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A Spherical Fuzzy ELECTRE III-Based Framework for Evaluating Flood Risk Management Strategies in Vulnerable Watersheds

Muhammad Shakir Chohan, Shahzaib Ashraf*, Shahida Bano, Laszlo Vasa, Vladimir Simic† and Dragan Pamucar

ABSTRACT: Flooding is one of the most widespread and damaging natural hazards worldwide, causing significant economic losses, environmental degradation, and risks to human life, particularly in vulnerable watersheds. The multi-criteria decision-making dilemma of managing flood risks in prone watersheds is associated with conflicting economic, social, and environmental objectives. To assess and rank the flood risk management options, this research suggests a single model that should be developed using a mix of the fuzzy analytic hierarchy process and ELECTRE III approaches. The fuzzy analytic hierarchy process is used to capture the uncertainty and subjectivity of the pairwise comparison of decision-makers. Alternative management strategies are ranked using the ELECTRE III technique. The suggested approach is applied to an empirically vulnerable watershed, demonstrating its viability. The suggested fuzzy framework aids decision-makers in selecting the best course of action even before a flood occurs. Watershed managers can use the findings as a scientifically validated tool for resource allocation in flood risk reduction, as they provide a clear and sound hierarchy of strategies that include both structural and non-structural measures.

Keywords: Fuzzy sets, flood risk management, ELECTRE III, outranking methods.

Contents

1. Introduction

Floods are becoming more frequent and more intense, endangering ecosystems, infrastructure, and society worldwide. The combined effects of climate change and human activity increase the risk, which is particularly true in watersheds that are already at risk. Because it requires tough trade-offs between economic, social, and environmental goals in the face of extreme uncertainty, managing these flood threats poses a complicated decision-making issue [6]. Conventional MCDM procedures are frequently insufficient, despite the fact that Multi-Criteria Decision-Making (MCDM) is a crucial tool for methodically assessing such competing criteria [7]. The aforementioned fuzzy logic approaches aim to address the inherent ambiguity, imprecision, and subjectivity present in hydrological data and expert judgment, which

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[*] Corresponding author.
[†] Corresponding author.

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they find difficult to manage [8]. In order to evaluate contemporary flood risk management strategic which are increasingly eschewing conventional structural approach this research develops a fuzzy-based MCDM model.

There is an urgent need for efficient flood risk management techniques as a result of watersheds' increasing susceptibility. This task is challenging, though, as a conventional reliance on structural restrictions, such as dams and levees, can give the impression of security. By promoting development on floodplains and interfering with natural water cycles, these practices can occasionally raise long-term risk [9]. As a result, a significant paradigm shift toward more robust and comprehensive approaches is currently taking place. These new tactics combine better land-use planning, community readiness initiatives, and nature-based remedies with structural defenses [10]. This is the exact setting in which our study is located. The effectiveness of such integrated flood risk management techniques for a highly vulnerable watershed is assessed in this paper. In accordance with the Integrated Water Resources Management (IWRM) principles promoted by international organizations, we seek to identify the most sustainable arrangement of flood control, ecological health, and socioeconomic stability strategies [11].

A specific vulnerable watershed was chosen as the empirical case study for this study based on a number of factors:

- Real-World Criticality: Due to its history of catastrophic flooding, the chosen watershed is extremely sensitive to work with and serves as a simulation of the framework being tested.
- Evaluation Complexity: Watersheds require a sophisticated evaluation framework that can handle a number of competing criteria since they are defined by a complex web of geophysical, hydrological, socioeconomic, and environmental interactions.
- Both Structural and Non-Structural: Structural and Non-Structural options may be considered in the different watersheds (e.g., dams, levees and early warning systems, land-use planning, etc.) and, therefore, demonstrate the versatility of the framework.
- Practical Impact: This research will provide watershed managers with a scientifically valid and transparent tool to assist prioritizing investments and allocating resources pragmatically to reduce flood risks by putting the framework into practice using a real-world example.

Our suggested framework incorporates two potent techniques to overcome these constraints. Initially, the weights of the criteria are determined using SFSs and the Fuzzy Analytic Hierarchy Process (Fuzzy AHP), which accurately captures the ambiguity in expert pairwise comparisons. Second, we use the ELECTRE III method to rank the strategies. Because ELECTRE III is a non-compensatory method that depends on an outranking relationship and, most importantly, includes veto thresholds, it is especially well-suited for this situation [21]. These objections have the power to directly enforce the non-negotiable limitations that are a part of sustainable flood risk management by preventing an alternative from being chosen if it fails miserably on any one criterion. Thus, the combination of ELECTRE III for ranking and fuzzy AHP for weighting produces a strong framework especially made for the high-stakes, non-compensatory decisions this domain demands.

