# Application of Fuzzy Multi-criteria Approach to Assess the Water Quality of River Ganges

**R. Srinivas and Ajit Pratap Singh**

**Abstract** The purpose of this study is to develop a fuzzy multi-criteria decision-making framework to evaluate the water quality status of a river basin. The rampant and indiscriminate growth in the urban, agricultural, and industrial sector has directly or indirectly disrupted the water quality of the major rivers by discharging mammoth quantities of wastewaters. Regular and accurate evaluation of water quality of a river has become an important task of water authorities. However, the conventional way of evaluating water quality index has been unsuccessful in incorporating uncertainties and subjectivities associated with water quality analysis. Such limitations can be dealt effectively by using fuzzy logic concepts. The present study proposes an Interactive Fuzzy Water Quality Index (IFWQI) to evaluate the water quality status of river Ganges at Kanpur city, India. Multi-Criteria Decision-Making (MCDM) tool namely Fuzzy Inference System (FIS) of MATLAB has been used to obtain a qualitative and quantitative measure of water quality index at six different sites of Kanpur throughout the year by taking into consideration the six important water quality parameters. The results indicate a significant improvement in the accuracy of the index values and thus providing emphatic information to the planners to decide the remedial measures for sustainable management of river Ganges.

**Keywords** Multi-criteria Decision-Making · Fuzzy inference · Water quality

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## 1 Introduction

In general, the problems associated with river water resources management consist of managing the water quality and quantity. Such problems depend on several qualitative and quantitative criteria, and a proper decision-making can be done by integrating all such criteria under a suitable mathematical framework. Effective and efficient evaluation of water quality status of different segments of a river based on critically polluting water quality criteria is one of the most important subject matters of water authorities and planners. Multi-criteria decision-making (MCDM) methods are considered as one of the popular approaches to deal with such problems. Several researchers have presented different MCDM methods in the field of water resource management namely: Elimination Et Choice Translating Reality I (ELECTRE) [1]; Analytic Hierarchy Process (AHP) [2]; Technique for Order Preference by Simulation of Ideal Solution (TOPSIS) [3]; Analytic Network Process (ANP) [4]; and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [5]. One of the primary limitations of these traditional methods is their inability to incorporate the uncertainties pertaining to complex water resource management problems as they employ the mathematical classic numbers. The uncertainties can be effectively treated in a fuzzy logic system. Therefore, there is a scope to develop a model which combines both MCDM and fuzzy set theory to achieve a fuzzy-based MCDM framework.

Rivers have been playing a very crucial role in sustaining the lives of living beings since age-old by serving them in various ways. Rivers support the majority of the developmental processes of a country like urbanization, agricultural production, power generation, industrial growth, low-cost navigation, and many others. Therefore, proper planning and management of rivers in a sustainable way should be the priority of all the countries. The Ganges river of India is the largest and most sacred river of the country. The river supports more than 450 million people by providing water for drinking, irrigation, and industrial purposes. Out of all the states benefitted by Ganga, Uttar Pradesh derives maximum benefit as the river traverses more than 1100 km in this state. Major cities like Kanpur, Allahabad, and Varanasi are profusely blessed with the holy water of Ganges. However, it is a very unpleasant fact that these cities are expressing their gratitude toward the Ganges by treating it as a drain. Therefore, there is an acute need to compute the water quality status of the river at these sites in order to implement necessary remedial measures to reduce pollution of Ganges. Evaluation of Water Quality Index (WQI) is found to be an effective and efficient tool for assessing the suitability of river water for various beneficial usages [6]. The WQI integrates all water quality parameters by comparison with their respective standard value and thus give a single dimensionless number, which indicates the overall water quality status [7, 8]. However, one of the major limitations of the conventional WQI approach is its inability to incorporate the uncertainty and ambiguity associated with the concentration of the quality parameters [9]. Such limitations and complexities involved in the deterministic and traditional methods for calculating WQI have motivated the development of a more advanced methodology, capable of aggregating and accounting for the vague, inaccurate, and fuzzy information pertaining to water quality. The application of fuzzy logic [9] in modeling water quality indices has shown a good promise [10, 11]. Reference [12] used a Fuzzy Comprehensive Assessment (FCA) to evaluate the soil environmental quality of the Taihu lake watershed. Reference [13] expressed groundwater sustainability in mathematical terms using MATLAB Fuzzy logic toolbox. Though various investigators have also applied the concept of fuzzy multi-criteria in water quality assessment and environmental management [14, 15], there is still enough scope to develop systematic and flexible models, which can be used in assessing water quality by combining multi-criteria approach and fuzzy logic concepts.

