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A novel approach for river health assessment of Chambal using fuzzy modeling, India

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ABSTRACT

The water quality (WQ) status of water bodies is highly uncertain and subjective in nature. The present paper addresses a "Fuzzy River Health Index" (FRHI) which is capable of dealing with subjectivities and uncertainties concerning river health at various sites of the Chambal River, India. By considering the parameters like temperature, total solids (TS), pH, dissolved oxygen (DO), biological oxygen demand (BOD), total coliform (TC), phosphate (P) and nitrate (N), the fuzzy model is established. The model uses triangular membership functions for fuzzification and centroid method for defuzzification. The proposed proficient method includes a fuzzy model which include IF-THEN ideas that help to determine River health using WQ parameters. The comparative performance models used are Carlson's trophic index (C-TSI), and Ecological health index (EHI). This study reveals that FRHI provides fairly good results; therefore, it concludes that the health of Chambal River is within excellent range (FRHI > 80). However, there is an urgent need to develop an effective and sustainable WQ monitoring for this study site, this proposed FRHI provides the flexibility for decision making in an integrated WQ management policies.

Keywords: Fuzzy model; Fuzzy River Health Index (FRHI); Decision making; Chambal River; Membership function

1. Introduction

Freshwater is an important resource, essential for sustaining life, its development, and the environment. Indiscriminate usage of natural resources has caused an imbalance to the environment. Existing policies related to water, river and environment have a direct effect on social and economic development. The challenging task of assessing water quality (WQ) based on limited observations is one of the key constituents in the ultimate goals of environment management. WQ has a direct impact on the quality of life. A good WQ leads to healthy ecosystems; thereby improving human well-being, while poor WQ adversely affects both environments as well as human well-being. According to Silvert [1], any environmental index should take into consideration various ramifications caused due to anthropogenic as well as natural activities and reflects it in a coherent, quantitative and qualitative manner. Deterioration of WQ and ecological integrity of rivers have attributed to anthropogenic activities in the catchments [2–6]. Also, river health is highly threatened by land-use and developmental activities which are not ecologically sustainable [7], its health originates from ecosystem health and cannot confine to river ecosystem only [8]. The river health is one which repairs itself from natural calamities such as floods,

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droughts, etc., it not only repairs its physical structure but also biological functions and provides a medium for the survival of surrounding flora and fauna. During their eternal surviving health cycle, rivers are also key to facilitate sediment transport, acclimatization of waste product and maintain the niche energy exchanges and nutrient cycles. Ecological health refers to the productivity of an ecosystem, its biological diversity and its resilience to the negative impacts of a variety of pressures. There have been four approaches so far applied to predict the ecological health of rivers viz. plant diversity, biological diversity, WQ modeling and eco-exergy [9–17]. However, the Fuzzy model has not been used to predict the ecological health of water bodies yet, although there are several reasons for applying fuzzy logic to complex situations, existing in the determination of river health index. To make concrete decisions based on promising results, one of the most important aspects amongst all is, the need to combine different indicators via applying the Fuzzy model. There was a much needed standardized index required in the international community w.r.t. technically quantify WQ. U.S. National Sanitation Foundation [NSF, 18], came up with one such standardized index and termed it as Water Quality Indices (WQIs) [2–17], which is prominently referred in national as well as in international scenarios.

The practical limitations of traditional indices arise prominently in two quantifications: a) distance measure does not signify in the case of different orders (all such distances of different magnitude even in order get converted into similar indices), b) the expressive deficit of uncertainty and subjectivities are of suitable challenges to overcome in traditional approaches. Therefore, the need of models capable to inculcating such deficiencies are need of hour and fuzzy logic based model is one of the best suited one [19–24]. There is lot of popular literature available on WQIs making use of the applications of fuzzy [1,11,26–29]. Various water quality indices have been formulated to model water quality in numerous regions. Till date, very few literature has been reported regarding river health calculation using fuzzy logic. Here, novel approach of fuzzy is being employed of river health index to know the better results as compared with other indices discussed above. Fuzzy logic has proven an excellent tool in modeling new WQIs. This technique has been greatly used to predict surface WQ and may be very easy in comparison with environmental issues since it could solve the inherent ambiguities and subjectivity thoroughly. Similar approaches to using fuzzy logic with air quality and water pollution have tried with significant results [25]. However, FRHI is tactically novel in its approach towards accessing river health.

