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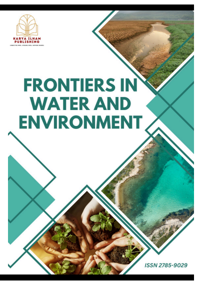

Integrating Fuzzy Maclaurin Symmetric Mean and DEMATEL Method for Water Management Strategies

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ABSTRACT

Water management is a critical challenge faced globally, as efficient management of this vital resource is essential for sustainable development. This study aims to identify and analyze key factors influencing water management strategies, specifically focusing on water availability, water quality, environmental, population growth, pollution & contamination and technological factors. To achieve this, the study develops an integrated decision-making framework combining the fuzzy Maclaurin Symmetric Mean (MSM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. The study is conducted under fuzzy environment as accounting for uncertainty in decision-making and MSM is used to aggregate multiple data. DEMATEL is then applied to model the causal relationships among the factors. The case study results highlight the significant interdependencies between population growth, water availability and pollution with technological factors identified as crucial in addressing challenges related to water quality and contamination. The findings demonstrate that the integrated framework provides valuable insights into the prioritization and optimization of water management strategies, offering a comprehensive approach to tackle the complex and dynamic challenges of water resource management. This research contributes to the development of more analytical and effective solutions for sustainable water management in a rapidly changing environment.

1. Introduction

Water is a vital resource that supports human life, agriculture and industry which making effective water management crucial for global sustainability. However, growing challenges such as rapid urbanization, climate change, population growth and environmental damage are putting more pressure on water resources. These challenges make it increasingly difficult to manage water

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efficiently and equitably. Water management strategies must address complex issues like water scarcity, contamination, quality damage and equality in access to water to ensure that everyone receives an appropriate share based on their needs. Traditional methods of water management strategies may fall short because they often fail to consider interrelationship between various influencing factors [1-4]. This complexity requires a study capable of addressing the multiple factors of water management including uncertainty and dynamic relationships among factors.

Over the years, multi-criteria decision-making (MCDM) methods have emerged as effective tools for managing complex decisions, such as those encountered in water resource management. These methods allow decision-makers (DM)s to evaluate multiple criteria or factors which is essential in choices must be made by weighing the benefits and drawbacks of different options. Among these methods, fuzzy set (FS) has gained popularity due to its ability to handle uncertainty and imprecision. FS is common in water management scenarios [5-9].

The aggregation operator (AO) is highly useful in MCDM methods to combine the preferences of DMs into a single representative preference. Due to the effectiveness of AO in completing MCDM procedures, many scholars have developed studies on AO. Typically, traditional AOs are based on basic averaging such as simple additive weighting [10], weighted average [11], ordered weighted average [12] and average of rank method [13]. However, studies on AO should not be limited to basic average only. The Maclaurin Symmetric Mean (MSM) is a proven useful method to capture the relationships between multiple arguments and offer more flexibility with the inclusion of a parameter. The application of the MSM has been extensively studied by various researchers. For instance, Xing *et al.,* [14] applied the MSM operator in medical studies, Ning *et al.,* [15] used it for supplier selection, and several other authors have implemented the MSM method in decision-making processes [16-19].

Additionally, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method has been widely used for analyzing the causal relationships between criteria. DEMATEL helps to visualize how different criteria of a system influence each other and making it easier to identify key factors for action to be taken. While DEMATEL has been applied in various areas [20 – 23], no studies have integrated DEMATEL and MSM methods to simultaneously address uncertainty, aggregate multiple preferences and identify the complex interdependencies among factors in water management strategies. Study by Lazim *et al.,* [references] do not account the aggregation in their framework.

There is a clear gap in the current literature regarding the integration of fuzzy MSM with causal analysis methods like DEMATEL in the case study of water management strategies. While individual methods have been used to assess various factors in water management, an integrated approach remains underexplored. Most existing research tends to focus on a limited set of factors, without fully considering the interdependencies between these factors. As a result, there is a need for a more comprehensive framework that not only aggregates multiple factors in a way that accounts for uncertainty but also analyzes how different factors influence one another. This research aims to fill this gap by combining these two methods to develop a more effective MCDM framework for water management. The significance of this study lies in its innovative approach to improving water management strategies through the integration of fuzzy MSM (Maclaurin Symmetric Mean) with causal analysis methods like DEMATEL.