The purpose of this study is to propose an interactive fuzzy-based water quality index (IFWQI) which can be computed using a multi-criteria decision-making tool having an artificial intelligence interface known as MATLAB fuzzy inference system. The water quality of river Ganges is analyzed at six different stations of Kanpur city for several beneficial usages.

## 2 Materials and Methods

As mentioned above, the uncertainties encountered in water quality analysis can be dealt adequately by incorporating concepts of fuzzy logic [16–19]. In this paper, a MATLAB-based fuzzy inference system (FIS) framework has been developed which maps input water quality parameters values to outputs (overall water quality). The methodology involves four steps (a) fuzzification of the crisp input values by mapping them into linguistic variables using membership functions, (b) evaluation of fuzzy inference rules which consists of linguistic rules in the form of IF-THEN statements, (c) aggregation of rule outputs using the fuzzy union of all the individual rule contributions to obtain a single aggregated membership function. (d) defuzzification of aggregated output fuzzy set using centroid method.

### *2.1 Sampling Sites and Water Quality Parameters*

Kanpur, the largest city in the state of Uttar Pradesh is rated as the most polluted city along the Ganges river basin primarily due to more than 700 tanneries indiscriminately discharging wastewater in the river. The length of the Ganges in Kanpur is 38.7 km. In this paper, a total of six sampling stations namely Bithoor Ghat (S1), Rani Ghat (S2), Permat Ghat (S3), Sarsaiya Ghat (S4), Nanarao Ghat (S5), and Siddhnath Ghat (S6) have been chosen from Kanpur city (Fig. 1). The suitability of the water for particular beneficial usage is determined by evaluating FWQI at all the sampling sites. Six critical water quality parameters namely Dissolved Oxygen

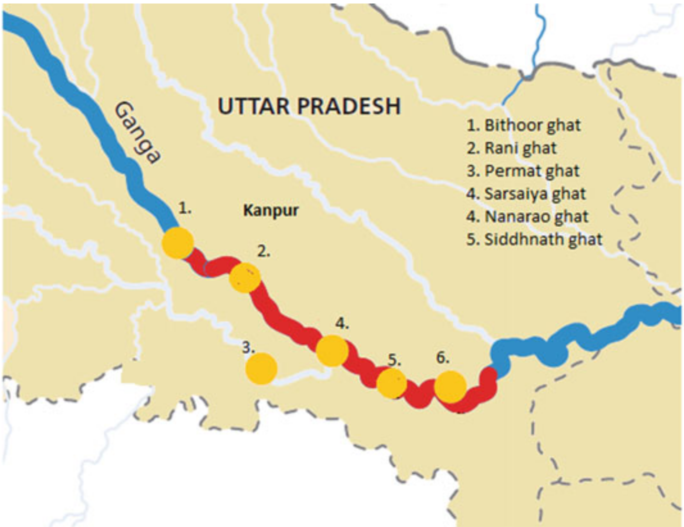


**Fig. 1** Study area representing the six sampling stations

(DO), Biochemical Oxygen Demand (BOD), Total Dissolved Solids (TDS), Total Alkalinity (TA), Phosphate ($PO_4^{3-}$), and Chromium (Cr) have been chosen to evaluate the water quality index.