Nema and Rai [26] developed a Fuzzy Water Quality Index using temperature, biological oxygen demand (BOD), pH, nitrate and coliform as input variables, to investigate the quality of ground water in Kolkata City, India. The index was further developed by Bai et al. [27] to determine the WQ of the Semenith River, Malaysia, using BOD, dissolved oxygen (DO), chemical oxygen demand (COD), suspended solids, pH, NH_3–N as input variables [27]. The fuzzy index has been effective in avoiding the loss or non-detection of information crucial for classification of WQ [28]. The key objective of present work is to develop a fuzzy model to promote better assessment of river health at various sites alongside with the Chambal River, using pH, temperature, DO, BOD, total solids (TS), total coliform (TC), phosphate (P) and nitrate (N) as water quality parameters. The results are compared with Carlson Trophic State Index (C-TSI), and Ecological Health Index (EHI) to justify the performance of the model.

2. Background

2.1. Water quality indices (WQIs)

The quantities of nitrogen, phosphorus, and other biologically useful nutrients are primary determinants of the body of water. Nutrients such as nitrogen and phosphorus tend to be limiting resources in fresh water bodies, so increased concentrations tend to result in increased plant growth, followed by corollary increases in subsequent trophic levels. The C-TSI can be calculated using the following formulae:

a. TSI for Chlorophyll-a (CA) TSI = 9.81 In Chlorophyll-a ($\mu g.L^{-1}$) + 30.6 (1)

b. TSI for Secchi depth (SD) TSI = 60–14.41 In Secchi depth (m) (2)

c. TSI for Total phosphorus (TP) TSI = 14.42 In Total phosphorous ($\mu g.L^{-1}$) + 4.15 (3)

$$\text{C-TSI} = [\text{TSI (TP)} + \text{TSI (CA)} + \text{TSI (SD)}]/3 \quad (4)$$

EHI of rivers lakes was calculated based on the NSF-WQI & C-TSI as shown in Table 1. Based on the WQI, Simpson Diversity Index (SDI) & C-TSI, the overall EHI can be calculated using equation [13]:

$$\text{EHI} = [\text{EHI of CTSI} + \text{EHI of WQI} + 1/\text{SDI}]/3 \quad (5)$$

2.2. Fuzzy inference

Fuzzy logic or fuzzy inference system is one of the most widely used soft computing techniques. Under the umbrella of heuristic approaches, soft computing techniques including fuzzy inference system, provides a syntactically sound approach for modeling real-world complex problems [30], with their semantically clear

Table 1
EHI based on WQI & C-TSI

NSF-WQI	Carlson's TSI	EHI value	EHI range	Status
0–25	10–30	1	<1	Excellent
25.1–50	31–50	2	1–2	Good
50.1–75	51–70	3	2–3	Medium
75.1–100	71–90	4	3–4	Poor
Above 100	>90	5	4–5	Very poor

numerical results. The quality measures expressed in natural language adjectives are beautifully quantified through fuzzy inference systems and determine the quality of defuzzified results. Zadeh introduced fuzzy logic in 1965 [25] and coined the word "computing with words" in 1994 [44]. Rather than numerical reasoning Zadeh proposed and explained the notions of linguistic reasoning. The linguistic reasoning is gaining significance in many emergent fields including engineering and applied sciences and has been applied successfully by many authors in numerous disciplines [32–40].

The ability to deal effectively and efficiently with uncertainties (encompassing vagueness) has been the key to the rising demand in the usability of fuzzy logic approach with scenarios having vagueness or uncertainty. The Fuzzy approach has applied in environmental systems modeling and risk assessment to develop fuzzy WQI for different river basins by many authors [21–24]. There is a need for strategic change in the approach followed in concern with juxtaposing fuzzified environment variable with their raw values. In the present analysis, fuzzy inference system has been used to develop river health index. The following ranges have been used to calculate the fuzzy river health index (Table 2).

