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Fuzzy Logic Approach to Quantify Water Pollution

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Abstract:
In designing of water quality index more rational approach is needed as present indices have number of discrepancies and need to be rectified. Water quality parameters considered for obtaining WQI is different for all indices. Some important parameters have not been considered at all and allotment of weight age factor is completely subjective. At the same time some parameters can change the results dramatically without justifying it. Because of these limitations of crisp set theory an advanced computation method is required which is capable of handling imprecise, vague and fuzzy information in decision making on water quality. Hence there is need for more robust approach which can deal with uncertainty and ambiguity involved in assessment of water quality. To reduce uncertainty, ambiguity, vagueness and subjectivity in environmental issues fuzzy set theory has emerged as an excellent tool. In present work of quantifying EIA by using fuzzy set theory, fuzzy logic has been used for quantifying pollutants in water and instead of WQI new nomenclature is done as FWPI (Fuzzy Water Pollution Index). Higher the value of FWPI higher will be the concentration of pollutants.

Key words: Fuzzy water pollution Index, Water Quality index, Fuzzy Rule based System, Crisp Water Quality Index, Fuzzy Number System, Fuzzy Membership Function.

I. INTRODUCTION

In present era quality of water is one of the most important environmental issues as the surface and sub-surface quality of water is deteriorating day by day mainly due to industrialization. Industries discharge their effluents either on land or in water body and pollute the water. Water quality parameters are mainly classified into three different classes: physical, chemical and biological. All these classes have significant numbers of water quality indicators. Bureau of Indian standards and Indian council of medical research have given permissible and acceptable range of these indicators for drinking purpose. The traditional report of water quality is prepared by considering number of variables and hence becomes too technical and detailed. For purpose of analysis different indicators of water are identified, allotted a weightage factor and used to calculate a single numeric value that finally leads to water quality index. For scaling water quality index crisp set theory has been used which deals with standing boundary conditions. So far there is no globally accepted water quality index, some countries and regions have used, or are using aggregated water quality data in the development of water quality indices. Most water quality indices rely on normalizing, or standardizing, data parameters by parameters according to accepted concentration and some interpretation of 'good' verses 'bad' concentration. Water quality index is calculated by multiplying different weightage factor to different parameters and then by adding them. The WQI is obtained by considering nine parameters: biochemical oxygen demand (0.11), faecal coliforms (0.16), dissolved oxygen (0.17), temperature change (0.1), pH (0.11), turbidity (0.08), nitrates (0.10), Phosphate (0.10) and total solids (0.07) (William Ocampo_Duque).The weightage factors are shown in parentheses. Other WQI have also been developed at regional level considering different weightage factor and different parameters like total organic carbon, conductivity, suspended solids, heavy metals etc.