1.1. Literature Review

The decision-making process of selecting the most suitable alternative from a set of available options while considering multiple factors to achieve organizational goals is known as decision-making [1]. One of the most widely studied approaches for addressing complex decision problems involving multiple and often conflicting objectives is multicriteria decision making (MCDM) [2]. To address such complexity, particularly under uncertain conditions, numerous MCDM techniques have been developed to address the decision-making problems that comprise a range of competing criteria in unclear situations. Some of these methods are airport security screening [3], cyber security control [4], and others.Furthermore, a major drawback of these conventional methods is their dependence on exact numerical values, which frequently find it difficult to account for the vague and imprecise character of human judgment. A more realistic modeling of expert judgments in complicated decision settings is made possible by researchers integration of fuzzy logic into MCDM frameworks to systematically quantify linguistic imprecision [5].

This article presents a forecasting-enhanced framework to further support MCDM processes, with a specific application in environmental risk management. It builds upon this development of techniques created to address uncertainty.

This study uses a fuzzy set-based technique, the details of which are described in the next section, to precisely imitate the uncertainty and expert judgment involved in assessing these intricate tactics. In contrast to traditional approaches that necessitate accurate data, Zadeh's fuzzy set (FS) theory offers a mathematical basis for managing such imprecision by permitting partial membership [12]. Traditional FSs, however, are not able to fully capture the range of human judgment. As a result, increasingly sophisticated extensions were created. For example, Intuitionistic Fuzzy Sets (IFS) offered a more sophisticated means of expressing support and opposition by introducing the idea of a degree of non-membership [13].

IFS are nevertheless limited by the requirement that the total of membership and non-membership degrees not surpass 1 [14]. In order to get around this, Pythagorean Fuzzy Sets (PFS) were put forth, which relax this requirement and provide a wider, more adaptable space for expressing uncertainty [15]. Spherical fuzzy sets (SFS), which build directly on PFS, provide an additional crucial development for our situation [16]. Membership, non-membership, and a critical neutral/hesitancy degree are the three independent variables that SFS adds to the model [17]. This ternary structure is especially well-suited to environmental risk assessment, because expert opinions frequently include substantial ”indeterminacy” or neutrality in addition to ”agreement” or ”disagreement” with a criterion. Since the SFS framework offers the most thorough and adaptable mathematical model to describe the intricate, three-dimensional character of expert preferences while assessing flood management solutions, we have chosen to use it for this study.

A sophisticated decision-support framework is clearly needed given the unique challenges of flood risk management, which are typified by conflicting criteria, extreme uncertainty, and the complex human judgment captured by SFSs. Although there are many MCDM techniques, a few well-known ones are not appropriate for the non-compensatory nature of this problem. When an ecological disaster cannot be exchanged for financial gain, it is unacceptable that basic Weighted Sum Models (WSM) or Weighted Product Models (WPM) are fully compensatory, allowing a high score in one criterion to directly offset a critically low score in another [18]. In a similar vein, the TODIM approach, which models the psychological behavior of decision-makers under risk and is founded on Prospect Theory, is ultimately compensatory in its final ranking [19]. Additionally, approaches such as VIKOR concentrate on reaching acceptable compromise solutions; however, this compromise principle itself presents challenges when addressing environmental or social risks that warrant rejection [20].

As a result, the combination of ELECTRE III and fuzzy AHP produces a powerful tool ideal for making difficult flood risk decisions. The primary objective of this study is to develop a clear and useful tool to assist in resolving the intricate issues related to flood risk management [22]. Every component in our suggested approach has a distinct function: First, the relative importance of each factor is determined using fuzzy AHP. The ”fuzzy” part is crucial because it realistically addresses the ambiguous and unsure expert opinions [23]. However, understanding what matters is insufficient. Additionally, we must rank the various flood control options. We use ELECTRE III for this. Because it recognizes that some issues are too serious to be balanced out, this approach is unique. For instance, even if a plan saves a lot of money, it should be rejected if it results in an ecological disaster. In order to ensure that responsible decision-making occurs, ELECTRE III employs ”opposition thresholds” [24].

Using ELECTRE III with SFSs helps us better capture the complex and subtle ways experts make judgments in uncertain, real-world situations. Earlier versions of fuzzy sets, like Intuitionistic or Pythagorean, had a limitation: the sum of their membership and non-membership degrees was restricted. This limited an expert's freedom to express doubt or hesitation independently. SFSs solve this problem. They use a more flexible, three-dimensional model where the degrees of membership, non-membership, and hesitancy can be assigned independently. This allows us to represent expert opinions more accurately and naturally. When we use this realistic SFS model to calculate the agreement (concordance) and disagreement (discordance) indexes in ELECTRE III, the results are much more reliable. This powerful combination is excellent at handling problems where one major failure cannot be compensated for by other strengths and where we need absolute vetoes. Therefore, this synergy between SFS and ELECTRE III leads to a more credible and realistic ranking of flood management strategies. Because expert opinions in this field are inherently complex and ambiguous, this combined approach is the ideal tool for creating and updating effective flood risk plans.

