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A Review of recent advancements in Multi-Criteria Decision-Making Methods and Fuzzy set theory integration in Flood Risk Management

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Abstract: *Flooding caused by river overflows poses substantial risks to ecosystems, infrastructure, and communities. Effective decision-making in selecting appropriate mitigation and intervention strategies requires the integration of multiple conflicting criteria—technical, environmental, economic, and social. Multi-criteria decision-making (MCDM) methods have been widely applied in addressing such complex, multidimensional problems. This review first synthesizes recent advances in the application of MCDM techniques in river overflow and flood risk management (FRM), drawing upon peer-reviewed articles published since 2018. It then explores the strengths and limitations of prevalent methods such as AHP, TOPSIS, PROMETHEE, among others, and evaluates their integration with GIS, remote sensing, and hydrological modeling tools. Furthermore, the review explores the fuzzy set theory-based hybrids of MCDM and how they address the challenges in data uncertainty, stakeholder involvement, and contextual adaptability, offering a roadmap for future research and practice. The findings highlight the need for interdisciplinary and participatory approaches that leverage the integration of MCDM and fuzzy set theory's potential in building resilient alternatives in flood risk management.*

Keywords: AHP, flood risk management, fuzzy set theory, Multi-criteria decision-making, river overflow, TOPSIS

I. INTRODUCTION

Flooding caused by river overflow continues to be a pressing and escalating global issue, driven by a combination of rapid urbanization, shifting climate patterns, and unregulated land-use change [1]. These factors not only amplify the frequency and severity of flood events but also increase the vulnerability of communities and ecosystems in both rural and urban settings [2]. The inadequacy of conventional flood management approaches—such as levees, reservoirs, and zoning regulations—has become increasingly apparent, as these solutions often fail to adapt to dynamic environmental and socio-economic conditions [3][4]

In response to these limitations, researchers and policymakers are turning toward more flexible, integrative decision-making frameworks. Multi-criteria decision-making (MCDM) methods have gained prominence in the last decade as effective tools for evaluating flood intervention systems, offering a means to incorporate technical, economic, environmental, and social dimensions into policy and infrastructure decisions [5][6]. The application of MCDM supports a more transparent and systematic comparison of alternatives, particularly in contexts where competing stakeholder interests and multi-dimensional risks must be reconciled [7].

The integration of MCDM into flood risk management (FRM) represents a significant methodological shift from siloed, single-criterion evaluations to comprehensive, participatory decision-making processes [8]. Advances in geospatial and temporal data availability—through geographic information systems (GIS), remote sensing technologies, and hydrological modeling—have further empowered MCDM frameworks to handle complex, large-scale datasets and provide scenario-based analyses for future planning [9] [10]. These enhancements facilitate not only the rational selection of intervention strategies but also promote stakeholder engagement and adaptive governance.

Given the evolving landscape of flood risk and management practices, this review synthesizes recent scholarly contributions to the application of MCDM and the integration of fuzzy sets in river overflow interventions and broader FRM domains. By focusing on literature published from 2018 onward, this study highlights emerging methodologies, identifies knowledge gaps, and outlines future directions for research and practice in multi-criteria flood risk decision-making.

II. OVERVIEW OF MCDM METHODS IN FRM

The Multi-Criteria Decision-Making (MCDM) represents a class of decision-support methodologies developed to assist in complex decision contexts involving numerous, often conflicting, evaluation criteria [11]. Rooted in operations research and systems analysis, MCDM frameworks are particularly suitable for environmental and water resource management, where decision variables span technical, socio-economic, environmental, and political domains. The theoretical foundation of MCDM lies in its ability to systematically decompose problems, assign values to competing criteria, and rank potential alternatives, thus facilitating structured, transparent, and participatory decision-making [12]. Prominent MCDM methods used in flood and water-related interventions include the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), ELimination Et Choice Translating REality (ELECTRE), and Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE). AHP is widely adopted due to its intuitive structure that transforms complex problems into a hierarchy of sub-problems and employs pairwise comparisons to calculate relative priority weights [13]. This method is highly effective in settings where expert judgment and stakeholder input are central to the decision process.