Table 2
Fuzzy river health index ranges

FRHI	Range
Excellent	>80
Good	60–80
Medium	40–60
Poor	20–40
Very poor	0–20

3. Study area

Chambal River, with a vast tract of ravines, originates from Mhow near Indore in Madhya Pradesh (M.P.), India, and is the main tributary of Yamuna River, part of greater Gangetic drainage system in the central India. The total length of the Chambal River is 960 km with catchment area 143,219 Km^2 and an average discharge of 456 m^3s^{-1}. The river flows in the North-North-East through M.P passing through some parts of Rajasthan forming a boundary between M.P. and Rajasthan and finally turning towards the south-east direction to merge with the Yamuna in Etawah (U.P.). Location of Chambal River and the sampling points are as shown in Fig. 1 (detail have been given in our previous paper [13,14]).

4. Development of Fuzzy River Health Index (FRHI)

This section elaborates on the development of Fuzzy River Health Index (FRHI) to assess the quality of river water flowing into the Chambal River using WQ parameters such as pH, temperature, DO, BOD, total solids (TS), total coliform (TC), phosphate (P) and nitrate (N). The proposed index formulation consists of three major steps, Fuzzification, Aggregation, and defuzzification; they have been elaborated consequently [45]. The major driving force in this concept is WQ measure. There are eight parameters identified and categorized into four groups, each consisting of two WQ parameters. Subsequently to ascertain the group index, compositional rules have framed. These groups are used to calculate the river health indices. There are three prominent steps in analyzing fuzzy model viz.: a) to establish fuzzy set values; b) grouping (aggregation) of the WQ parameters; c) calculation of river health index using accumulated values.

The process of fuzzification involves translation of crisp values into fuzzified counterparts: involving the central concept of membership functional and the participatory membership value (μ) contend by the linguistic

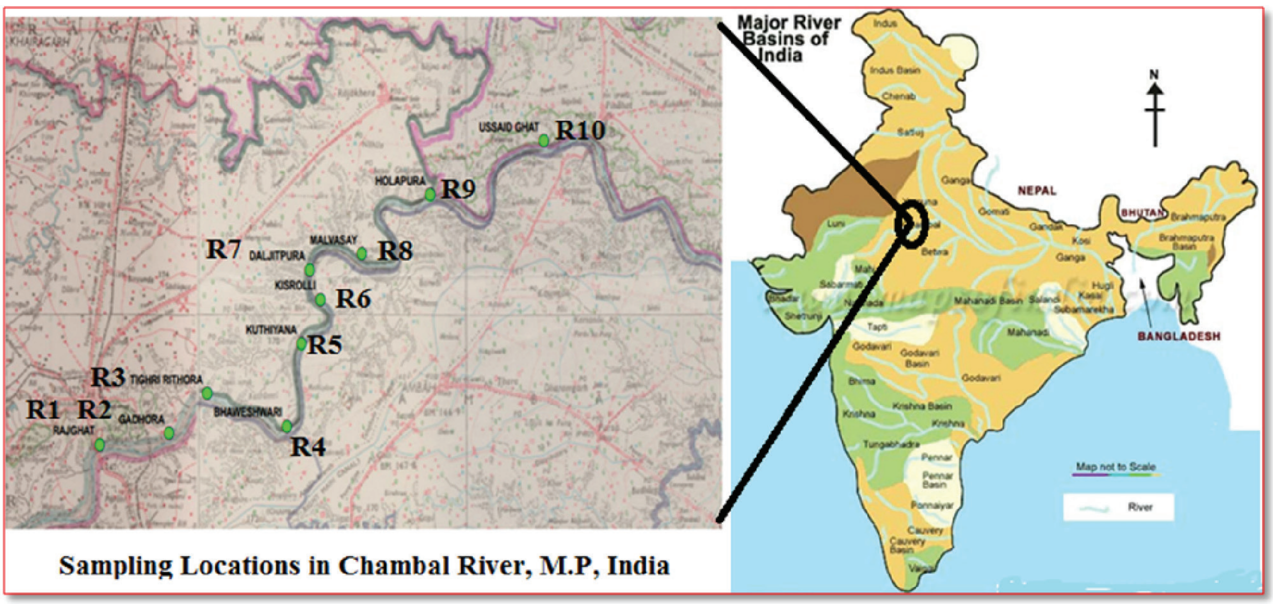

Fig. 1. Map showing sampling location in Chambal River, India.