The application of the ELECTRE III technique in an SFS context is motivated by the need to comprehend the complex and nuanced aspects of human judgment during uncertainties in the real environment. The traditional fuzzy sets and their variants, such as intuitionistic or Pythagorean fuzzy sets, typically fall short by limiting the sum of membership and non-membership degrees, which limits the decision-maker's ability to express autonomous hesitancy. In order to better represent expert judgments, SFS employs a more expansive, three-dimensional domain wherein membership, non-membership, and hesitancy parameters can be independently specified [25]. When paired with the robust outranking principles of ELECTRE III, SFS can more realistically construct the concordance and discordance indexes, effectively addressing the veto effects and non-compensatory criteria. When dealing with the non-compensatory and affirmative effects of complicated multi-criteria problems, like sustainable watershed management, this leads to a more realistic credibility ranking. This synergy is the best way to update flood risk plans because special appraisals are complicated and unclear.

This research makes its main contribution by developing a new hybrid model that combines Fuzzy AHP with ELECTRE III. What makes this model unique and effective is how it uses the strengths of both methods. First, Fuzzy AHP carefully measures the importance (weights) of each criterion based on expert opinions, honestly capturing their uncertainty. Then, ELECTRE III uses these weights to rank the flood management strategies without allowing a good score in one area to hide a disastrous score in another [26]. This combined approach is a significant step forward for environmental planning. It provides a powerful tool that can handle the many uncertainties and conflicting goals involved in responding to natural disasters like floods. Ultimately, this framework can lead to more resilient and sustainable governance for vulnerable watersheds.

The unique features of flood risk management decision problems are what led to the choice of ELECTRE III over previous ELECTRE approaches like ELECTRE I and ELECTRE II. ELECTRE I and II are less appropriate for problems with high uncertainty and imprecise expert judgments because they are primarily intended for basic outranking or partial ranking and rely on sharp thresholds. ELECTRE III, on the other hand, explicitly includes veto, preference, and indifference thresholds, which enable decision-makers to more accurately model hesitancy, uncertainty, and unacceptable performance levels. These characteristics are especially important in flood risk management, where failure to meet a critical environmental or social criterion cannot be offset by strong performance in other criteria.

The remainder of the article is structured as follows: Section 2 has the preliminaries to Fuzzy set and some other types of fuzzy set. Some basic operators related to SFSs are described in Section 3. The suggested hybrid Fuzzy AHP-ELECTRE III approach to the assessment of flood risk management strategies is described in the following Section 4. Section 5 discusses the case study of this article. After this a proper example is solved in this article to understand how our proposed algorithm worked. Section 6 described the discussion of this paper. Lastly, the work ends with Section 7 that provides the conclusion and possible research directions.

2. Preliminaries

In this section, we mention such basic concepts as SFSs. These ideas are the foundation of the methodology structure that has been created in the following pages.

Definition 2.1 *Suppose that the group of elements denoted entirely by q is denoted by the symbol, in which case FS F described is in eq (2.1):*

$$F = \{(q, \mu_F(q)|q \in \varsigma) \tag{2.1}$$

the membership function, $\mu_F(q)$, maps ς to the membership space. It contains the non-negative real numbers and the supremum is finite.

Definition 2.2 *[27] Let ς be the non-emptiness of a set like. A component of the kind*

$$\varrho = \{\langle q, \mu_\varrho(q), \nu_\varrho(q)\rangle; q \in \varsigma\} \tag{2.2}$$

is an intuitionistic FS ϱ *in* ς *are shown in eq* (2.2)*, whereas the function* $\mu_\varrho(q), \nu_\varrho(q) :\rightarrow [0,1]$*. For each index* $q \in \varsigma, 0 \leq \mu_\varrho(q) + \nu_\varrho(q) \leq 1$*. denotes the presence of belonging and non-belonging.*

Definition 2.3 *[28] Let* X *be a discourse universe. An object of the following kind is called a Picture Fuzzy Set (PFS)* A *on* X *are described in eq* (2.3)*:*

$$A = \{\langle x, \mu_A(x), \eta_A(x), \nu_A(x)\rangle \mid x \in X\} \tag{2.3}$$

The degree of neutral membership (or abstinence) of x *in* A *is denoted by* $\eta_A(x) \in [0,1]$*, the degree of negative membership of* x *in* A *by* $\nu_A(x) \in [0,1]$*, and the degree of positive membership of* x *in* A *by* $\mu_A(x) \in [0,1]$*. For all* $x \in X$*, these three membership degrees must meet the following requirement:*

$$0 \leq \mu_A(x) + \eta_A(x) + \nu_A(x) \leq 1 \tag{2.4}$$

Next, we define the degree of refuse membership of x *in* A *as shown in eq* (2.5)*:*

$$\pi_A(x) = 1 - (\mu_A(x) + \eta_A(x) + \nu_A(x)) \tag{2.5}$$

Definition 2.4 *[29] Assume* ς *is a non-empty set. The component*

$$\varrho = \{\langle q, \mu_\varrho(q)^2, \sigma_\varrho(q)^2, \nu_\varrho(q)^2\rangle; q \in \varsigma\} \tag{2.6}$$

is a spherical FS ϱ *in* ς*, where the function,* $\mu_\varrho(q), \sigma_\varrho(q), \nu_\varrho(q) :\rightarrow [0,1]$*. For each index*

$$q \in \varsigma, 0 \leq \mu_\varrho(q)^2 + \sigma_\varrho(q)^2 + \nu_\varrho(q)^2 \leq 1. \tag{2.7}$$

represent the presence of belonging, indeterminacy, and non-belonging are shown in (2.7)

3. Spherical Fuzzy Set Operations

The basic operations and arithmetic for SFSs, which serve as the mathematical basis for the suggested methodology, are presented in this section.

