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Unveiling Water Quality Insights by Exploring Intuitionistic Fuzzy TOPSIS in Multi-criteria Decision Analysis

Priya Mani[1], Kumaravel Ranganathan[2*]

[1] Department of Mathematics, College of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur 603203, India
[2] Department of Career Development Center, College of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur 603203, India

Corresponding Author Email: kumaravr@srmist.edu.in

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ABSTRACT

The groundbreaking study employs the Intuitionistic Fuzzy Sets-TOPSIS (IFT) model to systematically evaluate the Cauvery River's water quality. To properly handle the complexity of intuitionistic fuzzy sets, the method starts with building a decision matrix. The Analytic Hierarchy Process (AHP), which tackles the imprecision of evaluation indices, produces weight coefficients that are properly defined. This produces a weighted decision matrix that makes it easier to establish membership tiers for different states with regards to water quality. Water quality is mostly determined by the highest membership level at the top of the hierarchy. The tremendous precision of the procedure shows how useful it could be for upcoming evaluations of water quality. In order to boost robustness even more, the technique gains legitimacy and credibility through the integration of the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI).

1. INTRODUCTION

Water is a priceless natural resource that is essential for societal development and human life [1] and serves as the foundation for long-term economic growth. But as the global economy has grown and the population has increased exponentially, there is a growing shortage of water sources and a decline in the quality of the water, which has led to serious problems [2]. Due to the overflow of domestic sewage from cities, agricultural effluents, and industrial wastewaters, water quality integrity has suffered significantly [3]. It is crucial to conduct thorough examinations into the water quality levels of various rivers in order to stop further deterioration in light of the escalating water resource problem [4, 5].

Numerous academics from various countries have studied methods for determining water quality [6]. Notably, Horton et al. developed the Water Quality Index (WQI) approach in the US in 1965, which is a framework that includes eight different water quality indices [7-9]. Since the 1990s, a variety of mathematical methods and models have been used to study the worldwide water quality, with encouraging results. These approaches include, among others, evaluations based on neural networks [10, 11], studies of matter elements [12], the complete approach to identifying water quality [13], the projection pursuit method [14] and the grey index method [15]. These methods have significantly accelerated the development of water quality evaluation. However, underlying flaws and deficiencies continue [16].

Enter the world of intuitionistic fuzzy set theory, a field awash in uses for decision-making, multi-criteria decision-making, networking, computing, smart systems, economics, and more. The notion of Multi-Criteria Decision-Making (MCDM), which seeks to identify the best option from a variety of options, is well suited to meet the difficulty of assessing several alternatives, which is a necessity in decision-making. MCDM, which was founded by Bellman and Zadeh, has recently experienced exceptional growth.

A new paradigm that tackles common issues in the field is presented by combining intuitionistic fuzzy set theory with the TOPSIS model. Mishra et al. [17] have observed that conventional fuzzy mathematics approaches have faced difficulties related to notable discrepancies, subjective perceptions, and complex computation. Alternatively, our novel strategy departs from the state of the art by introducing non-membership functions into intuitionistic fuzzy sets. By enabling a more nuanced depiction of fuzziness, this augmentation lessens the drawbacks of conventional methods.

The TOPSIS Model has been well recognized for its geometric clarity, careful use of original data, little information loss, and wide applicability; nevertheless, when combined with intuitionistic fuzzy set theory, it is a groundbreaking development [18-20]. Together, they provide a potent new model that outperforms existing approaches. In addition to addressing the drawbacks of current methods, the merging adds a degree of efficiency and adaptability that goes beyond the capabilities of tried-and-true multi-attribute decision-making strategies.

The introduction of CCME-WQI, pioneered by Horton in

1965, marks a paradigm-shifting moment in the evaluation of water quality. This all-encompassing gauge quickly won praise for its unmatched usefulness, crossing geographical boundaries to encroach on areas as different as Asia, Africa, and Europe [21]. The CCME-WQI's global applicability underlined its fundamental relevance and encouraged widespread adoption across continents, establishing it as a de facto standard for evaluating water quality worldwide.

The paper is structured as follows: In Section 1, the research area's engineering overview is first presented. A novel method of assessing water quality is provided in Section 2. It is predicated on the intuitionistic fuzzy set model. The IFT model is created for the Cauvery River's water quality evaluation in Section 3, and the evaluation results of the suggested model are examined. Likewise, the WQI is examined. Section 4 presents the conclusions.