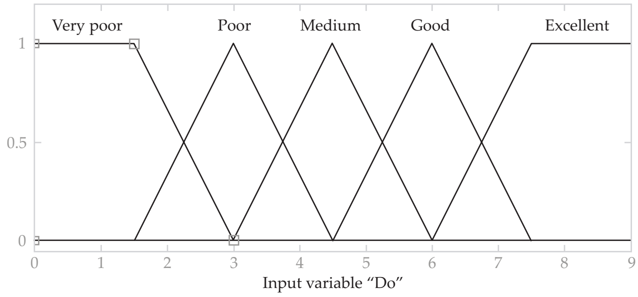

Fig. 2. Membership functions of the Fuzzy set (DO).

counterpart (x), which is in the usual range (0,1). The fuzzy membership function assumes any justified shape according to information available. The triangular or trapezoidal fuzzy membership functions are most frequently used functions to represent linguistic variables [32]. In the present study, five fuzzy subsets (excellent, good, medium, poor and very poor) have been used for the assessment of river health (Fig. 2). Generally, a mix of triangular and trapezoidal membership functions are used. If only triangular membership functions are used for all the subsets of parameters, then only the value 0, would be having a membership grade of 1 for very poor subset and the value of 100 would have a membership grade of 1 for excellent subset. Hence, fuzzy subsets have been defined using triangular and trapezoidal fuzzy membership function. Fuzzy sets and linguistic terms for input parameters of Group 1,2,3,4 and output parameter have given in Table 3. Other values of WQ parameters obtained from the sites are fuzzified using membership functions are also given in Table 3, denoted as membership grades; they have been further used in the calculation of FRHI.

Trapezoidal:

$$f(x;a,b,c,d)=\begin{cases}0 & x<a \text{ or } d<x\\ \dfrac{a-x}{a-b} & a\le x\le b\\ 1 & b\le x\le c\\ \dfrac{d-x}{d-c} & c\le x\le d\end{cases}$$

Triangular:

$$f(x;a,b,c,d)=\begin{cases}0 & x<a \text{ or } d<x\\ \dfrac{a-x}{a-b} & a\le x\le b\\ \dfrac{c-x}{c-b} & b\le x\le c\end{cases}$$

Fuzzy rule-based is established to determine the health index. There was a need to range over voluminous data scattered around different distributions and hence to make encompassing fuzzy rules [29,41]. After modeling the fuzzy data membership, the system lifts with two decision-making parameters at each step. The compact algorithm as in Fig. 3 shows the fuzzy based WQI. The preprocessing step involves the normalization of data in the range [0,100], divided into four groups; the secondary measure of this preprocessing involves a further reduction into two significant groups. The aggregated values of these groups by fuzzy inference system result into FRHI. In this study, normalizations were performed using the fuzzy inference system. The algorithm proposed in Fig. 3 have a proximity with Mamdani inference system [42]. Hence, all the involved system parameters are aligned with this model, resulting in the reduction of approximately all possible constraints into merely 175 rules involving two fuzzified parameters. Due to the grouping of parameters, the number of rules have been significantly reduced. Only two parameters have been merged at a time so the number of rules for merging 2 parameters are $5^2 = 25$. With four groups the number of rules is 100. These four groups have again been grouped into two creating 50 rules. Finally, the last two groups have again been merged with 25 rules. Hence, the total number of rules are 175.