Crisp Water Quality Index

Traditional reports on water quality tend to be too technical and detailed, presenting monitoring data on individual substances, without providing a whole and interpreted picture of water quality. To resolve this gap, various water quality indices have been developed to integrate water quality variables worldwide (SAFE, 1995; Mitchell and Stapp, 1996; WEP, 1996; Cude, 2001; Liou et al., 2004; Said et al., 2004). Most of these indices are based on the Water Quality Index (WQI) developed by the U.S. National Sanitation Foundation (NSF, 2005). The WQI is obtained by adding the multiplication of the respective weight factor by an appropriated quality-value for each parameter. The WQI index consists of nine parameters: dissolved oxygen (0.17), faecal coliforms (0.16), biochemical oxygen demand (0.11), pH (0.11), temperature change (0.1), phosphates (0.10), nitrates (0.10), turbidity (0.08), and total solids (0.07). In parentheses are given the weight factors according to the importance of the parameters. Other indices are also used at regional level to evaluate water quality. The Simplified Water Quality Index (ISQA) is currently applied by the Catalan Water Agency. It is mainly a correlation of dissolved oxygen, total organic carbon, suspended solids, and conductivity, with a weight matrix of 0.30, 0.25, 0.25, and 0.20, respectively. However, WQI, ISQA, and other similar indices exhibit a number of weak points, which enable the assignation of a quality value using a limited number of parameters. Most indices do not consider toxic pollutants such as heavy metals, hydrocarbons, or pesticides. In turn, some parameters in the index equations can influence dramatically the final score without valid justification, while their formulations are rather elementary, and the number of variables involved is too limited. However, the most critical deficiency of these indices is the lack of dealing with uncertainty and subjectivity present in this complex environmental problem (Chang et al., 2001; Mpimpas et al., 2001; Silvert, 2000). These indices cannot deal with uncertainty, ambiguity and subjectivity involved in complex environmental system. More rational approach in designing of water quality index is needed as present indices have number of discrepancies and need to be rectified. Water quality parameters considered for obtaining WQI is different for all indices. Some important parameters have not been considered at all and allotment of weightage factor is completely subjective. At the same time some parameters can change the results dramatically without justifying it. Because of these limitations of crisp set theory an advanced computation method is required which is capable of handling imprecise, vague and fuzzy information in decision making on water quality. Hence there is need for more robust approach which can deal with uncertainty and ambiguity involved in assessment of water quality. To reduce uncertainty, ambiguity, vagueness and subjectivity in environmental issues fuzzy set theory has emerged as an excellent tool. In present work of quantifying EIA by using fuzzy set theory, fuzzy logic has been used for quantifying pollutants in water and instead of WQI new nomenclature is done as FWPI (Fuzzy Water Pollution Index). Higher the value of FWPI higher will be the concentration of pollutants. The need for more appropriated techniques to manage the importance of water quality variables, the interpretation of an acceptable range for each parameter, and the method used to integrate dissimilar parameters involved in the evaluation process is clearly recognized. In this sense, some alternative methodologies have emerged from artificial intelligence. These methodologies, mainly fuzzy logic and fuzzy sets, are being tested with real environmental problems. The final aim is to reduce the uncertainty and imprecision in criteria employed in decision-making tools (Chang et al., 2001; McKone and Deshpande, 2005).

Fuzzy Water Pollution Index

Fuzzy sets, characterized to be conceptually easy of understanding, and based on natural language, have been successfully used to model non-linear functions, to build inference systems on top of the experience of experts, and to deal with imprecise data (Zadeh, 1996; Pham and Pham, 1999; Romano et al., 2004; Ross, 2004). These advantages have been applied to face water related complex environmental problems (Sadiq and Rodriguez, 2004; Vemula et al., 2004; Liou and Lo, 2005; McKone and Deshpande, 2005; Ghosh and Mujumdar, 2006). In the present study, the fuzzy logic formalism has been used to assess water quality by developing a water quality index based on fuzzy reasoning.

It is proposed that methods based on fuzzy sets theory should be applied to the way the uncertainties in the decision making on the drinking water quality can be handled. Keeping the importance of uncertainty handling in the water quality assessment and versatility of the fuzzy set theory in the decision making in the imprecise environment', the pollution level of water has been classified by an index considering the fuzzy set theory. Out of numbers of physical, chemical and biological parameters certain important parameters namely pH, total dissolved salts (TDS), total alkalinity (TA), total hardness (TH), Fluoride and iron are considered for the Fuzzy synthetic evaluation (FSE) approach as suggested earlier by Garg et al. (1998) and Dahiya et al. (2005, 2007) for the water quality assessment for domestic usage. Fuzzy set theory may be regarded as a generalization of classical set theory. A fuzzy set is defined in terms of its membership function, which maps the domain of interest, e.g. concentrations, onto the interval [0, 1]. The membership functions represent the truth value, the degree, belongingness or weighting that the specified value belongs to the set. Based on expert judgement and limits prescribed by BIS (1991) and WHO (1984), fuzzy membership functions were designed for all considered parameters. As the parameters for assessing water quality are more in numbers, they are divided into two groups for ease in operation. In first group pH, total dissolved solids; total alkalinity was considered that results in Fuzzy Water Pollution Index Group-1 (FWPI_Gr-1) as an output. In second stage of model FWPI_Gr-1 was considered as an input variable along with total Hardness, fluoride and iron that finally give the output as FWPI.

Model Development to Find Fuzzy Water Pollution Index Group-1 (FWPI_Gr-1)- Program_1

Input Variables with their Membership Functions

pH, Total Dissolved Solids and Total Alkalinity were selected as input variable to find Fuzzy Water Pollution Index. The nature of the curve for membership functions were considered trapezoidal. For example, membership function for pH, linguistic variable "Desirable" has fore values in parameter column i.e. [6,6.5,8.5,9] that represents that truth value (membership function) varies from 0 to 1 for 6 to 6.5, between 6.5 to 8.5 it is 1 and between 8.5 to 9 it varies between 1 to 0.