The main objective of this research is to develop an integrated MCDM framework for water management by combining the fuzzy MSM and the DEMATEL method. The study aims to identify and analyze the key factors influencing water management strategies, including water availability, water quality, environmental factors, population growth, pollution & contamination and technological actors. The study implemented the DEMATEL method to evaluate the causal relationships between these factors and provide insights into how they influence each other. By achieving these objectives, the study will contribute to the development of more effective and comprehensive water management strategies that are capable of addressing the complex challenges of managing water resources in a rapidly changing world.

2. Methodology

2.1 Preliminaries and Basic Concept

Preliminaries and basic concepts are important to provide the necessary foundation that supports the study process, from formulation of the problem to the analysis and interpretation of results.

2.1.1 Fuzzy set

In year 1965, Zadeh [24] introduced the FS theory to address the vagueness in information and the uncertainty in human judgment throughout the MCDM process. The definition of a fuzzy set is as follows:

Definition 2.1

In a universe of discourse X, a fuzzy subset $\tilde{A}$ of X is defined by a membership function $\mu_{\tilde{A}}(x)$ that assigns to each element $x \in X$ to a real number in the interval [0,1]. The value of $\mu_{\tilde{A}}(x)$ represents the grade of membership of x in the fuzzy set $\tilde{A}$.

Definition 2.2

A fuzzy number $\tilde{A} = (\tilde{l}, \tilde{m}, \tilde{u})$ on X is a triangular fuzzy number (TFN) if its membership function $\tilde{A}: X \to [0,1]$ satisfies the following conditions.

$$\tilde{A}(x) = \begin{cases} \dfrac{x - \tilde{l}}{\tilde{u} - \tilde{l}}, & for\ \tilde{l} \le x \le \tilde{u} \\ 1, & for\ x = \tilde{u} \\ \dfrac{\tilde{u} - x}{\tilde{u} - \tilde{m}}, & for\ \tilde{m} \le x \le \tilde{u} \end{cases}$$

Definition 2.3

Fuzzy arithmetic operators are defined by Ali *et.al.*, [25]. Let $\tilde{A}$ and $\tilde{B}$ are two TFNs. Then

i. $\tilde{A} + \tilde{B} = \langle l_1 + l_2, m_1 + m_2, u_1 + u_2 \rangle$
ii. $\tilde{A} - \tilde{B} = \langle l_1 - u_2, m_1 - m_2, u_1 - l_2 \rangle$
iii. $\tilde{A} \times \tilde{B} = \langle min(l_1 l_2, l_1 u_2, u_1 l_2, u_1 u_1), m_1 m_2, \max(l_1 l_2, l_1 u_2, u_1 l_2, u_1 u_1) \rangle$

2.1.2 Maclaurin Symmetric Mean

The MSM was first introduced by Maclaurin [26] and later developed by DeTemple and Robertson [27]. MSM recognizes as a more powerful and preferred AO compared to others because of its ability to model the interrelationships among multiple input arguments. The inclusion of a parameter in MSM also allows it to reflect the DMs' risk preferences in judgment. The definition of the MSM operator is provided in Definition 2.2.

Definition 2.4

Let $x_1, x_2, \cdots x_n$ be a collection of non-negative real numbers. The MSM is defined as:

$$MSM(x_1, x_2, \cdots x_n) = \left(\frac{\sum_{1 \le i_1 < i_k < n} \prod_{r=1}^{k} x_{i_r}}{C_n^k}\right)^{\frac{1}{k}} \quad (1)$$

where $C_n^k = \frac{n!}{k!(n-k)!}$ is the binomial coefficient with $1 \le k \le n$ and $i_1, i_2, \cdots i_k$ traverses all the k-tuple combination of $(1,2, \cdots n)$.