## 2.2 *Fuzzy Water Quality Index Using MATLAB FIS*

In this paper, a fuzzy methodology is proposed to derive water quality index of a particular sampling site. The membership functions of different water quality parameters considered for the study are developed under expert guidance based on the standards given by regulatory bodies [19]. The method used to generate membership functions of the input and output parameters is very simple. Depending upon the nature of the parameter, a particular shape of the membership function is derived. For example, for DO to be considered as "average," its measurements must fall between 2 mg/l to 5 mg/l. Hence, a trapezoidal membership function ($\mu_{DO}$) with ranges [2–5] is chosen to represent the linguistic term 'average' which can be written in equation form "(1)," as given below:

$$\mu_{DO} = \begin{cases} 0, x < 2 \text{ or } x > 5 \\ \frac{(x-2)}{(3-2)}, 2 \leq x \leq 3 \\ 1, 3 \leq x \leq 4 \\ \frac{(5-x)}{(5-4)}, 4 \leq x \leq 5 \end{cases} \quad (1)$$

where x = value of DO (mg/l).

In a similar way, membership functions of other input parameters and output have been derived. In this study, only trapezoidal membership functions have been used, as they are capable of representing the real life situation in a better way. Figures 2 and 3 represent the shapes of the membership functions of input parameter BOD and the output (fuzzy water quality index), respectively, where each color range of the trapezoid represents a linguistic variable as explained further.

'Excellent (E)', 'Good (G)', 'Average (A)', 'Poor (P)', and 'Very Poor (VP)' are linguistic representation of the input water quality parameters having linguistic variables DO, BOD, Cr, TDS, TA and DO and $PO_3^{-4}$. These linguistic values are assigned to each parameter based on their fuzzified value. 'Very bad (VB)', 'Bad (B)', 'Satisfactory (S)', 'Good (G)' and 'Very good (VG)' are the linguistic representation of the FWQI of a given sampling station along the river. In general, the total number of rules that can be formed is given by R = [number of linguistic variables] $^{\text{(number of parameters)}}$. For example, considering five linguistic representations (i.e., excellent, good, average, poor, and very poor) for 6 parameters corresponding to a given site, there will be $5^6$ rules that can be formed under expert guidance to obtain the crisp measure the WQI. Once these rules are formed using the data values of the input criteria, they are aggregated and finally defuzzified to

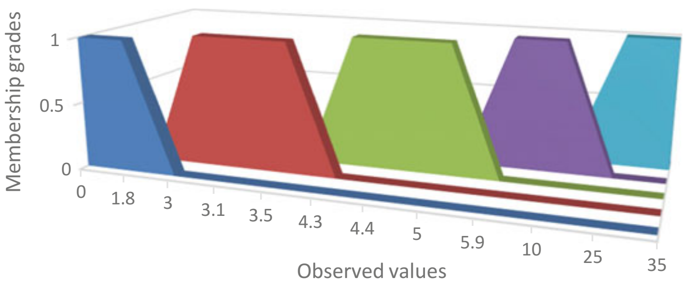


**Fig. 2** Membership function for input parameter BOD

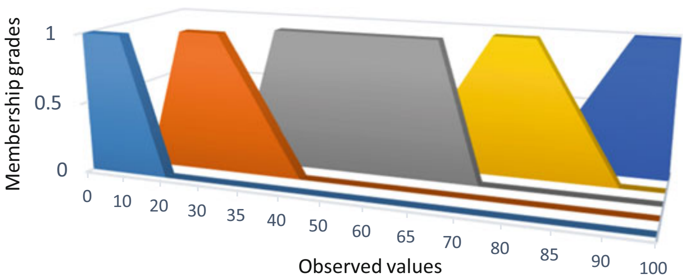


**Fig. 3** Membership function for output parameter FQWI

obtain a crisp measurement of WQI. Since the rules and input parameters can be modified, added, or deleted, hence the model developed herein is called an interactive model as the model is flexible to accommodate changes based on the opinion of experts or decision makers. Depending on the observed values of the input parameters, several rules are fired by the system and are aggregated to obtain to fuzzified membership function which upon defuzzification gives the final crisp score of water quality index.

Some of the IF–THEN rules formed under expert guidance for assessing the fuzzy water quality index based on the concentration of DO, BOD, Cr, TDS, TA, and $PO_4^{3-}$ are given below:

Rule 1: IF DO is 'excellent' AND BOD is 'poor' AND Cr is 'poor' AND TDS is 'good' AND TA is 'poor' AND $PO_4^{3-}$ is 'average' THEN water quality index is 'very bad'.
Rule 2: IF DO is 'very good' AND BOD is 'very poor' AND Cr is 'good' AND TDS is 'good' AND TA is 'very poor' AND $PO_4^{3-}$ is 'good' THEN water quality index is 'very bad'.