For this study, the following linguistic variables and groups were defined: (G1): DO and BOD; G2: pH and Temperature; G3: TS and TC; G4: N and P. FRHI defined by linguistic values: Excellent (E), Good (G), Medium (M), Poor (P) and Very Poor (VP). Table 3 shows the physico-chemical and biological parameters with their input fuzzy sets. The consequents after applying these rules always adhere the aggregation and normalization operations as defined below:

If the first parameter is E and the second parameter is E, then group output is E

If the first parameter is E and the second parameter is G, then group output is E

If the first parameter is E and the second parameter is M, then group output is G

If the first parameter is VP and the second parameter is P, then group output is VP

If the first parameter is VP and the second parameter is VP, then group output is VP

The experimental testbed comprises Fuzzy Logic Toolbox of Matlab 2013b edition for analysis and computation related to Fuzzy modeling and inferences. The data model presented for scoring river health assessment ranges over [0,100], representing 0 as 'Very poor (VP)' and 100 as an 'Excellent (E)' measures, presented in Table 2. FRHI is the resultant fuzzy set formed by parameters as explained in the schematic diagram (Fig. 3).

The determination of final crisp output in fuzzy inference system involves a crucial step commonly known as defuzzification; it helps in aggregating the result involving multi-criterion decision making. The crisp value represents, a deterministic feature of fuzzy reasoning process based on the assessment matrix. Out of the extensive list of defuzzification methods, the most prominent used in the literature are centroid, First of maximum, mean of the maximum and other central measure approaches [43]. In this study, centroid method has been employed for defuzzification.

Table 3
Fuzzy sets and linguistic terms for input parameters of Group 1, 2, 3, 4 and output parameter

	G1								G3								G4							
Parameter	Dissolved Oxygen				Biological Oxygen Demand				Total Solids				Total Coliform				Nitrate				Phosphate			
Symbol	DO				BOD				TS				TC				N				P			
Unit	mg/l				mg/l				mg/l				Colonies/100 ml				mg/l				mg/l			
Interval	0–9				0–30				0–750				0–18000				0–35				0–6			
Linguistic variable	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
Excellent (E)	6	7.5	9	9	0	0	5	10	0	0	125	250	0	0	3000	6000	0	0	10	15	0	0	1	2
Good (G)	4.5	6	7.5		5	10	15		125	250	375		3000	6000	9000		10	15	20		1	2	3	
Medium (M)	3	4.5	6		10	15	20		250	375	500		6000	9000	12000		15	20	25		2	3	4	
Poor (P)	1.5	3	4.5		15	20	25		375	500	625		9000	12000	15000		20	25	30		3	4	5	
Very poor (VP)	0	0	1.5	3	20	25	30	30	500	625	750	750	12000	15000	18000	18000	25	30	35	35	4	5	6	6
	G2								Output															
Parameter	pH				Temperature				Output															
Symbol	pH				Temp				Output															
Unit					degree Celsius																			
Interval	1.0 – 14				(–6 to 45)				0–100															
Linguistic variable	a	b	c	d	a	b	c	d	a	b	c	d												
Excellent (E)	6.5	6.8	7.5	8	14	16	24	28	100	100	90	70												
Good (G)	7.5	8	8.5		24	28	32		90	70	50													
Good* (G)	6.8	6.5	6.2		14	10	2																	
Medium (M)	8	8.5	9		28	32	36		70	50	30													
Medium* (M)	6.5	6.2	5.6		10	0	–2																	
Poor (P)	8.5	9.5	10.5		32	36	40		50	30	10													
Poor* (P)	6.2	5.6	4		0	–2	–4																	
Very poor (VP)	9.5	10.5	14	14	36	40	45	45	30	10	0	0												
Very poor* (VP)	5.6	4	1	1	–2	–4	–6	–6																