2. STUDY AREA: THE CAUVERY RIVER

The Cauvery River, which runs through the center of the Indian subcontinent, is evidence of the dynamic interaction between nature, culture, and human civilization. This important watercourse begins its trip in the mist-covered peaks of the Western Ghats and travels through a variety of environments, habitats, and communities. The Cauvery River, which flows through the southern states of Karnataka and Tamil Nadu, has evolved into more than just a physical feature; it now serves as a lifeline for a variety of communities throughout its vast basin.

The Cauvery basin is a vast region with a surface area of about 27,700 square miles (72,000km^2) and is noted for its intricate network of rivers and streams. This vast catchment area serves as a reservoir for the water that nourishes life as it runs through the delicate veins of the Cauvery River and its tributaries. It starts its amazing trip in Karnataka's southwest, where its origin is acknowledged. From there, it covers an astounding distance of more than 475 miles (765km) in a southeasterly direction. This journey gives the Cauvery River its distinct character and magnitude, which culminates in its grandeur as it embraces the Bay of Bengal in a gentle embrace. Its source is located in the Kodagu region of Karnataka, high in the Western Ghats, near Talakaveri, a venerated location. From this holy source, it flows through the lush Western Ghats, into Tamil Nadu, and continues across the beautiful plains of that state [22] (Figure 1). The Cauvery River eventually makes its way to the Bay of Bengal, where it comes to an end.

The river feeds agriculture as it flows through Karnataka and Tamil Nadu, sustaining a variety of crops that fuel regional economies. Because of the diverse topographies it passes through, the Cauvery River watershed is home to a great variety of habitats. The waters of the river support a complex web of life, from the forests in the Western Ghats, which are rich in biodiversity, to the fertile delta at its confluence. Along its path, wetland, grassland, and marsh ecosystems support a wide variety of plants and fauna, some of which are indigenous and threatened. Beyond its physical boundaries, the Cauvery River is ingrained in the region's cultural landscape. It is referred to as the "Dakshina Ganga," and it has spiritual importance for many cultures, inspiring rituals, celebrations, and artistic expression.

The Cauvery River is a representation of the precarious balance between humans and nature due to its historical significance, natural richness, and modern complexity. The complex story of its beginnings, digressions, and final destinations relates to a larger narrative of balancing human goals with environmental management. Assuring that the Cauvery River continues to nourish the environment and people it affects for future generations requires a collaborative and interdisciplinary approach that incorporates conservation, sustainable development, and fair water-sharing.

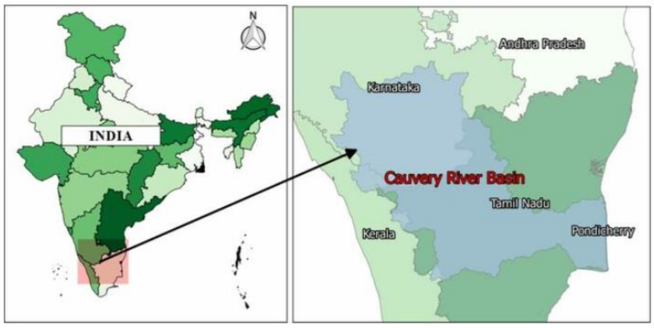

Figure 1. Cauvery River map

3. MATERIALS AND METHODS

The AHP technique made it easier to organise the decision problem in a hierarchical manner. AHP provides a structured method to prioritise and assess alternatives through pairwise comparisons and the creation of weights. The IFT approach was used in parallel to deal with the inherent uncertainties and ambiguity in the decision-making process. This method accommodated uncertainty and hesitancy in the evaluation of criteria and alternatives by using intuitionistic fuzzy sets. A strong basis for efficient decision-making in the setting of complex material selection considerations was created by the combination of the structural clarity of the AHP and the ability of the IFT to manage uncertainty.

3.1 Analytic Hierarchy Process (AHP)

The AHP appears as a potent instrument in the decision-making space, particularly when dealing with complicated scenarios. The late 1970s Thomas L. Saaty, a mathematician and operations researcher, develop AHP, which provides a structured method for addressing the difficulties MCDM presents [12]. AHP serves as a pillar of rational decision analysis by assisting decision-makers in making well-informed decisions through a systematic process of prioritization and comparison.