(1) pH

Table.1. Membership Function for pH

Sr. No.	Membership Function for pH	pH value
1	Unacceptable_Low	[0,0,5,6.5]
2	Desirable	[6,6.5,8.5,9]
3	Unacceptable_High	[8.5,9,14,14]

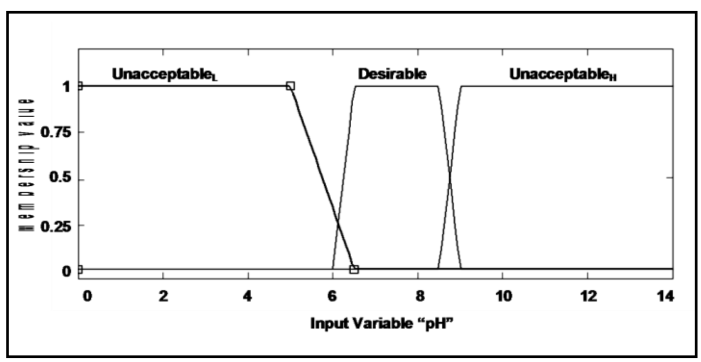

Figure.1. Fuzzy Set for Input Variable "pH"

(2) Total Dissolved Solids

Table.2. Membership Function for TDS

Sr. No.	Membership Function for TDS	mg/l
1	Desirable	[0,0,500,600]
2	Acceptable	[500,600,1900,2100]
3	Unacceptable	[1900,2100,2500,2500]

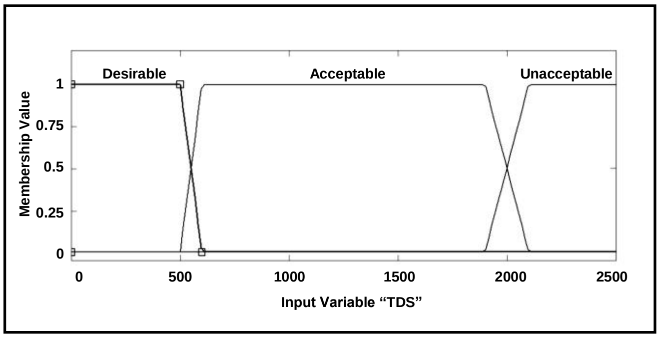

Figure 2: Fuzzy Set for Input Variable "TDS" (mg/l)

(3) Total Alkalinity

Table.3. Membership Function for TA

Sr. No.	Membership Function for TA	mg/l
1	Desirable	[0,0,175,225]
2	Acceptable	[175,225,575,625]
3	Unacceptable	[575,625,1000,1000]

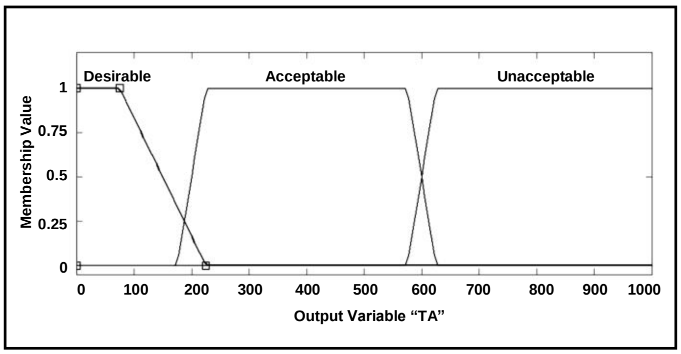

Figure.3. Fuzzy Set for Input Variable "TA" (mg/l)

Output Variable with its Membership Function FWPI_ Gr-1

Table.4.Membership Function for FWPI_Gr-1 Variables

Sr. No.	Membership Function for FWPI_Gr-1	Index value
1	Desirable	[0,0,30,40]
2	Acceptable	[30,40,60,70]
3	Unacceptable	[60,70,100,100]