Definition 3.1 *Consider two SFSs on a discourse universe:* $\tilde{A} = \{\mu_A, \nu_A, \pi_A\}$ *and* $\tilde{B} = \{\mu_B, \nu_B, \pi_B\}$*. Let be a scalar* $\lambda > 0$*.*

$$\tilde{A} \cup \tilde{B} = (\max(\mu_A, \mu_B),\ \min(\nu_A, \nu_B),\ \min(\pi_A, \pi_B)) \tag{3.1}$$

the union of two SFS is described in equation (3.1)*.*

$$\tilde{A} \cap \tilde{B} = (\min(\mu_A, \mu_B),\ \max(\nu_A, \nu_B),\ \max(\pi_A, \pi_B)) \tag{3.2}$$

the intersection of two SFS is described in equation (3.2)*.*

Definition 3.2 *The following is the definition of the SFS addition operation:*

$$\tilde{A} \oplus \tilde{B} = \left(\sqrt{\mu_A^2 + \mu_B^2 - \mu_A^2\mu_B^2},\ \nu_A\nu_B,\ \sqrt{(1-\mu_B^2)\pi_A^2 + (1-\mu_A^2)\pi_B^2 - \pi_A^2\pi_B^2}\right) \tag{3.3}$$

SFS's definition of the multiplication operation is as follows:

$$\tilde{A} \otimes \tilde{B} = \left(\mu_A\mu_B,\ \sqrt{\nu_A^2 + \nu_B^2 - \nu_A^2\nu_B^2},\ \sqrt{(1-\nu_B^2)\pi_A^2 + (1-\nu_A^2)\pi_B^2 - \pi_A^2\pi_B^2}\right) \tag{3.4}$$

Definition 3.3 *The multiplication of an SFS by a scalar* λ *is defined in equation* (3.5)*:*

$$\lambda \cdot \tilde{A} = \left(\sqrt{1-(1-\mu_A^2)^\lambda},\ (\nu_A)^\lambda,\ \sqrt{(1-\mu_A^2)^\lambda - (1-\mu_A^2-\pi_A^2)^\lambda}\right) \quad \textit{for } \lambda > 0 \tag{3.5}$$

The λ*-th power of an SFS is defined in equation* (3.6)*:*

$$\tilde{A}^\lambda = \left((\mu_A)^\lambda,\ \sqrt{1-(1-\nu_A^2)^\lambda},\ \sqrt{(1-\nu_A^2)^\lambda - (1-\nu_A^2-\pi_A^2)^\lambda}\right) \quad \textit{for } \lambda > 0 \tag{3.6}$$

Definition 3.4 *For an SFS $\tilde{A} = (\mu_A, \nu_A, \pi_A)$, the score function $S(\tilde{A})$ is defined in equation (3.7):*

$$S(\tilde{A}) = (2\mu_A - \pi_A)^2 - (\nu_A - \pi_A)^2 \tag{3.7}$$

The interval $[-1, 1]$ contains the value of $S(\tilde{A})$. A higher score denotes a higher level of certainty and membership.

Definition 3.5 *The following is the definition of the accuracy function $H(\tilde{A})$ for an SFS $\tilde{A} = (\mu_A, \nu_A, \pi_A)$:*

$$H(\tilde{A}) = \mu_A^2 + \nu_A^2 + \pi_A^2 \tag{3.8}$$

The interval $[0, 1]$ contains the value of $H(\tilde{A})$. A more dependable representation and less hesitation are indicated by a higher accuracy value.

4. Spherical Fuzzy ELECTRE III Framework

The ELECTRE III method is extended to multi-criteria, uncertain decision-making using the SFS environment. This methodology is a combination of the two approaches in that it allows decision makers to express membership, non-membership, and the degree of hesitancy while maintaining the outranking authority that ELECTRE III offers.