AHP proves useful when a decision-making team must make complicated decisions and develop a structured method to deal with complexity [23]. The core of AHP entails creating a hierarchical arrangement, similar to a ranking, of decision components as shown in Figure 2. Decision-makers can systematically weigh the importance of various components by using this hierarchy, which captures the links between them. Matrix comparisons are made between each potential pair inside each cluster of choice components to aid in the evaluation. The consistency ratio helps decision-makers to evaluate the internal consistency of their preferences and judgements, ensuring that the decision-making process is logical and well-founded [24]. By assigning weights to each component in a cluster based on their relative relevance, AHP increases the usability of its results. These weightings give you a methodical way to quantify the importance of various components.

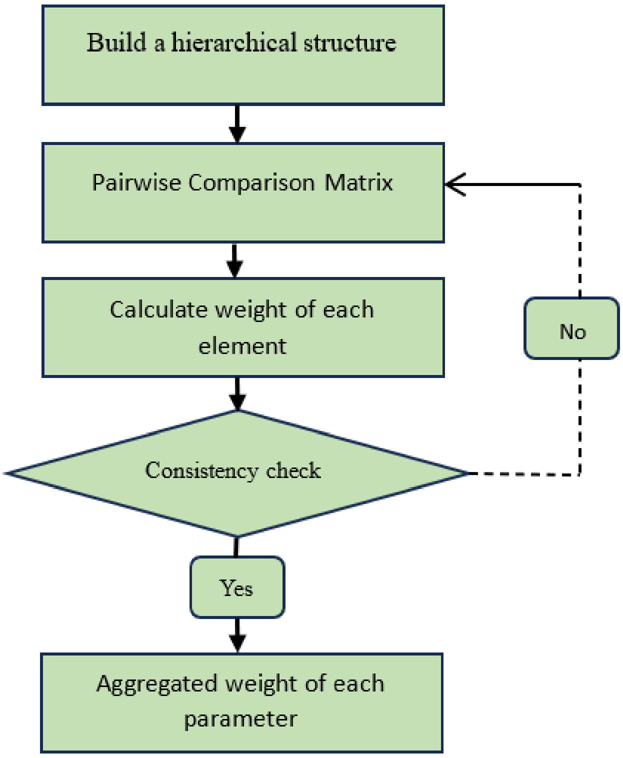

Figure 2. Structure of AHP

Table 1. Comparison scale

Relative Scale	Definition
1	Equal importance
3	Moderate importance of one or another
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgements

Step 1. Identification and selection of attributes for the decision tree in a hierarchical structure.

Every AHP analysis begins with defining the study's hierarchy structure, which can be defined as a split of a series of levels of attributes, each of which represents a number of tiny groups of interrelated sub-attributes.

Step 2. The matrix of pair-wise comparisons has to be setup:

The matrix of pair-wise comparison is a matrix (MPC) Collects findings of expert and expert ratings. Professional judgments are stated in an MPS Analysis of the MADM problem using AHP, where a result. The producer specifies a judgment by inserting the entry a_{ij} where (a_{ij}>0), indicating how much more important attribute i is than attribute j.

A MPC is defined as:

$$A=(a_{ij}) = \begin{bmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{21} & \cdots & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & \cdots & a_{mn} \end{bmatrix} \quad (1)$$

where, a_{ij} is the weighted average of the ascribed a_i and a_j. The MPC would be a square matrix A, encompassing n qualities each with relative weights. The weights of all qualities in this matrix are measured in multiples of that unit with regard to each other.

Step 3. Weighting vectors of attributes to be calculated

Cardinal numerical values that represent the overall preference of each defined choice are taken into account via additive weighting methods. Saaty offered comparable scores ranging from 1 to 9 (Table 1) as a basis for translating language judgments into cardinal.

Step 4. Calculating the relative weights to approach principal eigen vector

The weights of characteristics are calculated during the averaging procedure over the normalized columns. A priority matrix reflecting the estimation of the matrix's eigen values is necessary to provide the best match for attributes. so that the weights added together equal one to accomplish this, divide the relative weights of each individual characteristic by the column-sum of the acquired weights.