2.1.3 DEMATEL

The DEMATEL method was introduced by Gabus & Fontela [28] as part of the Science and Human Affairs Program to handle complex and interrelated problems. The fuzzy DEMATEL method improves the traditional DEMATEL by integrating with FS to offer a more accurate and detailed representation of uncertainty, vagueness, and imprecision in MCDM. This enhancement makes causal analysis more reliable and flexible when dealing with complex real-world issues. The five steps of the DEMATEL method are summarized as follows:

Step 1: Evaluate linguistic data
Linguistic evaluations are performed by evaluating criteria based on the linguistic scales presented in Table 1. These evaluations reflect the degree of influence that criterion *i* exerts on criterion *j*.

Table 1
Linguistic scale of fuzzy DEMATEL

Linguistic variable	TFNs
No influence (N)	[0.00,0.00,0.25]
Low influence (L)	[0.00,0.25,0.50]
Medium (M)	[0.25,0.50,0.75]
High influence (H)	[0.50,0.75,1.00]
Very high influence (VH)	[0.75,1.00,1.00]

Step 2: Determine initial direct-relation
The TFNs are defuzzified using Eq. (3) by Yager [29] to obtain the initial direct-relation

$$DeF(A) = \frac{1}{4}\left(\tilde{l} + 2\tilde{m} + \tilde{u}\right) \quad (2)$$

Step 3: Normalize initial direct-relation
The initial direct-relation is normalized using Eq. (4)

$$D = \frac{DeF(A)}{S} \quad (3)$$

where $s = max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} z_{ij}, \max_{1 \le i \le n} \sum_{i=1}^{n} z_{ij}\right)$. z_{ij} is the element in the initial direct-relation matrix with *i* denoting the rows and *j* denoting the columns. Normalization is crucial to ensure the data are comparable, improving the accuracy of the MCDM process and ensuring that all criteria are evaluated on a consistent scale.

Step 4: Calculate the total-influence matrix using Eq. (5) where *I* is denoted as the identity matrix.

$$T = D(1 - D^{-1}) \quad (4)$$

Step 5: Construct causal diagram by performing structural analysis using Equation (6)-(8).

$$T = [t_{ij}]_{n\times n,}, \qquad i, j = 1,2, \cdots, n \quad (5)$$

$$D = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1=[t_i]n\times 1} \quad (6)$$

$$R = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n=[t_i]1\times n} \quad (7)$$

The horizontal axis, $(D + R)$ called 'prominence' indicates the importance level of each criterion. The vertical axis, $(D - R)$ called 'relation,' represents the net effect of criterion *i* on the system. A positive value of $(D - R)$recognizes a net causer, while a negative value recognizes as a net receiver.

2.2 Integrating Fuzzy Maclaurin Symmetric Mean and DEMATEL Method

This study examines water management strategies to provide valuable insights into prioritizing and improving water management approach, providing a clear approach to handle the complex challenges of managing water resources. The study is carried out in three phases. Phase 1 involves collecting data by assessing the influential factors, which are identified from a review of relevant literature. Phase 2 focuses on aggregating the DMs' preferences into a single preference using the MSM operator. Phase 3 consists of analyzing the study with the DEMATEL method to explore the interrelationships among the factors and visualize the causal connections by creating a causal diagram. The implementation of the study is explained in detail below.

Phase 1: Data collection

In this phase, three DMs are involved. They are required to evaluate the six influential factors (Table 2) using the linguistic variable and TFNs presented in Table 1.

Table 2
Factors of water management strategies

Factors	Description
F1: Water Availability	It encompasses factors such as the volume of freshwater sources and the accessibility of water for human consumption, agriculture, and industry.
F2: Water Quality	Assesses the purity and cleanliness of water including its chemical, physical, and biological properties.
F3: Environmental Factor	Focuses on the ecological impact of water management practices on ecosystems and biodiversity.
F4: Population Growth	Focuses on the ecological impact of water management practices on ecosystems and biodiversity.
F5: Pollution & Contamination	The presence of harmful substances in water bodies that degrade water quality such as chemical, industrial, agricultural, and household waste
F6: Technological Factors	Focus on the role of innovations and advancements in technology in improving water management.