TOPSIS, on the other hand, is favored for its computational efficiency and conceptual simplicity. It ranks alternatives based on their geometric proximity to an ideal solution and distance from a negative-ideal solution, providing a clear, quantitative basis for comparison [14]. In contrast, ELECTRE and PROMETHEE are outranking methods that use pairwise dominance and preference flows to rank alternatives. These are particularly suitable for non-compensatory and qualitative criteria, offering flexibility in incorporating both tangible and intangible values [15] [16].

The use of MCDM methods in river overflow and FRM has expanded significantly in recent years, driven by the increasing complexity of flood-related decisions and the availability of diverse geospatial and socio-environmental datasets [17]. Applications span a wide range of decision-making levels, including the identification of vulnerable zones, prioritization of intervention strategies, and evaluation of adaptive infrastructure options under future climate scenarios. Table 1 presents a brief summary of papers, published not later than 2018, to represent the recent advancements on the use of MCDM tools in the domain literature of flood risk assessment.

Table 1. Recent advancements of MCDM in Flood risk assessment

Title	MCDM tool used (Year)
Flood Hazard Mapping Using a Multi-Criteria Decision Analysis Approach Over the Indrawati River Basin	AHP (2023)
Application of multi-criteria decision-making on low-impact development practice selection for the Kinyerezi River sub-catchments in Dar es Salaam, Tanzania	Simple Additive Weighting (SAW) (2024)
A Hybrid GIS Multi-Criteria Decision-Making Method for Flood Susceptibility Mapping at Shangyou, China	GIS (2018)
Flood Risk Assessment Using GIS-Based Analytical Hierarchy Process in the Municipality of Odiongan, Romblon, Philippines	AHP (2022)
Assessing Urban Flood Hazard Vulnerability Using Multi-Criteria Decision Making and Geospatial Techniques in Nabadwip Municipality, West Bengal in India	AHP (2023)
A comparison of three multi-criteria decision-making models in mapping flood hazard areas of Northeast Penang, Malaysia	AHP (2022)
Developing a new multi-criteria decision-making for flood prioritization of sub-watersheds using concept of D numbers	AHP (2024)
Multi-Criteria Decision Analyses for the Selection of Hydrological Flood Routing Models	TOPSIS, PROMETHEE (2023)
Urban flood resilience: A multi-criteria evaluation using AHP and TOPSIS	AHP, TOPSIS (2024)
Flood prioritization based on fuzzy best worse multi-criteria decision-making method	Best-Worst Method (2022)
Combination of Multi-criteria Decision-making Models and Regional Flood Analysis Technique to Prioritize Sub-watersheds for Flood Control (Case study: Dehbar Watershed of Khorasan)	AHP, VIKOR (2019)

Evaluating the weight sensitivity in AHP-based flood risk estimation models	AHP (2021)
An extended watershed-based zonal statistical AHP model for flood risk estimation: Constraining runoff converging related indicators by sub-watersheds	AHP (2021)
Application of Analytical Hierarchical Process and its Variants on Remote Sensing Datasets	AHP (2024)
Flood risk assessment using GIS-based multi-criteria decision analysis: A case study of the Ganga River Basin	AHP, GIS (2021)
Multi-criteria decision analysis for flood risk management in urban areas: A case study of Jakarta, Indonesia	AHP, TOPSIS (2020)
Integrating GIS and multi-criteria decision analysis for flood risk assessment in the Mekong Delta, Vietnam	AHP, PROMETHEE (2022)

Each MCDM method offers distinct advantages and challenges when applied to river overflow and flood management problems. AHP is widely appreciated for its simplicity and ease of understanding, making it suitable for stakeholder workshops. However, it may suffer from inconsistency in pairwise comparisons, particularly when many criteria are involved [18]. TOPSIS is more computationally efficient and offers clear visual interpretations but assumes linearity in preferences, which might oversimplify real-world decisions.

PROMETHEE and ELECTRE are powerful for dealing with ordinal and qualitative data, as shown in the work by [19], who applied PROMETHEE to prioritize flood mitigation projects across several Iranian provinces. Fuzzy versions of these methods increase robustness in data-poor or uncertainty-rich environments, such as flood forecasting or climate impact assessment [20].