Step 5. Checking of the consistency of attributes

If the calculated discrepancies are greater than 10, the result of the manufacturer may have to make compensatory transactions within the characteristic values. Only if there are comparative metrics the calculated priorities may be consistent or almost consistent is valid. The equation can be used to calculate approximations stability ratio.

$$CR = \frac{CI}{RI} \quad (2)$$

where, CR represents consistence ratio, CI represents consistency index, RI represents random index for the size of the matrix 'n' proceeding with Eq. (2) the consistency ratio satisfies with CR<0.1

Based on the above steps the criteria weights are evaluated for the parameters DO, BOD and FC to evaluate the quality of the water as shown in Table 2.

Table 2. Criteria weight by AHP

Criteria	DO	BOD	FC
Weight	0.4358	0.3807	0.1814

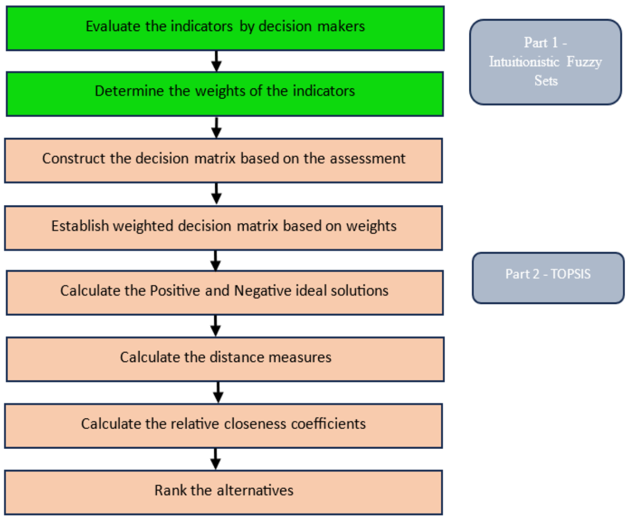

Figure 3. Structure of IFT

3.2 Intuitionistic Fuzzy Sets-TOPSIS (IFT)

IFT emerges as a sophisticated framework that effortlessly combines the strength of fuzzy logic with the analytical skill of decision analysis in the decision-making domain, where uncertainty, imprecision, and subjectivity abound. This approach, which was developed to address situations when choice qualities and preferences are characterized by increased ambiguity and indistinctness, is an advanced extension of the traditional TOPSIS [25-29]. The working of IFT is given in Figure 3.

Using intuitionistic fuzzy sets and the TOPSIS model, the priority ranking of MCDM items is solved [30]. Additionally, the evaluation of water quality risk can be transformed into a problem comprising different degrees of probability rankings. The procedures for using this specific approach are as follows:

Step 1. The production of the water quality evaluation indices and categorization criteria is possible following a thorough examination of the factors that affect the water quality.

Step 2. Weighting factors are calculated, and the significance of the index weights is conveyed using intuitionistic fuzzy numbers that are based on the idea of intuitionistic fuzzy sets. The weight coefficients of various indices are then solved using the AHP weight theory.

Step 3. Assuming that $\mu=\mu_1, \mu_2, ... \mu_n$, and $\gamma=\gamma_1, \gamma_2, ... \gamma_n$, respectively, are the weights of the membership function and the non-membership function, respectively, the following weights coefficients are used to represent the combination of the two functions:

$$\varphi_n=(\mu_n,\gamma_n)=(min(\mu_n,\gamma_n,1)-max(\mu_n,\gamma_n)) \quad (3)$$

Step 4. At various stable levels of assessment indices, the evaluation systems calculate the corresponding solutions C^+ and C^-.

$$\begin{aligned} C^+ &= [(\mu_1^+,\gamma_1^+),(\mu_2^+,\gamma_2^+), \ldots\ldots(\mu_n^+,\gamma_n^+)] \\ C^- &= [(\mu_1^-,\gamma_1^-),(\mu_2^-,\gamma_2^-), \ldots\ldots(\mu_n^-,\gamma_n^-)] \end{aligned} \quad (4)$$

Step 5. The evaluation of the water quality to determine the degree of membership by calculating the Euclidean distance between positive and negative ideal solutions.