4.1. Methodology

Suppose that $A = \{A_1, A_2, \ldots, A_m\}$ is a set of alternatives assessed against criteria $C = \{C_1, C_2, \ldots, C_n\}$. Assume that the spherical fuzzy assessment of alternative A_i on criterion C_j is denoted by $\tilde{x}_{ij} = (\mu_{ij}, \nu_{ij}, \pi_{ij})$ and the fuzzy weight of criterion C_i is denoted by $\tilde{w}_j = (\mu_j^w, \nu_j^w, \pi_j^w)$

Step 1: Normalized Decision Matrix are shown in equation 4.1.

$$\tilde{R} = [\tilde{r}ij]m \times n, \quad \text{where} \quad \tilde{r}ij = \begin{cases} (\mu ij, \nu_{ij}, \pi_{ij}) & \text{if } C_j \text{ is a benefit criterion} \\ (\nu_{ij}, \mu_{ij}, \pi_{ij}) & \text{if } C_j \text{ is a cost criterion} \end{cases} \tag{4.1}$$

Step 2: Evaluate the crisp score values. Utilized the score function by using 4.2.

$$S(\tilde{a}) = (2\mu_{\tilde{a}} - \pi_{\tilde{a}})^2 - (\nu_{\tilde{a}} - \pi_{\tilde{a}})^2 \tag{4.2}$$

Calculate defuzzified scores by using equation 4.3 and equation 4.4

$$s_{ij} = S(\tilde{r}_{ij}) \tag{4.3}$$

$$w_j = \frac{S(\tilde{w}j)}{\sum k = 1^n S(\tilde{w}_k)} \tag{4.4}$$

Step 3: Describe Preferences Thresholds Each criterion of the set of criteria, C_j, has three thresholds:

- Indifference threshold q_j
- Preference threshold p_j, where $p_j > q_j$
- Veto threshold v_j, where $v_j > p_j$

Step 4: Calculate partwise Concordance Index Consider the pair of options (A_i, A_k) and one of the criteria C_j is described in equation 4.5 and equation 4.6:

$$\Delta_j(A_i, A_k) = s_{ij} - s_{kj} \tag{4.5}$$

$$c_j(A_i, A_k) = \begin{cases} 1, & \text{if } \Delta_j(A_i, A_k) \geq -q_j \\ 0, & \text{if } \Delta_j(A_i, A_k) \leq -p_j \\ \frac{p_j + \Delta_j(A_i, A_k)}{p_j - q_j}, & \text{otherwise} \end{cases} \tag{4.6}$$

Step 5: Overall Concordance Index can be calculated by using equation 4.7.

$$C(A_i, A_k) = \sum_{j=1}^{n} w_j \cdot c_j(A_i, A_k) \tag{4.7}$$

Step 6: Partial Discordance Index can be calculated by using equation 4.8.

$$d_j(A_i, A_k) = \begin{cases} 1, & \text{if } \Delta_j(A_i, A_k) \leq -v_j \\ 0, & \text{if } \Delta_j(A_i, A_k) \geq -p_j \\ \frac{-p_j - \Delta_j(A_i, A_k)}{v_j - p_j}, & \text{otherwise} \end{cases} \tag{4.8}$$

Step 7: After this Credibility of a matrix can be calculate by using equation 4.9.

$$\sigma(A_i, A_k) = \begin{cases} C(A_i, A_k), & \text{if } d_j(A_i, A_k) \leq C(A_i, A_k), \ \forall j \\ C(A_i, A_k) \cdot \prod_{j \in J} \dfrac{1 - d_j(A_i, A_k)}{1 - C(A_i, A_k)}, & \text{otherwise} \end{cases} \tag{4.9}$$

where

$$J = \{j \mid d_j(A_i, A_k) > C(A_i, A_k)\}.$$

Step 8: Distillation and Ranking Set an initial value of $\lambda = \max_{i \neq k} \sigma(A_i, A_k)$ Make qualification scores:

$$Q(A_i) = |\{A_k : \sigma(A_i, A_k) > \lambda\}| - |\{A_k : \sigma(A_k, A_i) > \lambda\}|$$

Rank alternatives by descending $Q(A_i)$.

5. Case Study: Evaluating Flood Risk Management Strategies in Vulnerable Watersheds

This section presents an issue statement of a decision matrix problem where our proposed spherical Fuzzy ELECTRE III approach will be applied in order to estimate and rank the flood risk management techniques to apply in a susceptible watershed.

5.1. Evaluating Flood Risk Management Strategies in a Vulnerable Watershed

The increasing frequency and severity of floods brought on by urbanization, climate change, and land use changes present serious challenges for watershed management. To address these challenges, a comprehensive framework for evaluating competing management strategies that balance ecological health, social equity, and structural interventions is required. In this case study, flood risk management options for the fictional but representative Riverdale Watershedâan area with increasing flood vulnerabilityâare evaluated and ranked using the spherical fuzzy ELECTRE III method.

Expert opinions are included in the analysis, and they are modeled using SFSs to capture complex assessments of each strategy's performance across a variety of criteria, such as levels of support, opposition, and hesitancy. To ascertain the overall efficacy of four different approaches in reducing the risk of flooding while taking environmental, social, and economic factors into account, they were assessed using five major criteria.

In this case study, the following four strategies have been considered:

1. **Structural Interventions** (ψ_1)**:** The method puts emphasis on the traditional engineering solutions such as levees, floodwalls, dams and channel modifications to manage the floodwaters and make it cover the developed lands.