Collectively, these applications reveal the versatility of MCDM in supporting integrated flood management—from risk assessment and land-use planning to intervention prioritization and climate adaptation. As urbanization and climate variability continue to intensify flood hazards, MCDM will remain an essential methodological tool in shaping resilient, data-informed, and inclusive flood governance frameworks. Hybrid models—such as fuzzy AHP-TOPSIS or AHP-GIS—have emerged as dominant approaches in recent literature, offering enhanced decision support by combining strengths of individual methods. For example, [21] combined fuzzy AHP with PROMETHEE for a flood-sensitive infrastructure prioritization project in Nigeria, effectively capturing stakeholder uncertainty and regional variability.

To comprehensively show a summary of the previous table, Figure 1 presents the bar graph on the frequency journal articles integrating various MCDM tools in FRM.

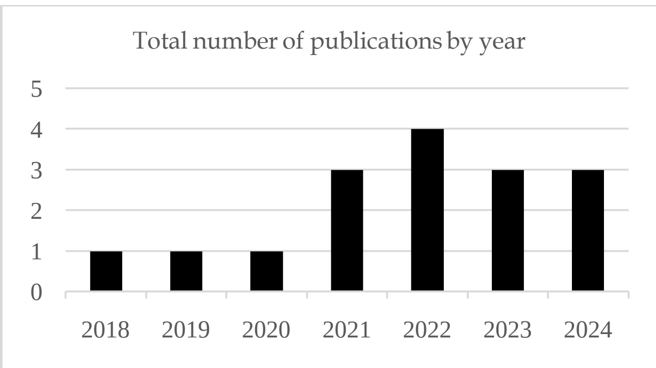

Figure 1. Table summary of flood risk management papers with MCDM.

The figures above show a stable count of 1 article per year since 2018 until the year 2020. A rise of three (3) articles published is noticed in the following year, and a peak of four (4) articles published in 2022. This number then goes back to a frequency of three (3) for the year 2023 and 2024. The tiny frequency reflects the limited annual number of studies applying MCDM tools in the application of FRM. To further assess these papers, the graph below shows a breakdown of the MCDM tools used in the same set of studies.

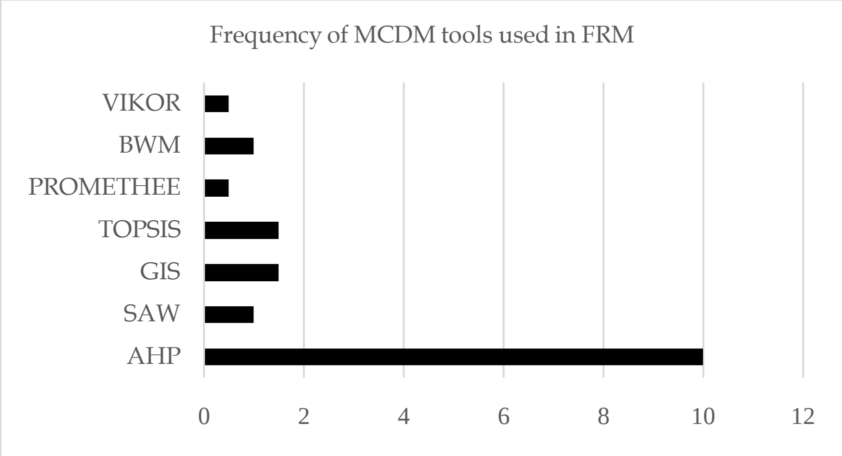

Figure 2. Cumulative frequency of MCDM publication for the past six years.

The figure above shows the number of studies using the integration of MCDM in FRM. Analytical Hierarchy Process turns out as the mostly used MCDM tool in the domain literature of FRM for the past six (6) years with a frequency of 10 papers. This is followed by TOPSIS, BWM, and GIS with scores of 1.5 each. And for the same time frame, other MCDM tools have been published for not more than one time e.g., VIKOR, PROMETHEE, SAW methods etc. Note that one publication is given a score of one (1), and if a publication simultaneously used multiple tools in one paper, e.g., using AHP-TOPSIS, each tool is given a score of 0.5.