Phase 2: Aggregation

The data evaluations provided by the DMs are aggregated using MSM method with $n = 3$ and parameter $k = 2$. Firstly, the value of binomial coefficient is calculated as follows:

$$C_3^2 = \frac{3!}{2!(3-2)!} = 3\ .$$

For example, the evaluation of factor F3's influences on F1 using TFNs provided by DMs is as follows:

DM_1: [0.25, 0.50, 0.75]
DM_2: [0.50, 0.75, 1.00]
DM_3: [0.00, 0.00, 0.25]

The combinations of *k*-tuples involve the products of pairs such as DM_1DM_2, DM_1DM_3 and DM_2DM_3. For instance, the products of DM_1 and DM_2 is calculated using arithmetic operator defined in Definition 2.3 as follows:

$$\begin{aligned} DM_1DM_2 &= [min(l_1l_2, l_1u_2, u_1l_2, u_1u_1), m_1m_2, \max(l_1l_2, l_1u_2, u_1l_2, u_1u_1)] \\ &= [min(0.25 \times 0.50, 0.25 \times 1, 0.75 \times 0.50, 0.75 \times 0.75), 0.50 \times 0.75, \max(0.25 \times \\ &\quad 0.50, 0.25 \times 1.00, 0.75 \times 0.50, 0.75 \times 0.75)] \\ &= [0.125, 0.375, 0.563] \end{aligned}$$

The same calculations are applied to the combinations DM_1DM_3 and DM_2DM_3, resulting in the following:

$DM_1DM_3 = [0,0,1]$, $\quad DM_2DM_3 = [0,0,1]$

Afterward, defuzzification is applied to the combinations of *k*-tuples using Eq.(2). For example, the defuzzification of DM_1DM_2 is calculated as:

$$\begin{aligned} DeF(DM_1DM_2) &= \frac{1}{4}(0.125 + 2(0.375) + 0.563) \\ &= 0.359 \end{aligned}$$

The results for the defuzzification of other combinations are shown in Table 3 to Table 5.

Table 3
Defuzzification of DM_1DM_2

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0.016	0.281	0.719	0.250	0.250	0.219
F2	0.281	0.016	0.219	0.594	0.719	0.141
F3	0.359	0.063	0.016	0.125	0.359	0.719
F4	0.125	0.891	0.359	0.016	0.438	0.141
F5	0.359	0.719	0.594	0.125	0.016	0.281
F6	0.281	0.250	0.281	0.063	0.125	0.016

Table 4
Defuzzification of DM_1DM_3

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0.016	0.281	0.719	0.031	0.047	0.719
F2	0.359	0.016	0.547	0.250	0.594	0.016
F3	0.250	0.016	0.016	0.141	0.469	0.719
F4	0.281	0.250	0.594	0.016	0.250	0.016
F5	0.594	0.469	0.594	0.359	0.016	0.281
F6	0.359	0.047	0.281	0.016	0.281	0.016

Table 5
Defuzzification of DM_2DM_3

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0.016	0.281	0.719	0.031	0.047	0.719
F2	0.359	0.016	0.547	0.250	0.594	0.016
F3	0.250	0.016	0.016	0.141	0.469	0.719
F4	0.281	0.250	0.594	0.016	0.250	0.016
F5	0.594	0.469	0.594	0.359	0.016	0.281
F6	0.359	0.047	0.281	0.016	0.281	0.016

Then, the completion of MSM method is computed using Table 3 to 5 by Eq.(1). The aggregated evaluation is presented in Table 6.