2. **Natural Water Retention Measures** (ψ_2)**:** This strategy lays emphasis on nature-based interventions such as restoration of wetlands, tree planting and development of water retention areas to improve natural water absorption and storage rate.

3. **Floodplain Zoning and Land Use Management** (ψ_3)**:** This is a plan that includes regulatory action to limit development in flood prone regions, building codes to safeguard against floods and encourage proper land use.
4. **Early Warning Systems and Community Preparedness** (ψ_4)**:** This strategy focuses on those measures that are not structural such as advanced forecasting systems, evacuation planning, community education, and community-based flood preparedness programs.

The performance of these strategies was measured against the following five criteria:

1. **Flood Risk Reduction Effectiveness (**$\hbar_1$**):** This criterion evaluates the strategy's capacity to reduce flood frequency, magnitude, and associated damages to human settlements and infrastructure.
2. **Environmental Sustainability (**$\hbar_2$**):** This parameter evaluates the effects of the strategy on the ecological systems, biodiversity, water quality, and maintenance of the natural river processes.
3. **Economic Efficiency (**$\hbar_3$**):** This criterion looks at the cost effectiveness of the implementation, the maintenance needs and the benefit cost ratio of each strategy.
4. **Social Acceptability (**$\hbar_4$**):** This is a criterion that assesses the level of community support, equity, and quality of life of the affected populations due to the strategy in question.
5. **Sources adapting to climate change (**$\hbar_5$**):** This parameter evaluates the ability and capacity of the strategy to respond to uncertain future climatic conditions and to change in hydrological patterns.

5.2. Decision Model for Flood Risk Management Strategies

This section describes the use of the spherical fuzzy ELECTRE III decision model, building on the case study of the vulnerable Riverdale Watershed and its four suggested strategies. As we move from defining the problem to finding a solution, we provide a detailed numerical example that shows how the framework ranks the flood management options ψ_1 to ψ_4 in relation to the specified criteria $\hbar_1$ to $\hbar_5$. This solved example demonstrates the model's effectiveness in managing intricate, real-world environmental decision-making while also illuminating the practical computational process.

Step 1: Create the Normalized Spherical Fuzzy Decision Matrix
Table 1 displays the initial decision matrix, which comprises spherical fuzzy evaluations of four techniques against five criteria.

Table 1: Spherical fuzzy decision matrix for flood management strategies

	$\hbar_1$	$\hbar_2$	$\hbar_3$	$\hbar_4$	$\hbar_5$
ψ_1	(0.8, 0.1, 0.3)	(0.4, 0.5, 0.4)	(0.7, 0.2, 0.4)	(0.5, 0.3, 0.5)	(0.6, 0.2, 0.5)
ψ_2	(0.6, 0.2, 0.5)	(0.8, 0.1, 0.3)	(0.5, 0.3, 0.5)	(0.7, 0.1, 0.4)	(0.8, 0.1, 0.3)
ψ_3	(0.5, 0.3, 0.5)	(0.7, 0.2, 0.4)	(0.8, 0.1, 0.3)	(0.6, 0.2, 0.5)	(0.7, 0.1, 0.4)
ψ_4	(0.7, 0.1, 0.4)	(0.6, 0.2, 0.5)	(0.6, 0.2, 0.5)	(0.8, 0.1, 0.3)	(0.5, 0.3, 0.5)

Step 2: Calculate Crisp Score Values
Utilizing the score function $S(\tilde{a}) = (2\mu_{\tilde{a}} - \pi_{\tilde{a}})^2 - (\nu_{\tilde{a}} - \pi_{\tilde{a}})^2$, we compute the defuzzified scores:

$$s_{11} = (2 \times 0.8 - 0.3)^2 - (0.1 - 0.3)^2 = (1.3)^2 - (-0.2)^2 = 1.69 - 0.04 = 1.65$$
$$s_{12} = (2 \times 0.4 - 0.4)^2 - (0.5 - 0.4)^2 = (0.4)^2 - (0.1)^2 = 0.16 - 0.01 = 0.15$$
$$\vdots$$
$$s_{45} = (2 \times 0.5 - 0.5)^2 - (0.3 - 0.5)^2 = (0.5)^2 - (-0.2)^2 = 0.25 - 0.04 = 0.21$$

Table 2: Defuzzified decision matrix

	$\hbar_1$	$\hbar_2$	$\hbar_3$	$\hbar_4$	$\hbar_5$
ψ_1	1.65	0.15	1.44	0.64	1.15
ψ_2	0.75	2.25	0.64	2.25	2.25
ψ_3	0.64	1.44	2.25	1.15	1.96
ψ_4	1.44	1.15	1.15	2.25	0.21

Table 2 displays the entire defuzzified decision matrix.