Table 1 represents the fuzzy trapezoidal membership functions of the input parameters BOD and DO, where all the values are in milligram per liters (mg/l). Similar way, membership functions for other input parameters have been defined. Table 2 represents the fuzzy trapezoidal membership functions of the output parameter FWQI. The categorization of these values into different linguistic variables has been given by the experts based on the standards given by regulatory bodies [19]. Table 3 shows some of the fuzzy rules derived in this study for developing interactive fuzzy inference model.

The entire analysis is performed in MATLAB Fuzzy Logic Toolbox package R2015b (8.6.0). For illustration, the WQI calculations for the month of January for Siddhnath ghat are being explained in step by step manner.

**Table 1** Membership function values of BOD and DO

| Linguistic representation | BOD [a, b, c, d] | DO [a, b, c, d] |
|---|---|---|
| Excellent | [0, 0, 1.8, 3] | [7, 7, 20, 20] |
| Good | [1.8, 3, 3.5, 5] | [4, 5, 7, 7] |
| Average | [3.1, 4.3, 5, 10] | [2, 3, 4, 5] |
| Poor | [4.4, 5.9, 10, 25] | [0, 1, 2, 3] |
| Very poor | [5.9, 25, 35, 35] | [0, 0, 1, 1] |

**Table 2** Membership function values of FWQI

| Linguistic representation | FWQI [a, b, c, d] |
|---|---|
| Very good | [80, 90, 100, 100] |
| Good | [60, 70, 80, 90] |
| Satisfactory | [30, 35, 65, 70] |
| Bad | [10, 20, 30, 40] |
| Very bad | [0, 0, 10, 20] |

**Table 3** Some fuzzy rules formed using MATLAB FIS

| | Input parameters | | | | | | FWQI Output |
|---|---|---|---|---|---|---|---|
| Operators | IF | AND | AND | AND | AND | AND | THEN |
| Parameters | DO | BOD | Cr | TDS | TA | $PO_4^{-3}$ | Resulting integrity |
| Rule 1 | E | E | E | E | P | P | B |
| Rule 2 | E | E | G | E | E | E | G |
| Rule 3 | VP | P | VP | P | P | G | VB |
| Rule 4 | E | A | VP | G | G | G | VB |
| Rule 5 | A | G | A | G | A | VG | S |
| Rule 6 | G | G | G | VP | G | VP | VB |
| Rule 7 | VP | P | P | P | P | P | VB |
| Rule 8 | E | E | VP | VP | E | E | VB |
| Rule 9 | E | E | E | E | E | E | VG |
| Rule 10 | A | E | A | E | A | E | VG |
| Rule 11 | A | E | E | A | A | VG | S |
| Rule 12 | E | G | E | E | E | A | S |
| Rule 13 | A | VP | A | VP | A | VP | VB |
| Rule 14 | G | G | G | G | G | G | G |

Fuzzification (**Step 1**): The data values for six parameters [DO, BOD, TDS, TA, $PO_4^{3-}$, Cr] for the month of January are [6.6; 18.5; 228; 321; 1.01; 2.3] mg/l. These input-data values are fuzzified and represented linguistically using appropriate membership function.

Rule evaluation (**Step 2**): Several rules are fired depending on the input values and their corresponding membership function (s). In this case, one of the rule that is fired is as follows:

IF DO is 'good' AND BOD is 'poor' AND TDS is 'good' AND TA is 'very poor' AND $PO_4^{3-}$ is 'very poor' AND Cr is 'very poor' THEN water quality index is 'very bad'.