Table 6
Aggregated Evaluations

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0.001	0.086	0.352	0.009	0.014	0.194
F2	0.110	0.001	0.148	0.111	0.291	0.003
F3	0.087	0.002	0.001	0.029	0.162	0.352
F4	0.057	0.136	0.206	0.001	0.095	0.003
F5	0.206	0.229	0.264	0.073	0.001	0.086
F6	0.110	0.014	0.086	0.002	0.057	0.001

Phase 3: Analysis

The initial direct-relation is derived from aggregated evaluations. The initial direct-relation is normalized using Eq.(3) where each element of the matrix is divided by 1.056 since it is the largest value of sum of row and column. The outcome is presented in Table 7.

Table 7
Normalization

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0.001	0.082	0.333	0.009	0.013	0.184
F2	0.104	0.001	0.140	0.105	0.275	0.003
F3	0.082	0.002	0.001	0.027	0.154	0.333
F4	0.054	0.129	0.195	0.001	0.090	0.003
F5	0.195	0.217	0.250	0.069	0.001	0.082
F6	0.104	0.013	0.082	0.002	0.054	0.001

The total-influence, T can be acquired using Eq.(4) with the results presented in Table 8.

Table 8
Total-influence (T)

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0.125	0.136	0.472	0.048	0.149	0.377
F2	0.261	0.134	0.396	0.161	0.403	0.217
F3	0.204	0.085	0.189	0.061	0.239	0.454
F4	0.167	0.199	0.356	0.048	0.216	0.171
F5	0.351	0.313	0.515	0.134	0.201	0.336
F6	0.157	0.053	0.180	0.022	0.106	0.099

Structural correlation analysis is then performed using Eq.(5) – (7). The result is demonstrated in Table 9.

Table 9
Structural correlation analysis

Factor/Correlation	D + R	D - R
F1	2.571	0.044
F2	2.491	0.651
F3	3.339	-0.876
F4	1.630	0.682
F5	3.164	0.536
F6	2.269	-1.037

Based on the average of the elements in Table 9, the threshold value is determined to be 0.215. Any value in Table 8 that is less than this threshold is denoted as '0,' while values greater than or equal to the threshold are denoted as '1'. The total-influence with threshold (TT) is shown in Table 10.

Table 10
Total-influenced with threshold value (TT)

Factor / Factor	F1	F2	F3	F4	F5	F6
F1	0	0	1	0	0	1
F2	1	0	1	0	1	1
F3	0	0	0	0	1	1
F4	0	0	1	0	1	0
F5	1	1	1	0	0	1
F6	0	0	0	0	0	0

3. Results and Discussion

3.1 Causal Diagram

The causal diagram is constructed based on the values of *D + R* as horizontal axis and the values of *D – R* as vertical axis. The causal diagram in Figure 1 illustrates the complex relationships between various factors in a clear structural model, offering valuable insights for water management strategies. The diagram is divided into two groups which are the upper half represents the cause group (net causers) and the lower half represents the effect group (net receivers).

The net causers consist of water availability (F_1), water quality (F_2), population growth (F_4) and pollution and contamination (F_5), indicating that these factors have a greater influence on the system rather than being influenced by others. Among them, water quality (F_2) and population growth (F_4) appear to be the most significant causes, as they have high positive values. This suggests that changes in water quality and population growth drive the overall water management system which impacting other factors more than they are affected by them. Water availability (F_1) plays a foundational role in determining water management effectiveness, though it is less dominant than (F_2) and (F_4). Pollution and contamination (F_5) is another key factor, indicating that environmental contamination contributes significantly to the water management challenges.

The net receivers consist of environmental factors (F_3) and technology (F_6), indicating that these factors are more affected by other factors than they influence themselves. This means that environmental conditions and technological advancements are outcomes of changes in water availability, quality, population growth, and pollution. Environmental factors (F_3) have the lowest value, making them the most affected factor in the system. This suggests that any variations in water availability, pollution, and population growth can significantly impact environmental conditions. Technology factors (F_6) are also a net receiver, implying that the technological advancements in water management are shaped by external pressures rather than being a primary driver.