Step 6. The magnitudes of the pasting schedule can be used to calculate the levels of water quality. Following the determination of the degrees of membership regarding water quality, the magnitudes of each degree are rated from large to small, and the highest degree of membership is then chosen as the evaluation level of the related level of water quality.

4. RESULTS AND DISCUSSION

The use of the Intuitionistic Fuzzy TOPSIS (IFT) method, as mentioned in source [7], facilitates the thorough evaluation of water quality across the vast stretch of the Cauvery River (Figure 4). The complex integration of three crucial metrics, dissolved oxygen (DO), biological oxygen demand (BOD), and faecal coliform (FC), is required for this assessment of the water quality. These variables work together to create a multidimensional framework that encompasses the many sides of assessing water quality [16, 17], allowing for a more comprehensive knowledge of the environmental health of the river. The interaction of these fundamental variables, as seen through the astute lens of the IFT method [30], converges to provide a thorough evaluation that goes beyond simple individual measurements to encompass the complex dynamics that contribute to the overall water quality scenario in the Cauvery River.

Ideal solutions are then determined, representing best and worst performances. Intuitionistic fuzzy distances are computed for alternatives to these ideals, considering membership, non-membership, and hesitancy degrees. By assessing relative closeness coefficients based on these distances, alternatives are ranked, facilitating robust multi-criteria decision-making in scenarios characterized by imprecision and uncertainty.

The membership function and non-membership function are respectively depicted below to reflect the properties of intuitionistic fuzzy sets:

Based on Eq. (4), the assessment indices of positive and negative ideal solutions of the river are given as:

$$C^+=[(0.1772, 0.8132), (0.0837, 0.9057), (0.0019, 0.9890), (0.0705, 0.8946)]$$
$$C^-=[(0.9002, 0), (0, 1), (0, 0.9887), (0, 1)]$$

The degree of membership of the positive and negative ideal solutions corresponding to the intuitionistic fuzzy sets, as well as the Euclidean distance, may be calculated as:

This evaluation method results in the assigning of well-organized ranks to the nine different places under investigation. The relative performance displayed by these places in relation to the three key criteria of dissolved oxygen (DO), biological oxygen demand (BOD), and faecal coliform (FC) is represented by each rank. These rankings (Figure 5), which are the result of the interaction of positive and negative ideals and the complex proximity coefficient calculation, provide a clear hierarchy that emphasises the subtle changes in water quality seen across the Cauvery River's landscape (Tables 3-5).