As the inference is based on the minimum sub-index, an optimized solution can be obtained by using a disjunction of inputs by means of the "OR" operator: the FWQI is considered "very poor" if any one of the indicators is "very poor." In this study, the Max- Min approach has been used to build the 'FWQI' inference engine. The implication method used is the "min" and the aggregation method is "max." The extension of the union operator (OR) and intersection operator (AND) to fuzzy sets A and B for any value x defined over the same set U is represented in equation "(2)," and "(3)," respectively.

$$\mu_{A\cup B}(x) = \max[\mu_A(x), \mu_B(x)] \quad (2)$$

$$\mu_{A\cap B}(x) = \min[\mu_A(x), \mu_B(x)] \quad (3)$$

Rule aggregation and defuzzification (**Step 3**): All such rules are then aggregated to obtain a single shape of membership function which upon defuzzification gives the WQI value. In this case, the center of gravity (COG) method has been used for defuzzification to determine the output as expressed in equation "(4)." In this case, output value has come equal to 8.22 indicating that water quality during the month of January of at this location can be classified as "very bad."

$$z^* = \frac{\int \mu_c(z).zdz}{\int \mu_c(z)dz}; \text{ where } z \in C, C \text{ is the fuzzy set} \quad (4)$$

## 3 Results and Discussions

The FWQI values obtained using fuzzy inference system for all the six stations are below 10 indicating that the status of water quality at all the stations is very bad (Fig. 4). A very interesting observation is that the Siddhnath Ghat (S6) has obtained least score of FWQI almost through the year (Fig. 4). This is mainly because of the discharge of mammoth quantities of wastewaters from the tanneries and paper pulp industries consisting high content of BOD and Cr. On the other hand, Rani Ghat (S2) has obtained slightly better score than other sampling stations. Here, the river water is mainly contaminated due to several open drains containing a high content of BOD entering into the river without any treatment. On the basis of the FWQI values obtained, it can be clearly inferred that Ganges river water needs serious treatment before it is used for any beneficial purposes and there is an urgent need to put strict regulations on the industries, establish sewage treatment plants, and create public awareness in the Kanpur region to protect river Ganges. The proposed water quality fuzzy index has also revealed some of the drawbacks of the conventional water quality index approach. The fuzzy-based index is more effective and accurate in determining the overall water quality status of the river based on the standards proposed by the regulatory bodies. Fuzzy logic not just represents water quality linguistically and mathematically but also shows the variation of the water quality parameters in the form of well-defined membership functions. The model

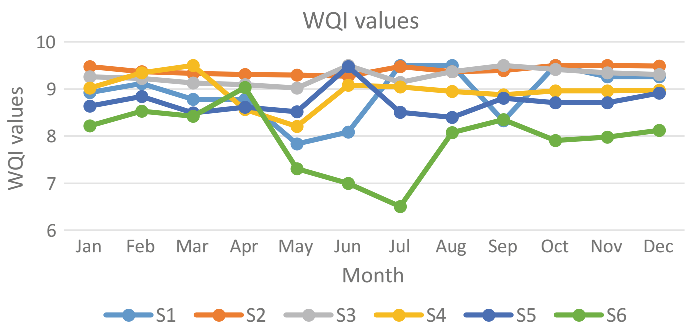


**Fig. 4** Final WQI scores of all sampling sites along Ganges

developed also gives the opportunity to the decision makers to assign different membership functions, change the parameters and values of the parameters, and accordingly observe the overall impact on the river. Thus the model is also known as an interactive fuzzy-based model as it gives prerogative to the policy makers to modify it according to their preferences.

## 4 Conclusions

Application of fuzzy logic to obtain WQI has proved to be an essential informative decision-making tool to obtain both qualitative and quantitative measure of the water quality of river Ganges. The proposed fuzzy inference model can effectively deal with the problems involving uncertainty and linguistic vagueness pertaining to river water quality. In addition, unlike the conventional index method, the FWQI provides a scope for the results to be interpreted both quantitatively and qualitatively with the help of expert defined membership grades. The model provides a scope for better analysis since experts can describe a sampling station quality status as closer to its upper or lower limit. The model developed is flexible and interactive as it allows the decision maker to add, delete or modify the input water quality parameters. Thus, it will assist decision makers in investigating the condition of water quality by incorporating spatial and temporal changes in the river. The ability of the model to provide a framework to the experts to define rules linguistically and thus obtain a crisp measure of water quality makes it an alternate tool for the analysis of river water quality and for sustainable planning in the context of integrated river basin management.

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