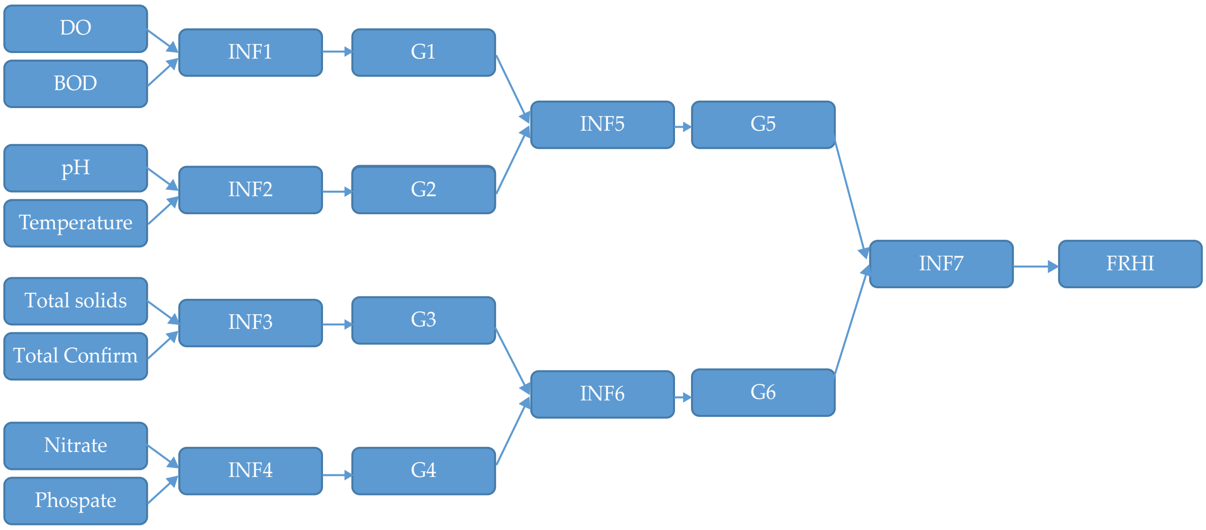

Fig. 3. Schematic flow-diagram of the FRHI.