This DEMATEL-based causal diagram provides a strategic understanding of how different factors interact in water management. From Figure 1, it can be seen that water quality (F_2) and population growth (F_4) are critical factors. Policy interventions should prioritize improving water quality and managing population growth to ensure sustainable water management. Meanwhile environmental factors (F_3) and technological factors (F_6) require flexible solutions. Since they are net receivers, improving them depends on controlling the influencing factors. Environmental policies and technological innovations should be responsive to a change in water availability, pollution levels, and demographic trends. Pollution and contamination (F_5) is a medium significant. Reducing pollution will improve water supply, protect the environment, and encourage better technology for water management [30]. This causal analysis highlights the need for proactive management of water quality and pollution, while also adapting to environmental changes through technology and policy innovations.

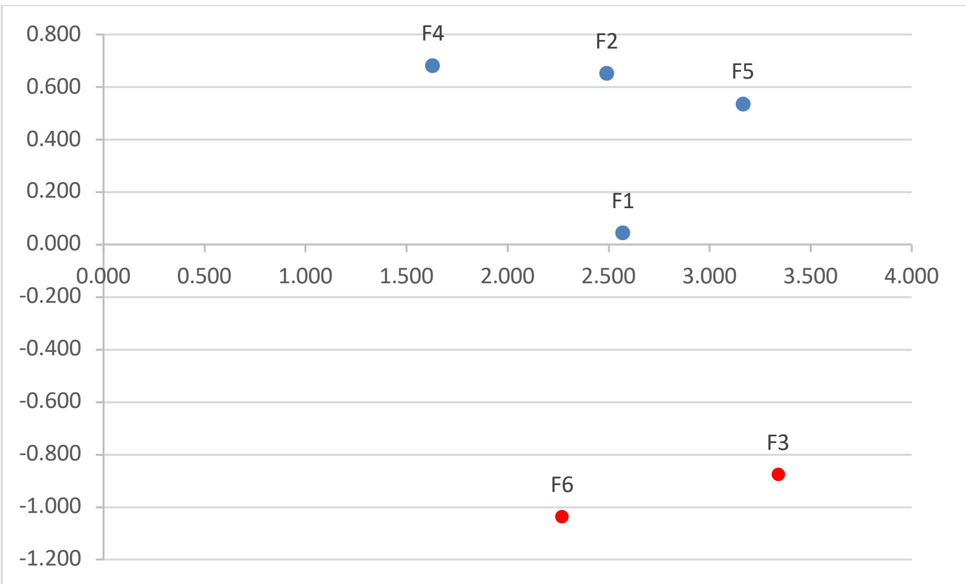

Fig. 1. Causal diagram of water management strategies

3.1 Network-relationship Map

Using the data from Table 10, a network relationship map is constructed to represent the network of relationships among the criteria. The interconnections between the factors are depicted in Figure 2. One of the most significant factors influencing water management is environmental factors (F_3) which are directly impacted by population growth (F_4). As populations expand, the demand for water increases which leads to environmental degradation, affecting both water availability (F_1) and pollution levels (F_5). Population growth drives urbanization and industrial activities which contribute to pollution and which contribute to pollution and harm water quality. To reduce this impact, better city planning, regulations to protect water sources, and more efficient water usage are necessary.

Water quality (F_2) is directly impacted by pollution and contamination (F_5), making pollution control a key focus in water management strategies. Pollution arises from various sources, including industrial waste, agricultural runoff, and improper sewage disposal. Since water quality (F_2) and water availability (F_1) are interconnected, ensuring clean water sources also improves overall water availability. Implementing stricter environmental regulations, advancing wastewater treatment technologies, and raising public awareness can help reduce contamination and maintain water quality. Technology (F_6) play a crucial role in addressing water management challenges. New methods like desalination, water recycling, and smart irrigation systems can help increase water availability (F_1) and improve water quality (F_2). Technology (F_6) can also help reduce pollution (F_4) by cleaning wastewater and monitoring water use. Investing in modern water management tools can help save water and prevent shortages.