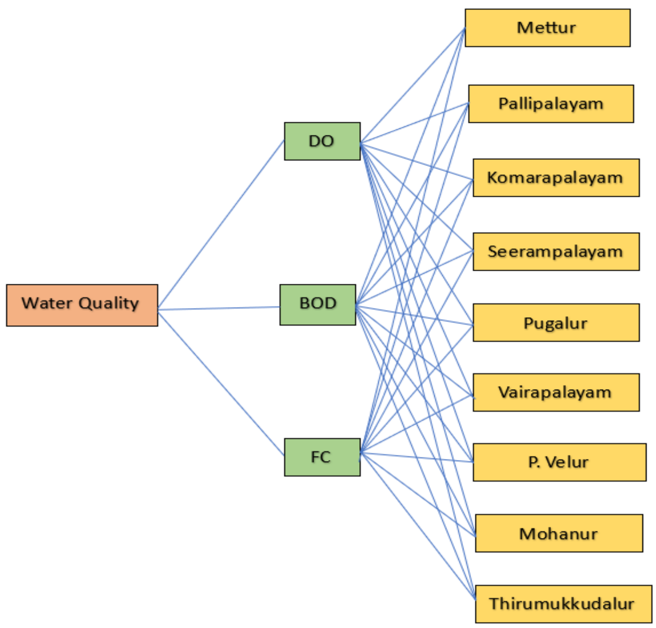

Figure 4. Hierarchy structure for performance evaluation

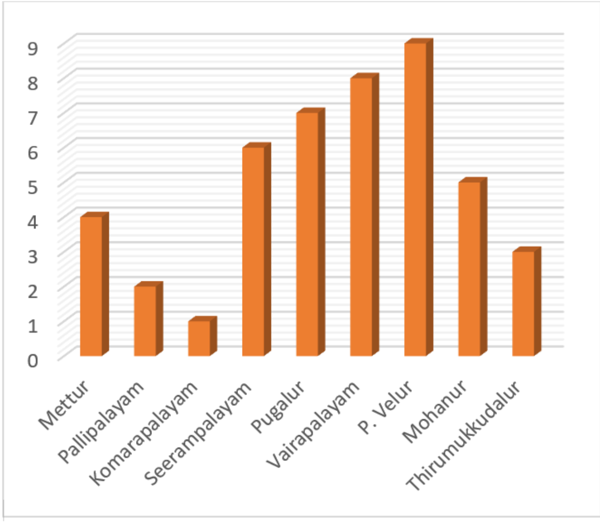

Figure 5. Rank representation by IFT

Table 3. IFT decision matrix

Area	DO	BOD	FC
Mettur	(0.1190, 0.8001)	(0.8143, 0.1233)	(0.2854, 0.7030)
Pallipalayam	(0.1255, 0.7386)	(1,0)	(0.7046, 0.2452)
Komarapalayam	(0.6063, 0.3726)	(0.2843, 0.7154)	(0.8507, 0.2485)
Seerampalayam	(0.108, 0.808)	(0.117, 0.813)	(0.9036, 0.0018)
Pugalur	(0.6967, 0.3055)	(0.5365, 0.4682)	(1,0)
Vairapalayam	(0.713, 0.2209)	(0.2681, 0.3556)	(0.7577, 0.2022)
P. Velur	(0.6439, 0.3866)	(0.7169, 0.2534)	(0.5336, 0.4545)
Mohanur	(0.0046, 0.9458)	(0.5741, 0.4822)	(0.9352, 0.0074)
Thirumukkudalur	(0.6670, 0.3976)	(0.8145, 0.2436)	(0.6411, 0.3511)

Table 4. Positive and negative ideal solution

Area	Positive Ideal Solution	Negative Ideal Solution
Mettur	0.2939	0.1456
Pallipalayam	0.2734	0.1072
Komarapalayam	0.2262	0.0864
Seerampalayam	0.2723	0.1536
Pugalur	0.3572	0.2483
Vairapalayam	0.1993	0.2452
P. Velur	0.0187	0.0238
Mohanur	0.2576	0.2423
Thirumukkudalur	0.1923	0.2545

Table 5. Closeness coefficient

Area	Closeness Coefficient
Mettur	0.3313
Pallipalayam	0.2816
Komarapalayam	0.2763
Seerampalayam	0.3980
Pugalur	0.4100
Vairapalayam	0.5523
P. Velur	0.5671
Mohanur	0.3775
Thirumukkudalur	0.2901

5. CCME WQI

The CCME, which consists of Canadian jurisdictions, has created a CCME WQI that may be utilised by several water authorities in numerous other countries. It came from the British Columbia WQI but was tweaked. The CCME WQI does not use typical index aggregation, subindexes, or weights for the variables [20]. According to the CCME, the CCME WQI measures three essential parts (factors) in order to produce a single unitless number that, in the end, represents the whole water quality. For each parameter that shouldn't be exceeded, goal values (objectives or guidelines) are employed.

Step 1. The percentage of parameters (failed parameters) that at least once during the time period under consideration failed to achieve their criteria is represented by F_1 (Scope) when compared to the overall number of parameters analysed. The words "target values" and "objectives" are equivalent to "guidelines."

$$F_1 = \left(\frac{No.of\ Failed\ Parameter}{Total\ no.of\ Parameter}\right) \times 100 \tag{5}$$

Step 2. The word F_2 (Frequency) denotes the frequency of individual tests that fail to meet standards. A test compares a parameter's value from a specific sample campaign and the corresponding guideline directly.

$$F_2 = \left(\frac{No.of\ Failed\ tests}{Total\ no.of\ tests}\right) \times 100 \tag{6}$$

Step 3. Calculating F_3 (Amplitude), which shows how far test results that failed are from the norm, takes three steps. An excursion is the number of times a certain concentration exceeds (or falls below, if the guideline is a minimum) the guideline and is shown as follows:

When the objective (guideline) of the j^{th} parameter cannot be exceeded by the i^{th} test value:

$$excursion_i = \left(\frac{Failed\ test\ value_i}{objective_j}\right) - 1 \tag{7}$$

