounting for uncertainty in the criteria, a consideration particularly crucial in the inherently unpredictable context of flood management. The analysis demonstrates that the level of certainty attached to a criterion substantially influences its prioritization for FMP. Consequently, strategic attention and resources must be directed toward improving the clarity, availability, and operational feasibility of key criteria. For example, criterion P1 was ranked a very high priority in the AHP; however, its placement in Q4 within the QMA framework indicates low certainty and limited readiness for practical application. This suggests that targeted efforts are required to enhance the certainty of P1 so that it can progress toward Q1, where highly important and highly certain criteria reside. Similarly, criteria L1 and L4 were ranked Very Highly by experts in the AHP but were positioned in Q3 in the QMA matrix, categorized as Nice-to-Have criteria due to their lower certainty. To enhance their feasibility, it is essential to strengthen the evidential basis, data availability, and operational clarity associated with these criteria so they can reliably inform FMP decisions. By explicitly integrating uncertainty considerations into the decision-making process, planners can better anticipate a range of potential scenarios and outcomes. This, in turn, supports the development of robust, adaptive, and context-responsive flood mitigation strategies that remain effective under varying levels of data reliability and situational unpredictability.

Table 7

Comparative Result Analysis based on AHP and QMA

Criteria	AHP (Global)	QMA	Criteria	AHP (Local)	AHP (Global)	QMA	Criteria	AHP (Global)	QMA	Criteria	AHP (Global)	QMA
P1	1	Q4	EC2	4	11	Q1	EN12	21	Q1	EN2	31	Q2
L1	2	Q3	EC6	5	12	Q3	T2	22	Q1	EN4	32	Q4
L4	3	Q3	S1	2	13	Q1	S7	23	Q1	EN11	33	Q1
L3	4	Q1	S4	3	14	Q3	T3	24	Q1	EN3	34	Q1
L2	5	Q2	EC3	6	15	Q4	S5	25	Q1	EN7	35	Q1
P2	6	Q4	EC4	7	16	Q3	T4	26	Q1	EN6	36	Q1
EC7	7	Q1	T1	1	17	Q1	T7	27	Q1	EN8	37	Q3
EC1	8	Q2	S3	4	18	Q1	T6	28	Q1	EN1	38	Q2
S8	9	Q2	S2	5	19	Q1	T5	29	Q1	EN10	39	Q1
EC5	10	Q1	S6	6	20	Q1	EN9	30	Q1	EN5	40	Q1

Legend:

	Very Highly Ranked & Must-Have Criteria		Medium Ranked & Could-Have Criteria
	Highly Ranked & Should-Have Criteria		Low Ranked & Nice-to-Have Criteria

The results reveal inconsistencies in identifying ideal FMP decision making criteria. Further analysis is required to ensure the certainty of the importance criteria is factored into the decision making process. Whilst AHP has facilitated ranking the ideal criteria at the macro level and within individual domains, QMA on the other hand, demonstrates the significance of the interplay between criterion importance

and certainty in criterion selection. Thus, to enhance FMP decision making, it is imperative to meticulously construct a hierarchical criteria structure to guide the selection and identification of criteria.

Development of Proposed Criteria Hierarchical Structure

Comparing AHP and QMA results can help identify FMP's ideal and trade-off criteria. It also helps structure the FMP based on the importance and certainty of the criteria. AHP focuses on the importance of criteria objectively, while QMA complements it by adding a two-dimensional view of certainty. This approach is optimal, as it can be supplemented and reinforced by other approaches during the analysis phase. The same colour codes assigned to both the AHP and QMA approaches were used to map the criteria and identify the ideal option. Preferably, the ideal criteria should be employed if they fall into the following groups, as shown in Table 8.

Table 8

Ideal Group of Criteria based on AHP and QMA

Group	Paired Colour-Code	Colour-Code Explanation	Group	Paired Colour-Code	Colour-Code Explanation
1		Very Highly Ranked and Must-Have Criteria	9		Medium Ranked and Must-Have Criteria
2		Very Highly Ranked and Should-Have Criteria	10		Medium Ranked and Should-Have Criteria
3		Very Highly Ranked and Could-Have Criteria	11		Medium Ranked and Could-Have Criteria
4		Very Highly Ranked and Nice-to-Have Criteria	12		Medium Ranked and Nice-to-Have Criteria
5		Highly Ranked and Must-Have Criteria	13		Low Ranked and Must-Have Criteria
6		Highly Ranked and Should-Have Criteria	14		Low Ranked and Should-Have Criteria
7		Highly Ranked and Could-Have Criteria	15		Low Ranked and Could-Have Criteria
8		Highly Ranked and Nice-to-Have Criteria	16		Low Ranked and Nice-to-Have Criteria