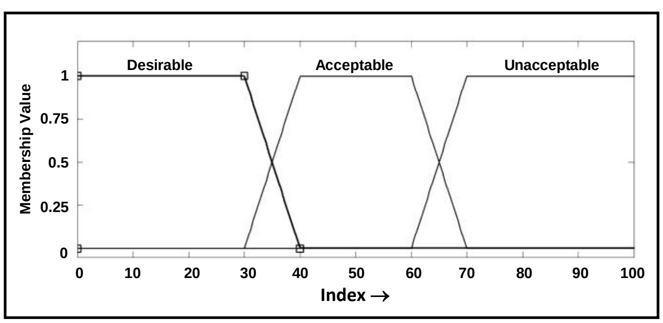

Figure.4. Fuzzy Set for Variable "FWPI_Gr-1"

Based on the concentration of any input variable water quality can be defined. For example, based on the concentration of Total Alkalinity, water quality can be defined as Desirable, Acceptable, and Unacceptable. It can be seen in Figure 5.13 that the fuzzy set of Total Alkalinity for Acceptable water varies from 175 to 625 mg/l. The first value (175 mg/l) is the minimum with zero membership value, next 225 mg/l with unit membership value which extends up to 575 mg/l and then the membership value falls down to zero at 625 mg/l. The membership function for this set is shown on Y axis. It is evident that the value 600 mg/l is in both sets: Acceptable and Unacceptable, but its degree of membership in both the set varies. This kind of classification is more apposite for describing the water quality as it takes variability into consideration. One may argue about the shapes of the membership function and its ranges, but certainly the traditional classical set cannot take into account variability/subjectivity of information into the procedure. Similarly fuzzy set of FWPI for group_1 contaminants is shown in **Figure 4**.

Rules for FWPI_Gr-1

In the crisp set based WQI system, the value of index is determined by algebraic operations of individual parameter values using a derived mathematical expression, which is then transformed into informative descriptors. In a fuzzy rule based system, the numerical value of FWPI is determined by rules based on expert knowledge. Each rule has a set of antecedent's propositions comprising of attributes for input variables. Attributes are linguistic expression like Desirable, Acceptable, and Unacceptable. These linguistic descriptions are invariably imprecise keeping in view of the inadequate information on the health implication of each parameter on the consumer and the integrated effect of all the parameters on the human health. Moreover the field data measured is also subjected to errors resulting into additional uncertainty into the system (Ross, 1997).

Rules can be expressed in the form of natural language like: IF antecedent, THEN consequent. For example:

Rule 1: **IF** {pH is not desirable OR TDS is unacceptable OR TA is unacceptable}

THEN { FWPI_Gr-1 is harmful}.

For FWPI_Gr-1 of three pollutants, rules are formed using OR / AND operators to cover all possible set of combination of pH, TDS and TA. Rules are shown in **Table 5**.

Table.5. Rules for FWPI – Group 1

	IF					THEN
Rule	**pH**		**TDS**		**TA**	**FWPI_Group-1**
1	Not Desirable	OR	Unacceptable	OR	Unacceptable	Unacceptable
2	Desirable	AND	Desirable	AND	Desirable	Desirable
3	Desirable	AND	Desirable	AND	Acceptable	Acceptable
4	Desirable	AND	Acceptable	AND	Desirable	Acceptable
5	Desirable	AND	Acceptable	AND	Acceptable	Acceptable

Estimation of FWPI_Gr-1

Fuzzy numbers are operated using Mamdani type fuzzy inference system. Rule based fuzzy inference system for the **FWPI_Gr-1** model is shown in **Figure 5** and surface generated is shown in **Figure 6**. The first step is to identify all the rules in which each parameter value falls. Based on these membership values and operators (OR / AND), the output fuzzy set is implicated. The implicated output from each rule is then aggregated and defuzzified to obtain the value of FWPI_Group1 and its class.