For situations when the test value must not be lower than the objective (guideline):

$$excursion_i = \left(\frac{objective_j}{Failed\ test\ value_i}\right) - 1 \tag{8}$$

Step 4. Divide the total number of tests (both those that adhere to the standards and those that do not) by the sum of the individual tests' deviations from the requirements to get the overall amount by which each test is out of compliance. The parameter known as the normalised sum of excursions (nse) is calculated as:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{Total\ no.of\ tests} \tag{9}$$

Step 5. After scaling the normalised sum of the excursions from the guidelines (nse) to produce a range between 0 and 100, an asymptotic function calculates F_3.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right) \tag{10}$$

Step 6. After obtaining the factors, the index can be determined by adding the three factors together as follows:

$$CCME - WQI = 100 - \left[\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right] \quad (11)$$

The resultant values are normalised to a range between 0 and 100 using the divisor 1.732, where 0 denotes the "worst" water quality and 100 denotes the "best" water quality.

The various rankings given to the nine locations scattered throughout the length of the Cauvery River are shown in Figure 6. The first rank in this graphical representation denotes regions with excellent water quality, while the ninth rank is designated for places with poor water quality. The variability of water quality along the river's length includes a wide variety of characteristics. In this context, Vairapalayam stands out as a regrettable exception because it suffers from poor water quality. In contrast, Komarapalayam is highlighted as a significant instance of a location where the water quality reaches a level deemed acceptable. This comparison highlights the notable differences in the state of the water resources at several locations along the Cauvery River.

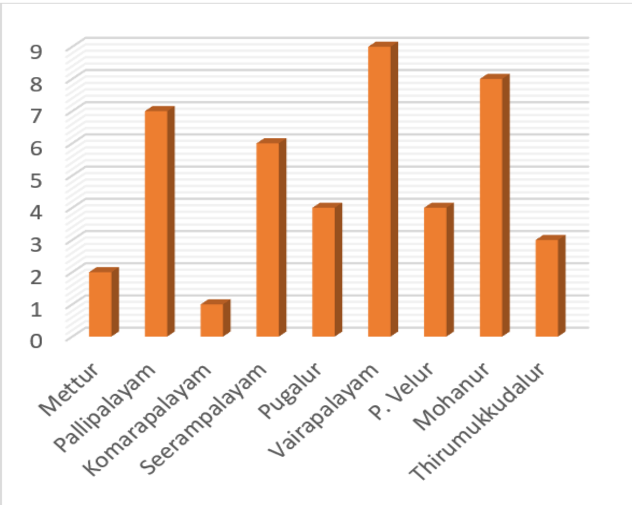

Figure 6. Rank representation by CCME WQI

6. CONCLUSION

In conclusion, the research introduces the utilization of the Intuitionistic Fuzzy Sets-TOPSIS model as an innovative approach for assessing water quality in temple tanks, with a focus on parameters like dissolved oxygen (DO), biological oxygen demand (BOD), and FC. The results from the innovative evaluation of Cauvery River's water quality using the Intuitionistic Fuzzy Sets-TOPSIS model are crucial. This model not only systematically ranks water quality levels but also accurately reflects them, showcasing its robustness and reliability according to current standards. Furthermore, the model introduces a new perspective and suggests directions for future water quality assessments. Future research is recommended to explore different Multi-Criteria Decision-Making (MCDM) methods for water quality estimation, enabling insightful comparisons and a comprehensive understanding of various approaches. To enhance its applicability, it is suggested to further refine the model. This includes adding important criteria, broken down into sub-criteria, for a more detailed examination of variables affecting water quality. This improvement ensures adaptability to diverse environmental contexts and guarantees a nuanced assessment.

The study's findings highlight Vairapalayam and P. Velur as unfortunate outliers in water quality, emphasizing the challenges these regions face. In contrast, Komarapalayam stands out as an example of excellent water quality, showcasing the diversity along the Cauvery River. This contradiction underscores the urgent need for targeted measures to address noticeable differences in water quality, posing a challenge to environmental managers and legislators.

In summary, this study extends beyond a simple water quality evaluation, providing fresh approaches and perspectives. It identifies urgent environmental disparities and enhances our understanding of water quality evaluation, guiding future research and intervention techniques for improved environmental management.

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