As indicated in Table 7, the most desirable criteria are those that simultaneously achieve a “Very Highly Ranked” status and fall within the “Must Have” category. This convergence appears to be strongly influenced by the certainty scores, which directly determine each criterion's quadrant position. Accordingly, the criteria L3, EC7, and EC5 are recommended for prioritization, as they exhibit both high importance and comparatively stronger certainty profiles. This interpretation is further reinforced by the observation that the three highest-ranked criteria in the AHP results (P1, L1, and L4) recorded certainty scores below the overall mean. This discrepancy suggests that certainty exerts a substantive

influence on the final selection of criteria for FMP. In practical terms, a criterion may be perceived as highly important, yet still be deprioritized if its underlying evidence base, measurability, or operational availability remains insufficient. Hence, the feasibility of implementation alone does not necessarily guarantee adoption; rather, criteria selection is contingent upon a combined evaluation of importance and certainty.

It should also be acknowledged that variability in expert judgement may affect the derived weights and quadrant allocations, as experts may implicitly favor criteria aligned with their professional background, familiarity, or perceived practicality. Nevertheless, such variation is not merely a limitation; it also provides a valuable basis for interrogating the drivers of divergent assessments and identifying potential interventions to improve criteria readiness. Importantly, the combined use of AHP and QMA offers decision makers a more holistic understanding of the criteria landscape, reducing the likelihood of omitting critical factors or over-emphasizing less consequential ones, thereby strengthening the efficiency and defensibility of FMP decisions. In addition, cross-method comparison enables the detection of contradictions between importance-based prioritization and certainty-based readiness. For instance, when a criterion is highly ranked in AHP but falls in a lower-certainty quadrant in QMA, further investigation can clarify the underlying reasons and inform targeted efforts to enhance its operational applicability.

Finally, the proposed criteria hierarchy presented in Figure 7 synthesizes the AHP rankings and QMA quadrant placements reported in Table 7. The resulting structure comprises a three-tier macro domain hierarchy designed to guide the identification and prioritization of key criteria for deployment in FMP decision making.

Figure 7

Proposed Criteria Hierarchical Structure



P1, EC7, S8, T1, EN12, and L3 criteria are significant in the PESTEL macro domain. Given their high importance and likely use, integrating them into decision making is recommended. The sub-criteria are listed in a manner that facilitates clear comprehension by decision-makers, helping them see the

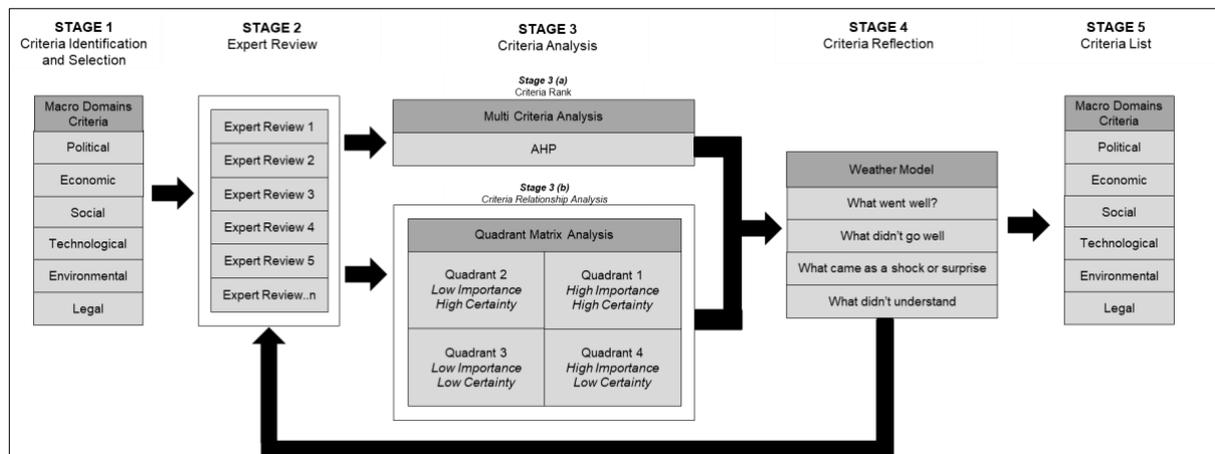
rationale for criterion selection. This helps them review and develop strategies to ensure these criteria fit the “Very Highly Ranked Criteria” and “Must-Have Criteria” categories for future decisions.