The diagram also shows that these factors affect each other in a cycle. For instance, improved water quality (F_2) leads to better water availability (F_1) which in turn reduces environmental stress. Likewise, technological advancements (F_6) can positively influence environmental conditions (F_3) and reducing pollution levels (F_5) and lessen the harmful effects of population growth (F_4). Recognizing these relationships enables policymakers to implement holistic water management strategies that address the root causes rather than just the symptoms.

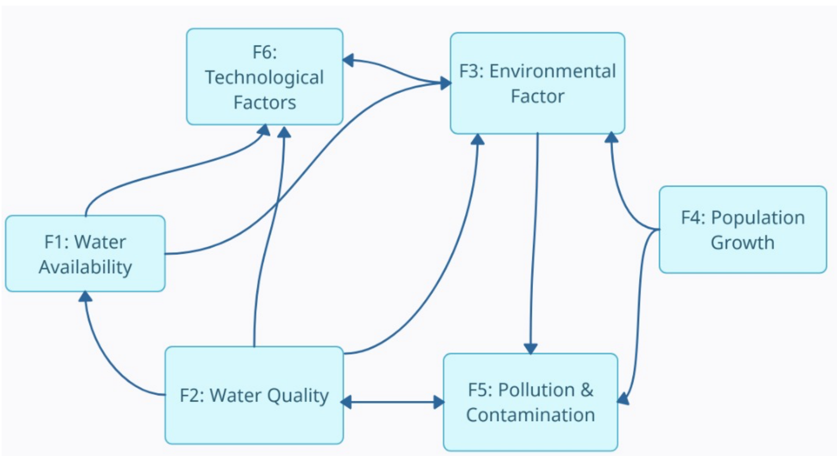

Fig. 2. Network relationship map of water management strategies

4. Conclusions

In conclusion, this study highlights the critical factors influencing water management strategies by applying an integrated decision-making framework using the fuzzy Maclaurin Symmetric Mean (MSM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. The findings emphasize the importance of understanding the causal relationships between water availability, water quality, population growth, pollution, environmental factors, and technology to develop effective and sustainable water management solutions. This is aligned with Adin *et al.*, [31] who suggested that addressing water quality through more comprehensive and holistic water management strategies can lead to the adoption of best management practices and promote sustainable water development.

The causal diagram constructed in this study categorizes the factors into two main groups: net causers and net receivers. Water quality (F_2) and population growth (F_4) emerge as the most significant driving forces affecting the overall water management system. Water availability (F_1) and pollution & contamination (F_5) also play crucial roles in shaping water management challenges. The study finds that environmental factors (F_3) and technological factors (F_6) are primarily influenced by other factors which are they require adaptive responses rather than being primary drivers of change.

The study underscores the necessity of prioritizing water quality improvements and managing population growth as key strategies for effective water management. Since environmental conditions and technological advancements depend on external factors, policies must be adaptable and flexible to the changes brought about by pollution and water availability. Pollution is identified as a medium level but significant factor, as it directly impacts water quality and availability. Reducing pollution through better regulations, improved water treatment technologies, and public awareness campaigns can help safeguard water resources.

Additionally, the findings show that technology plays a crucial role in addressing water management challenges. Innovations such as desalination, water recycling, and smart irrigation systems can enhance water availability and quality while mitigating pollution levels. Investment in modern water management tools is essential to ensure the sustainability of water resources, particularly in the face of rapid urbanization and industrialization.

The network relationship map further illustrates how these factors interact in a cyclical manner. For example, better water quality leads to improved water availability, which can reduce environmental issues. Likewise, technological advancements can positively influence environmental conditions and help manage pollution, thereby lessening the negative impacts of population growth. Understanding these interdependencies is vital for policymakers to implement holistic and long-term water management strategies that address the root causes rather than just the symptoms.

Overall, this research provides valuable insights into the prioritization and optimization of water management strategies. By recognizing the causal relationships between key influencing factors, DMs can adopt more effective policies and technologies to ensure sustainable water management in an increasingly complex and dynamic environment. Future studies may further explore additional influencing factors and test the proposed framework in different regional contexts to enhance its applicability in global water management challenges.

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