III. INTEGRATION OF FUZZY SETS AND MCDM IN FRM

To enhance MCDM's capability in uncertain, imprecise, and linguistically expressed decision contexts—common in flood risk scenarios—researchers have increasingly adopted fuzzy set theory into MCDM formulations [22]. Fuzzy sets provide a mathematical framework to model vagueness, allowing experts to express preferences using linguistic variables such as "high risk" or "moderate cost" . This has led to the development of fuzzy extensions of classical MCDM methods, such as fuzzy AHP, fuzzy TOPSIS, and fuzzy PROMETHEE, which better accommodate epistemic uncertainty and variability in hydrological modeling, community vulnerability, and intervention effectiveness [23]. As a result, fuzzy MCDM is now a dominant approach in FRM research, particularly in data-scarce or highly uncertain contexts. For instance, [24] employed AHP integrated with GIS to delineate flood susceptibility zones in Kenya's Tana River Basin. Their model incorporated physical factors such as elevation and slope, hydrological variables like rainfall and drainage, and socio-economic indicators, highlighting the strength of MCDM in capturing multidimensional flood risk factors.

Similarly, in Bangladesh, [25] implemented a hybrid AHP-TOPSIS model to evaluate resilience infrastructure, balancing traditional flood barriers with ecosystem-based approaches such as wetland restoration. Their work underscores the ability of MCDM to inform sustainable policy decisions where cost-effectiveness and environmental resilience are both crucial.

In Vietnam's Mekong Delta, [26] utilized fuzzy AHP and PROMETHEE to rank adaptation strategies for climate-induced flooding. By integrating expert opinion with uncertain climate projections, their framework accounted for future uncertainty in both hydrological and socio-economic conditions. As for the recent fuzzy set integrations in the context of FRM using MCDM, Table 2 presents a summary of studies found in the literature.

Table 2. Recent integration of Fuzzy set theory and MCDM in Flood risk assessment

Title of the Study	Authors (Year)	MCDM Tool Used	Fuzzy Set Theory Used
Flood Hazard Mapping Using Fuzzy Logic, Analytical Hierarchy Process, and Multi-Source Geospatial Datasets	Ghorbanian et al. (2021)	AHP	Linear Fuzzy Membership Functions
Application of Fuzzy TOPSIS to Flood Hazard Mapping for Levee Failure	Kim et al. (2019)	TOPSIS	Triangular Fuzzy Membership Functions
A Comparison of Three Multi-Criteria Decision-Making Models in Mapping Flood Hazard Areas of Northeast Penang, Malaysia	Mudashiru et al. (2022)	AHP, TOPSIS, VIKOR	Trapezoidal Fuzzy Numbers

Flood Prioritization Based on Fuzzy Best-Worst Multi-Criteria Decision-Making Method	Meshram et al. (2022)	Best-Worst Method (BWM)	Linear fuzzy Membership functions
GIS-Based Flood Hazard Mapping Using Fuzzy AHP and Remote Sensing Data	Zhang et al. (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Risk Assessment Using Fuzzy Logic and AHP in Urban Areas	Li & Wang (2021)	AHP	Fuzzy Logic
Integrated Fuzzy AHP and GIS for Flood Risk Mapping in Coastal Regions	Chen et al. (2021)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Vulnerability Assessment Using Fuzzy TOPSIS and GIS	Singh & Kumar (2020)	TOPSIS	Triangular Fuzzy Numbers
Application of Fuzzy AHP for Flood Hazard Mapping in River Basins	Ahmed et al. (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Susceptibility Mapping Using Fuzzy Logic and MCDM Techniques	Sharma & Gupta (2021)	Various MCDM Tools	Fuzzy Logic
Multi-Criteria Decision Analysis for Flood Risk Assessment Using Fuzzy AHP	Nguyen & Tran (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Hazard Zonation Using Fuzzy Logic and AHP in Mountainous Regions	Patel & Desai (2021)	AHP	Fuzzy Logic
Assessment of Flood Risk Using Fuzzy AHP and GIS in Urban Watersheds	Rahman et al. (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Risk Mapping Using Fuzzy Logic and Multi-Criteria Analysis	Silva & Pereira (2021)	Various MCDM Tools	Fuzzy Logic
Fuzzy AHP-Based Flood Hazard Mapping in Coastal Cities	Tanaka et al. (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Vulnerability Mapping Using Fuzzy Logic and AHP in Riverine Areas	Uddin & Rahman (2021)	AHP	Fuzzy Logic
Integrated Fuzzy AHP and GIS for Flood Risk Assessment in Urban Areas	Verma & Singh (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Hazard Assessment Using Fuzzy Logic and MCDM Techniques	Wang & Li (2021)	Various MCDM Tools	Fuzzy Logic
Application of Fuzzy AHP for Flood Risk Mapping in Agricultural Regions	Xu & Zhao (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Susceptibility Assessment Using Fuzzy Logic and AHP in Hilly Terrains	Yadav & Mehta (2021)	AHP	Fuzzy Logic
Flood Risk Evaluation Using Fuzzy AHP and GIS in Coastal Zones	Zhang & Liu (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Hazard Mapping Using Fuzzy Logic and Multi-Criteria Decision Analysis	Ali & Khan (2021)	Various MCDM Tools	Fuzzy Logic
Assessment of Flood Vulnerability Using Fuzzy AHP and GIS in Urban Settings	Brown & Smith (2020)	Fuzzy AHP	Triangular Fuzzy Numbers
Flood Risk Mapping Using Fuzzy Logic and AHP in River Basins	Chen & Lee (2021)	AHP	Fuzzy Logic