Proposed Macro Domain Criteria Analysis Framework for Flood Management Planning

The macro domain criteria analysis framework was developed based on the combined outcomes of both methodologies. The findings indicate that the AHP rankings do not fully correspond with the QMA quadrant classifications. This discrepancy may be attributed to variations in expert perspectives and interpretative judgments. Such divergence can arise from factors such as subjective perceptions, individual preferences, data limitations, accessibility constraints, and implicit assumptions underlying the criteria evaluation process. Accordingly, the conceptual framework presented in Figure 2 strengthens the methodological foundation of this study and provides a structured basis for future data collection and analysis. The framework comprises five sequential stages: criteria identification and selection, expert review, criteria analysis, criteria reflection, and criteria consolidation, as illustrated in Figure 8.

Figure 8

Macro Domain Criteria Analysis Framework for Flood Management Planning



In Stage 1, the criteria relevant to FMP are identified and selected based on expert knowledge, accumulated experience, and prior research evidence. These preliminary criteria are subsequently organized into the six PESTEL macro domains to ensure a comprehensive and structured representation of the decision context. In Stage 2, experts evaluate the identified criteria by assigning scores reflecting their judgments of importance and certainty. These evaluations are then subjected to two complementary analytical techniques in Stage 3: the AHP and QMA to derive prioritization weights and importance classifications. To enhance rigor and strengthen consensus, a Criteria Reflection stage is introduced in Stage 4. At this stage, experts revisit, reflect on, and reassess the criteria in light of the analytical results, aiming to reconcile discrepancies and refine their evaluations. This reflection process is adapted from Maclean’s Weather Model (Maclean, 2016), which incorporates four reflective prompts: Step 1: What went well? (Sunshine), Step 2: What did not go well? (Rain), Step 3: What came as a shock or surprise? (Lightening) Moreover, Step 4: What did you not understand? (Fog).

Reflection has been conceptualized as a process of critically examining experience and knowledge to construct meaning and deepen understanding (Mann et al., 2009), a view rooted in earlier theoretical contributions by Dewey (1933), Boud et al. (1985), and Moon (1999). This study draws upon multiple

theoretical perspectives on reflection, including those proposed by Schön (1983, 1987), Boud et al. (1985), Dewey (1933), Hatton et al. (1995), and Moon (1999), to provide a comprehensive conceptual foundation. Table 9 illustrates Maclean’s (2016) extended Weather model, which elucidates both the convergences and distinctions among the stages of the reflective process.

Table 9

Synthesized Models of Reflection and Reflective Practice

Author	Type of Model	Steps/Process
Schön (1983), Schön (1987)	Iterative Practice	<ol style="list-style-type: none"> 1. Knowing-in-action, 2. Surprise 3. Reflection-in-action 4. Experimentation 5. Reflection-on-action
Boud et al. (1985)		<ol style="list-style-type: none"> 1. Returning to experience 2. Attending to feelings 3. Re-evaluation of experience 4. Outcome/Resolution
Dewey (1933)	Vertical Practice	<ol style="list-style-type: none"> 1. Content and process reflection 2. Premise reflection/critical reflection
Mezirow (1991)		<ol style="list-style-type: none"> 1. Habitual action 2. Thoughtful action/Understanding 3. Reflection 4. Critical reflection
Boud et al. (1985)		<ol style="list-style-type: none"> 1. Association 2. Integration 3. Validation 4. Appropriation
Hatton et al. (1995)		<ol style="list-style-type: none"> 1. Description 2. Descriptive reflection 3. Dialogic reflection 4. Critical reflection
Moon (1999)		<ol style="list-style-type: none"> 1. Noticing, 2. Making sense, 3. Making meaning, 4. Working with meaning, 5. Transformative learning
Maclean (2016)		<ol style="list-style-type: none"> 1. What went well in the lesson/task? What was successful? 2. What didn’t go so well? What was challenging? 3. Was there a point where you couldn’t see clearly, or weren’t sure what to do? 4. Was there something you saw differently during the lesson? What was it? 5. What came as a surprise? 6. Did anything change the course of the lesson, or cause you to change what you had planned to do? 7. Was there any conflict during the lesson? What caused it? How did you respond to it?