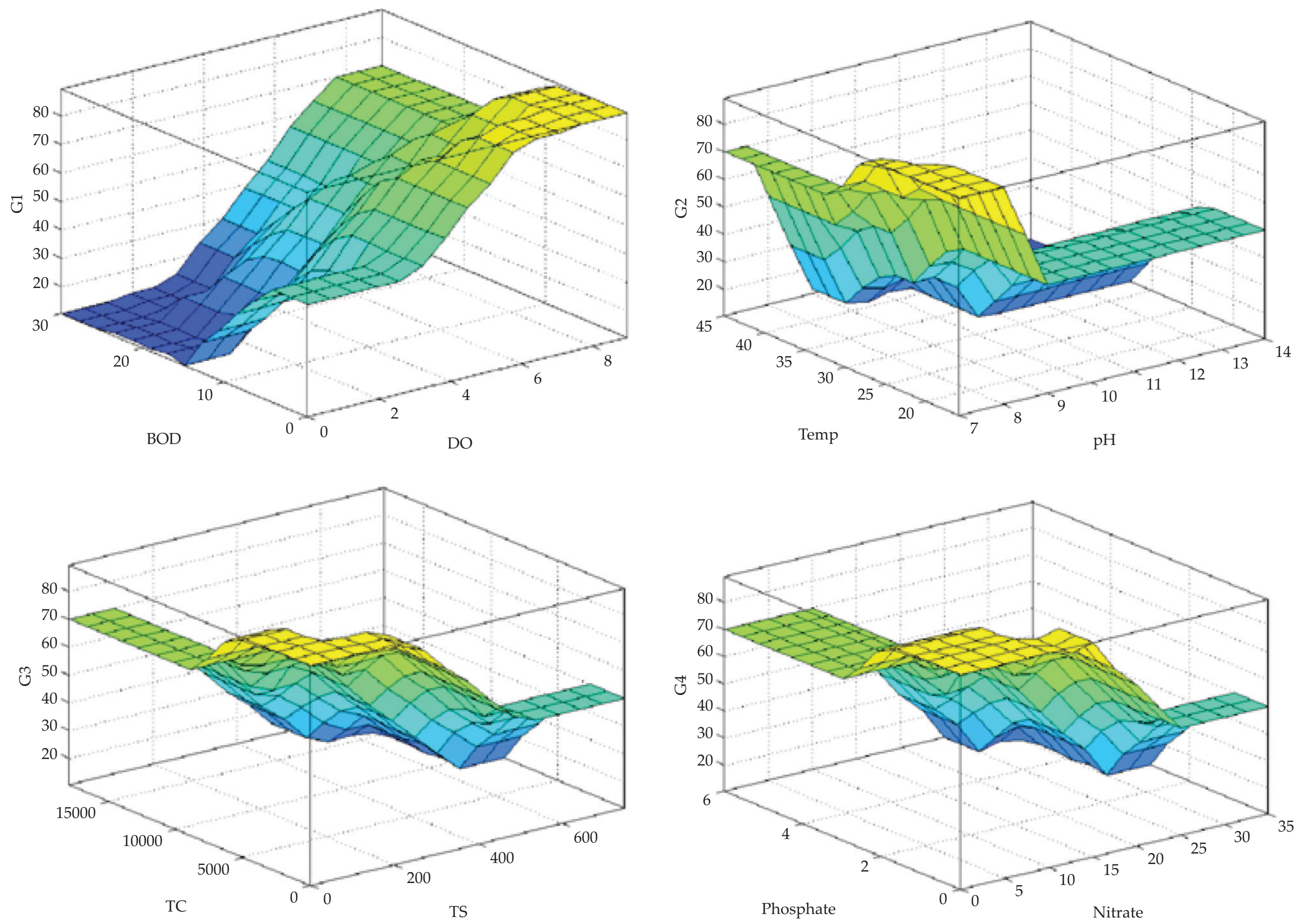

Fig. 4. Surface graph representing the interactions between parameters.

5. Results and discussions

An FRHI is mean to convert large amounts of river WQ data into single value usable by management and the public on regular basis. The present study used the results of eight WQ parameters collected during pre- and post-monsoon 2014 at 10 locations in Chambal River [13–14,16]. The NSF-WQI [18], C-TSI & EHI [13] at all locations in post-monsoon and pre-monsoon 2014 for the study of stretches of Chambal River has calculated. As stated in the previous study, NSF-WQI was coming under the range of medium categories (NSF-WQI: 66–71) at all the locations

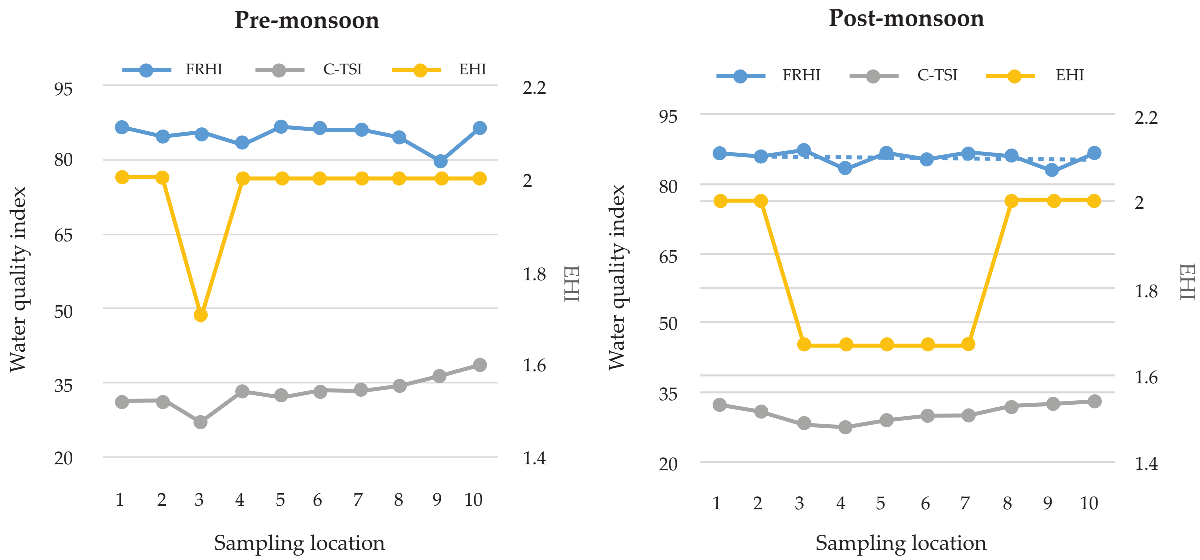

Fig. 5. Comperative representation of indices (pre and post-monsoon 2014).