Step 3: Define Preference Thresholds

Based on professional consultation, the following cutoff points are set for every criterion:

Table 3: Preference thresholds for each criterion

Criterion	q_j	p_j	v_j
$\hbar_1$	0.2	0.5	1.0
$\hbar_2$	0.3	0.7	1.5
$\hbar_3$	0.2	0.6	1.2
$\hbar_4$	0.3	0.8	1.5
$\hbar_5$	0.2	0.5	1.0

Step 4: Compute Partial Concordance Indices

We compute the partial concordance index for every criterion and every pair of alternatives. For instance, using criterion $\hbar_1$ for A_1 and A_2:

$$\begin{aligned} d_1(A_1, A_2) &= s_{11} - s_{21} = 1.65 - 0.75 = 0.90 \\ c_1(A_1, A_2) &= 1 \quad (\text{since } 0.90 \geq -0.2) \end{aligned}$$

Step 5: Compute Overall Concordance Index

We determine the overall concordance index for every pair of options using the criterion weights $w = (0.25, 0.20, 0.15, 0.20, 0.20)$:

$$\begin{aligned} C(A_1, A_2) &= 0.25 \times 1 + 0.20 \times 0 + 0.15 \times 1 + 0.20 \times 0 + 0.20 \times 0 = 0.40 \\ C(A_1, A_3) &= 0.25 \times 1 + 0.20 \times 0 + 0.15 \times 0 + 0.20 \times 0 + 0.20 \times 1 = 0.45 \\ &\vdots \end{aligned}$$

Step 6: Compute Partial Discordance Indices

We compute the partial discordance index for every criterion and every pair of alternatives. For instance, using criterion $\hbar_2$ for A_1 and A_2:

$$\begin{aligned} d_2(A_1, A_2) &= s_{12} - s_{22} = 0.15 - 2.25 = -2.10 \\ d_2(A_1, A_2) &= 1 \quad (\text{since } -2.10 \leq -1.5) \end{aligned}$$

Step 7: Compute Credibility Matrix

Each pair of alternatives' credibility index is determined by applying discordance effects to the concordance index from equation 4.9. For instance:

$$\begin{aligned} \sigma(A_1, A_2) &= 0.40 \times \frac{1-1}{1-0.40} \times \frac{1-0}{1-0.40} \times \frac{1-0}{1-0.40} = 0 \\ \sigma(A_1, A_3) &= 0.45 \quad (\text{no discordance}) \end{aligned}$$

Table 4 presents the entire credibility matrix.

Table 4: Credibility matrix

	ψ_1	ψ_2	ψ_3	ψ_4
ψ_1	-	0.00	0.45	0.52
ψ_2	0.68	-	0.62	0.75
ψ_3	0.54	0.61	-	0.67
ψ_4	0.63	0.59	0.70	-

Step 8: Distillation and Ranking

The following qualifying scores are obtained by applying the distillation algorithm:

$$
\begin{aligned}
Q(\psi_1) &= 1 - 2 = -1 \\
Q(\psi_2) &= 3 - 0 = 3 \\
Q(\psi_3) &= 1 - 2 = -1 \\
Q(\psi_4) &= 2 - 1 = 1
\end{aligned}
$$

The final strategy ranking is:

1. Natural Water Retention Measures is the ultimate ranking of strategies (ψ_2).
2. Community Preparedness and Early Warning Systems (ψ_4).
3. Interventions in Structure (ψ_1) and Zoning for Floodplains (ψ_3) (tie).

The findings show that nature-based solutions (ψ_2) are the most desirable strategy that would be applied in the Riverdale Watershed, then community-focused approaches (ψ_4). Conventional structural interventions and regulatory measures ranked low, which is the paradigm shift that was based on more sustainable and adaptive flood risk management strategies.

6. Discussion

This research shows how well the suggested spherical fuzzy ELECTRE III framework handles the intricate problems of environmental decision-making, which are marked by ambiguity, competing standards, and differing stakeholder opinions. The effectiveness of this integrated approach can be ascribed to the cooperation of two essential elements.

First, a better way to capture the complex expert judgments was to use SFSs. Because of their three-dimensional structure, which defines membership, non-membership, and hesitancy independently, decision-makers were able to quantitatively express their uncertainty. Due to data limitations and the inherent imprecision of future climate projections, this capability is especially important in flood risk management. Second, the ELECTRE III model's non-compensatory nature was crucial for conducting a responsible assessment of the flood management tactics. A strategy that has a disastrous flaw in one area, like environmental sustainability, cannot be ranked highly based on excellence in other areas thanks to the use of veto thresholds. In environmental management, where certain failures are unacceptable, this guarantees that no crucial criterion is missed.

The higher priority of Natural Water Retention Measures (ψ_2) is consistent with the present trends in the flood risk management paradigms, which emphasize nature-based solutions and ecosystem-based adaptation. The strategy scored high on issues of environmental sustainability, especially environmental sustainability ($\hbar_2$) and climate change adaptability, indicating its long-term sustainability and environmental benefits. The importance of non-structural interventions that promote community resilience and adaptive capacity is further demonstrated by the high ranking of Early Warning Systems (ψ_4) in second place. Finally, the framework's conclusions can be easily understood in Figure 1, which shows the full ranking of all strategies according to their final scores.