Source: Adapted from Mann et al., 2009

The Weather Model was selected from several established reflection frameworks for its conceptual clarity and procedural simplicity, qualities highlighted in the reflective practice literature (e.g., Mann et al., 2009). Its structured yet accessible format makes it particularly suitable for supporting systematic

reconsideration of expert judgments within multi-criteria decision-making processes. Accordingly, the results generated in Stage 3 undergo a further layer of evaluation using the steps of the Weather Model. In Step 1 (Sunshine), criteria identified by experts as both important and certain are acknowledged and retained, recognizing their strong alignment with decision making needs. Step 2 (Rain) focuses on criteria that did not meet the expected importance or certainty thresholds; these are revisited and deliberated to identify underlying issues, such as insufficient clarity, weak evidence, or operational limitations. Step 3 (Lightning) involves identifying unexpected or anomalous outcomes that may signal methodological inconsistencies, shifts in expert judgment, or overlooked contextual factors that require adjustments to the evaluation process. Finally, Step 4 (Fog) seeks to uncover sources of ambiguity or conflict, prompting clarification of misunderstandings, examination of the root causes, and the formulation of strategies to address these challenges. Through this structured reflective procedure, the Weather Model strengthens the overall analytical rigor of the study by promoting critical examination, enhancing transparency, and enabling refinement of the criteria prior to final consolidation.

Implications

This study contributes to FMP by introducing an integrated approach that combines the AHP and QMA to construct a hierarchical criteria structure. This combined method supports the identification of the most suitable criteria by considering both their importance and certainty, thus enabling more informed and transparent decision-making. The findings also show that criterion certainty plays a critical role in the evaluation process. A criterion ranked highly in importance may still be less useful if it lacks clarity, feasibility, or supporting evidence. Therefore, both importance and certainty must be considered to strengthen the reliability of FMP decisions. The comparative use of AHP and QMA further highlights the importance of managing trade-offs, as the combined results help decision-makers balance competing priorities and allocate resources more effectively.

In addition to methodological contributions, the study develops a conceptual framework that provides a structured basis for future research on the prioritization of evaluation criteria. The framework can also support policymakers in improving planning processes and reducing uncertainties associated with FMP. Beyond flood management, the approach is applicable to sectors such as healthcare, transportation, tourism, and hospitality, demonstrating its broader relevance. From a Malaysian perspective, the integrated application of AHP and QMA remains limited. The proposed framework offers practical value for strengthening FMP decisions, improving town planning, and reducing flood risk. It can inform the placement of residential areas, infrastructure, and public facilities in lower-risk zones, ultimately contributing to long-term cost savings, enhanced community well-being, and sustainable national development.

CONCLUSION

In conclusion, this study demonstrates how a structured decision analytics approach can strengthen criteria analysis in FMP by integrating the AHP and QMA. By operationalizing expert judgments through a transparent, multi-stage analytical workflow, the proposed decision analytics framework supports the systematic prioritization of criteria while simultaneously accounting for criterion certainty, an aspect frequently overlooked yet critical in high-uncertainty flood management contexts. The incorporation of a reflection stage further enhances analytical rigor by enabling iterative refinement of criteria prior to finalization, thereby reducing inconsistencies, mitigating ambiguity, and improving the defensibility of decisions. Collectively, these decision analytics outputs provide actionable insights for policymakers and practitioners, with the potential to inform more feasible FMP strategies and regulatory