in both seasons. Besides this, C-TSI values were in the range of Oligotrophic, i.e., 27–39; whereas, the EHI values at all locations were approaching towards medium range, i.e., (EHI: < 2.0). Henceforth, experiencing more pollution in pre-monsoon than post-monsoon, even though the overall EHI values were in good range (Fig. 5). FRHI is a complete Fuzzy inference system developed to model river health based on different parameters of water quality. The system experimented with varying membership functions based on their utility as per quality of application data. Experiment outcomes are the defuzzified crisp results supporting the modeling concepts proposed. Validation of methodologies involves standard indices such as C-TSI and EHI.

The detail of FRHI has been shown in Fig. 5 and Table 4. It shows that FRHI was found to be excellent (FRHI > 80) at all the location during pre and post-monsoon. The index ranged from a minimum of 83.0 during the pre-monsoon at Holapura to maximum of 87.2 at Tighrerithora, which indicates that there is an increase in river health indicated by a decrease in FRHI. Furthermore, the index ranged from a minimum of 79.7 during the post-monsoon at Holapura to maximum of 86.4 at Rajghat, which may be due to dilution of pollution. This show that there is increasing pollution trend (decrease river health from excellent to good), though very little, from pre- to post-monsoon. It requires taking corrective measures so that further pollution in the river may not increase.

The fuzzy model performed significantly at all levels except a dip in performance during selective monsoon. Moreover, the experimental test results of FRHI has been observed to be consistently better in the study period considered for all river health classes. Out of the existing pool of indices, three indices showed the comparatively encouraging results for assessing river health. Results in Fig. 5 indicates that EHI, C-TSI estimates are fairly close to the FRHI regarding river health, this figure also highlights the significance of using Fuzzy Inference system, as FRHI results are comparatively outperforming with their ancestor indices estimated. One of the many significant advantages of FRHI comprises, the ability to integrate not only the numerical data as well as the expert potentials and simplifies this combination of heterogeneity into simplified fuzzy data models.

Table 4
Estimated FRHI for pre and post-monsoon 2014

S. No	Sampling location	Pre-monsoon		Post-monsoon	
		FRHI	River health	FRHI	River health
1	Rajghat	86.6	Excellent	86.4	Excellent
2	Godora	86.1	Excellent	84.7	Excellent
3	Tighrerithora	87.2	Excellent	85.2	Excellent
4	Bhaveshri	83.6	Excellent	83.1	Excellent
5	Kuthiana	86.5	Excellent	86.4	Excellent
6	Kisrauli	85.7	Excellent	86.1	Excellent
7	Daljeetpura	86.6	Excellent	86.0	Excellent
8	Malvasi	86.0	Excellent	84.5	Excellent
9	Holapura	83.0	Excellent	79.7	Good
10	Kusaidghat	86.6	Excellent	86.2	Excellent

6. Conclusion

In this empirical study, a robust decision-making tool for river health management in the form of the FRHI is presented. FRHI Fuzzy model has tested that river health has high sustainability with the expected outcome in the Chambal River. The average value of three indices in each sampling station shows that FRHI estimates are the consistent one. FRHI shows that overall health of river slightly reduces from pre-monsoon (83.0–87.2) to post-monsoon (79.7–86.4), though in an excellent range indicating, there is decreasing the health of river which needs to be taken care by way of taking appropriate corrective measures to keep the river health in good condition.

FRHI fuzzy model estimates are comparatively superior with EHI and C-TSI estimates overall levels during selected period of study and also for all river health classes. The utility factor of FRHI is believed to be most significant in cases of spatial and temporal changes in river health. Authors justified the utilization of FRHI as a significant index for drafting policies about to matters related to environmental policies and management decisions in the domain of rivers.

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