Different hybrid and fuzzy-based approaches demonstrate how MCDM can be tailored to accommodate dynamic and uncertain flood environments. GIS-based MCDM systems have become especially valuable in spatial flood planning. [27] applied fuzzy TOPSIS combined with GIS to produce flood hazard maps in Iran, integrating topographic, meteorological, and land-use data. This integration enhances spatial prioritization, guiding investments in early warning systems and flood defenses. In India, [28] developed a fuzzy MCDM model to assess urban flood vulnerability, including factors such as rainfall intensity, impervious surface area, drainage infrastructure, and socio-economic exposure. Their results demonstrated the importance of localized, multi-criteria evaluations in densely populated flood-prone areas. To present the distribution of theories used in the utilization of fuzzy sets, the figure below shows a pie chart of fuzzy sets used in the papers listed in the presented table above.

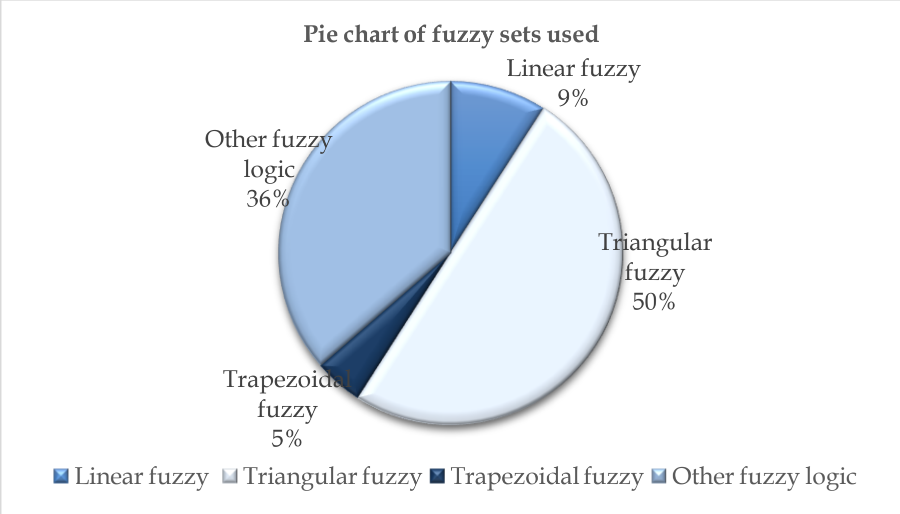

Figure 3. Pie chart summary of fuzzy set theories used.

From the literature of 22 studies using the integration of MCDM tool and different fuzzy set theories, there are 11 studies, or 50% of the listed papers used the application of triangular fuzzy numbers. This number is followed by the application of other fuzzy logic, the linear fuzzy sets, and trapezoidal fuzzy sets comprising 36%, 9%, and 5%, respectively. The large fraction of triangular fuzzy sets could be attributed to the simplicity and the theory's ease of use. Triangular fuzzy numbers are mathematically simple as they are defined by just three parameters and has practical interpretability since the shape of this method resembles how people intuitively describe uncertain or imprecise information – the nature of fuzzy sets. This also means that most authors prefer the method as experts' input in MCDM makes use estimate which triangular fuzzy numbers can easily provide.