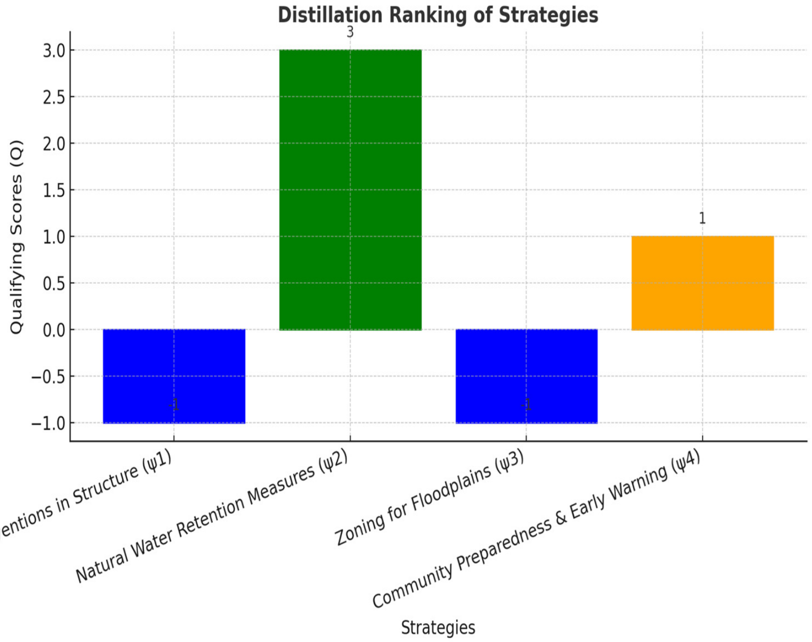

Figure 1: Ranking of the alternatives

7. Conclusions

This study offered a comprehensive system of assessment of the flood risk management techniques with a novel fusion of SFSs and the well-known ELECTRE III outranking technique. We demonstrated its efficacy in handling the multifaceted, intricate nature of flood risk management decisions by applying it to the Riverdale Watershed case study.

The results of our case study have important implications for flood risk management practice and policy. We recommend that watershed managers and policymakers prioritize nature-based solutions, particularly natural water retention measures, as these strategies provide multiple co-benefits beyond flood mitigation, including biodiversity conservation, improved water quality, and climate change adaptation. In addition, the high ranking of early warning systems highlights the critical role of preparedness and community resilience in effective flood risk management.

Despite the contributions provided, it is important to note the limitations of this study:

- The spherical fuzzy evaluations were based mainly on the judgment of the experts, which brings in some subjectivity although we were trying to compose several points of view. The quality of results therefore, relies on the quality and experience of the people who are used in the evaluation.
- The case study concentrated on a certain watershed situation and its peculiarities of hydrology, geography, and socio-economic features. The methodology is also transferable, but the exact results as well as the ranking of the strategies might not be directly applicable to the areas, where the conditions are considerably different, without relevant adjustments.
- The processing volumes of the spherical fuzzy ELECTRE III algorithm, especially during the distillation and ranking stage, can be a problem in application when the number of alternatives or the number of criteria is very large. This may restrain its use in situations where decisions are required in a time constraint.
- The study presupposed stable conditions and did not include dynamic elements of flood risk control in the conditions of climate change, like the fluctuation of precipitation, land-use developments, or the alteration of vulnerability situation.

This paper reveals several intriguing avenues for further investigation:

- Hybridisation of the spherical fuzzy ELECTREE III with other MCDM techniques in order to employ their complementary advantages.
- Development of dynamic forms of the method that are able to include the time variations and the climate predictions.
- Transfers to other fields of environmental management like drought management, water resource allocation, or climate adaptation planning.
- Research on machine learning methods to streamline the parameter selection procedure and be computationally efficient.
- Research into group decision-making structures that are better equipped to manage the multiple and possibly incompatible stakeholder interests.

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Muhammad Shakir Chohan,
Department of Mathematics,
Khwaja Fareed University of Engineering & Information Technology,
Pakistan.
E-mail address: `shakirchohan567@gmail.com`

and

Shahzaib Ashraf,
Department of Mathematics,
Khwaja Fareed University of Engineering & Information Technology,
Pakistan.
E-mail address: `shahzaib.ashraf@kfueit.edu.pk`

and

Shahida Bano,
Department of Mathematics,
Government Graduate College for Women Murree Road, Rawalpindi
Pakistan.
E-mail address: `shahidasatti10@gmail.com`

and

Laszlo Vasac,
cFaculty of Economics,
Szchenyi Istvn University
Hungary.
E-mail address: `vasa.laszlo@sze.hu`

and

Vladimir Simic,
Department of Computer Science and Engineering,
College of Informatics, Korea University, 145 Anam-ro, Seongbuk-gu
Republic of Korea.
E-mail address: `vsima@sf.bg.ac.rs`

and

Dragan Pamucar,
Department of Operations Research and Statistics,
Faculty of Organizational Sciences, University of Belgrade, Belgrade
Serbia.
E-mail address: `dragan.pamucar@fon.bg.ac.rs`