approaches aimed at minimizing the social, economic, and environmental consequences of flooding. Future research could extend the decision analytics capabilities of the framework by engaging experts from more diverse disciplinary backgrounds and by incorporating additional macro domain criteria to improve contextual coverage and strengthen the generalizability of the findings.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Abdullah, M. F., Siraj, S., & Hodgett, R. E. J. W. (2021). An Overview of Multi-Criteria Decision Analysis (MCDA) Application in Managing Water-Related Disaster Events: Analyzing 20 Years of Literature for Flood and Drought Events. *MDPI Water*, 13(10), 1358.
- Abdullah, M. F., Zainol, Z., Thian, S. Y., Ab Ghani, N. H., Mat Jusoh, A., Mat Amin, M. Z., & Mohamad, N. A. (2022). Big Data in Criteria Selection and Identification in Managing Flood Disaster Events Based on Macro Domain PESTEL Analysis: Case Study of Malaysia Adaptation Index. *MDPI Big Data and Cognitive Computing*, 6(1), 25. Retrieved from <https://www.mdpi.com/2504-2289/6/1/25>
- Abu El-Magd, S. A., Amer, R. A., & Embaby, A. (2020). Multi-criteria decision-making for the analysis of flash floods: A case study of Awlad Toq-Sherq, Southeast Sohag, Egypt. *Journal of African Earth Sciences*, 162, 103709.
- Boud, D., Keogh, R., & Walker, D. (1985). *Reflection: Turning experience into learning*: Routledge.
- CRED. (2023). Emergency Events Database (EM-DAT). Retrieved from <https://public.emdat.be/>
- Dewey, J. (1933). How we think, revised edition. *Boston: DC Heath*.
- Dockalikova, I., & Klozikova, J. (2014). *MCDM methods in practice: determining the significance of PESTEL analysis criteria*. Paper presented at the European Conference on Management, Leadership & Governance.
- Hammami, S., Zouhri, L., Souissi, D., Souei, A., Zghibi, A., Marzougui, A., & Dlala, M. (2019). Application of the GIS based multi-criteria decision analysis and analytical hierarchy process (AHP) in the flood susceptibility mapping (Tunisia). *Arabian Journal of Geosciences*, 12(21).
- Hatton, N., Smith, D. J. T., & education, t. (1995). Reflection in teacher education: Towards definition and implementation. *11*(1), 33-49.
- Iacovidou, E., Busch, J., Hahladakis, J. N., Baxter, H., Ng, K. S., & Herbert, B. M. J. (2017). A Parameter Selection Framework for Sustainability Assessment. *9*(9), 1497. Retrieved from <https://www.mdpi.com/2071-1050/9/9/1497>
- Khiavi, A. N., Vafakhah, M. & Sadegi, S. H. (2024). Strategic Flood Management Using Collaborative Game Theory: Conjoint Application of Hydrologic and Strategic Planning Models. *Environment, Development and Sustainability*, 27, 18381-18408.
- Liu, Q., Du, M., Wang, Y. Deng, J., Yan, W., Qin, C. & Liu, M. (2024). Global, Regional and National Trends and Impacts of Natural Floods, 1990-2022. *Bull World Health Organ*, 102(6), 410-420.
- Lynch, J., Carver Jr, R., & Virgo, J. M. (1996). Quadrant analysis as a strategic planning technique in

- curriculum development and program marketing. *Journal of Marketing for Higher Education*, 7(2), 17-32.
- Maclean, S. (2016). A new model for social work reflection: whatever the weather. *Professional Social Work*, 1, 28-29.
- Mann, K., Gordon, J., & MacLeod, A. (2009). Reflection and reflective practice in health professions education: a systematic review. *Adv Health Sci Educ Theory Pract*, 14(4), 595-621.
- Mezirow, J. (1991). *Transformative dimensions of adult learning*: ERIC.
- Moon, J. (1999). *A handbook of reflective and experiential learning: Theory and practice*. London: Kogan Page.
- Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, 15(3), 234-281.
- Saaty, T. L. (1980). *What is the analytic hierarchy process?* : Springer.
- Saaty, T. L., & Vargas, L. G. (1998). Diagnosis with dependent symptoms: Bayes theorem and the analytic hierarchy process. *Operations research*, 46(4), 491-502.
- Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. San Francisco: Jossey-Bass.
- Schön, D. A. (1987). *Educating the reflective practitioner: Toward a new design for teaching and learning in the professions*: Jossey-Bass.
- Triantaphyllou, E., & Mann, S. H. (1995). Using the analytic hierarchy process for decision making in engineering applications: some challenges. *International journal of industrial engineering: applications practice*, 2(1), 35-44.
- Wedley, W. C. (1990). Combining qualitative and quantitative factors-an analytic hierarchy approach. *Socio-Economic Planning Sciences*, 24(1), 57-64.
- Yang, W. C., Xu, K., Lian, J. J., Ma, C., & Bin, L. L. (2018). Integrated flood vulnerability assessment approach based on TOPSIS and Shannon entropy methods. *Ecological Indicators*, 89, 269-280.
- Zahmatkesh, Z., & Karamouz, M. (2017). An uncertainty-based framework to quantifying climate change impacts on coastal flood vulnerability: case study of New York City. *Environmental Monitoring and Assessment*, 189(11), 20.