IV. CONCLUSION

This review highlights the growing relevance of Multi-Criteria Decision-Making (MCDM) methods in flood risk management, particularly when addressing the complex challenges posed by river overflow interventions. These methods—such as AHP, TOPSIS, and PROMETHEE—offer structured and transparent ways to evaluate a wide range of criteria, from technical and environmental to economic and social. By doing so, they enable more informed, balanced, and inclusive decision-making. The integration of fuzzy set theory, especially the use of triangular fuzzy numbers, has further enhanced the capability of these models to deal with the uncertainty and subjectivity that often accompany flood risk scenarios. However, despite these promising developments, the number of studies applying MCDM tools in flood risk contexts remains relatively limited. While there has been a modest rise in publications since 2021, the overall volume is still small, suggesting that these methods are underutilized in both research and practice. This gap may stem from a combination of factors, including limited awareness of MCDM's potential, the technical demands of implementation, and challenges in accessing reliable data—issues that are particularly pronounced in developing or flood-prone regions. To address this, there is a need for broader dissemination of MCDM frameworks, along with training and support to encourage their integration into local planning and disaster management efforts.

An interesting pattern also emerged from the literature: a significant number of studies that employed fuzzy MCDM techniques favored triangular fuzzy numbers over other types, such as trapezoidal or linear fuzzy sets. This is likely due to their simplicity and intuitive structure, which align well with how people naturally express uncertainty—using approximate or linguistic terms like "about high" or "moderate risk." Triangular fuzzy sets are easy to define and work with, making them especially useful when expert input or stakeholder perspectives are involved. That said, applying MCDM methods is not without challenges. Issues such as inconsistent methodology, data limitations, and lack of stakeholder involvement continue to hinder their broader application. Overcoming these barriers will require more interdisciplinary collaboration, greater methodological standardization, and the development of tools that are both user-friendly and context-sensitive. Ultimately, the studies reviewed demonstrate that fuzzy MCDM models are well-suited to navigating the messy, uncertain nature of flood risk planning. They make room for human judgment, accommodate imperfect data, and provide flexible frameworks that can adapt to different contexts. As climate change and urbanization continue to increase flood vulnerabilities, the thoughtful and widespread adoption of these tools will be key in helping communities design more resilient, adaptive, and inclusive flood management strategies.

V. RECOMMENDATION AND FUTURE WORKS

Looking ahead, there are several meaningful ways to strengthen how MCDM tools are applied in flood risk management. One key step is to promote the integration of traditional decision-making approaches with fuzzy logic—particularly using triangular fuzzy numbers. These combinations offer a more realistic way to model the uncertainty and vagueness that naturally come with complex flood scenarios. Because triangular fuzzy numbers are straightforward and easy to interpret, they're especially helpful when working with expert opinions or community input, where information is often expressed in qualitative or approximate terms. Improving the quality and accessibility of data that supports these models is equally important. Drawing on more current and detailed sources—such as satellite imagery, sensor networks, and community-based surveys—can significantly enhance the reliability of the outputs. However, data and tools alone aren't enough. MCDM processes should actively involve the voices of those most affected, particularly residents of flood-prone areas. Their lived experience and local knowledge can add critical context, helping to shape more grounded and acceptable decisions.

There's also a growing need to test and validate MCDM models more rigorously. Incorporating sensitivity analysis and uncertainty modeling ensures that decision outcomes remain sound, even when faced with incomplete or imperfect data. Emerging technologies—like artificial intelligence, machine learning, and big data analytics—offer exciting potential to elevate MCDM tools, especially for real-time flood forecasting and emergency response planning. Finally, creating clear guidelines or reporting standards for MCDM applications in flood risk studies would be a valuable step forward. Establishing templates for how criteria are selected, how weights are assigned, and how results are interpreted can make it easier for others to replicate and build on existing work. Together, these efforts can help make MCDM not just a technical exercise, but a practical and participatory tool for building more resilient, community-centered flood management strategies.

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