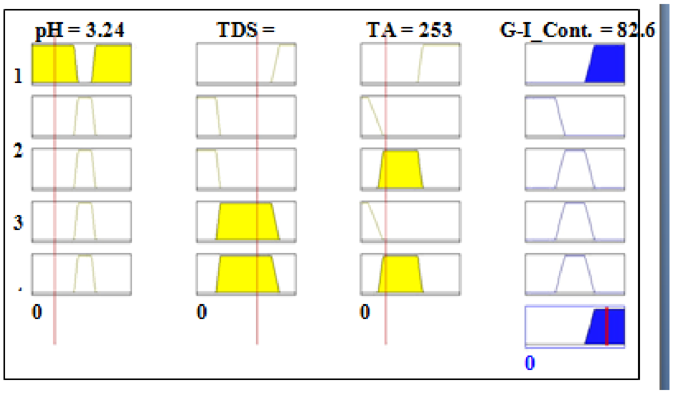

Figure .5. Rule View of Rule based FWPI – Group 1

Surface

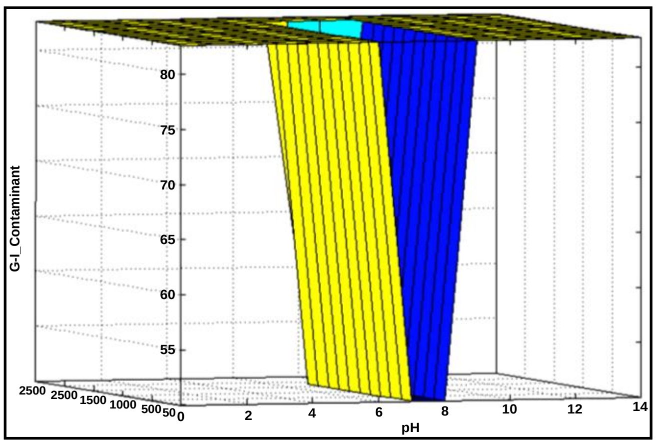

Figure.6. Surface Generated for FWPI_Group-1 by Rule Based Fuzzy Inference System

As all the parameters to determine FWPI could not be considered in first model (Program_3), the remaining parameters total hardness, Iron and Fluoride were considered in next model (program_4). The output of Program_3, **FWPI_Gr-1**, was considered as an input variable in program_4 to accommodate the effect of 'pH', 'total dissolved solids' and 'total alkalinity' in order to find final FWPI.

Model Development to Find Fuzzy Water Pollution Index FWPI (Program_2)

Input Variables with their Membership Function

FWPI_Group1, Total Hardness, Iron and Fluoride were selected as input variable to find final Fuzzy Water Pollution Index. The nature of the curve for membership functions were considered trapezoidal. For example, membership function for Total hardness, linguistic variable "Acceptable" has fore values in parameter column i.e. [275,325,575,625], that represents that truth value (membership function) which varies from 0 to 1 for 275 to 325, between 325 to 575 it is 1 and between 575 to 625 it varies between 1 to 0.

(1) Fuzzy Water Pollution Index Group 1 (FWPI_Gr-1)
Membership function for FWPI_Gr-1 is given in **Table 4** and its fuzzy set is shown in **Figure 4**.

(2) Total Hardness

Table. 6. Membership Function for Total Hardness

Sr. No.	Membership Function for TH	mg/l
1	Desirable	[0,0,275,325]
2	Acceptable	[275,325,575,625]
3	Unacceptable	[575,625,800,800]

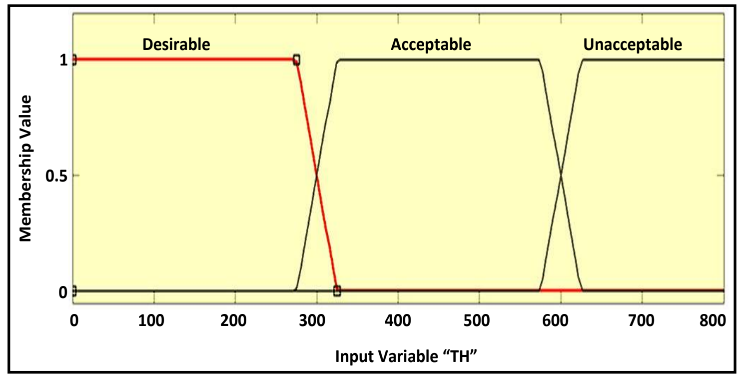

Figure.7. Fuzzy Set for Input Variable "Total Hardness" (mg/l)

(3) Fluoride

Table .7.Membership Function for Fluoride

Sr. No.	Membership Function for Fluoride	mg/l
1	Desirable	[0,0,0.2,0.3]
2	Acceptable	[0.2,0.3,1,1.5]
3	Unacceptable	[1,1.5,2.5,2.5]

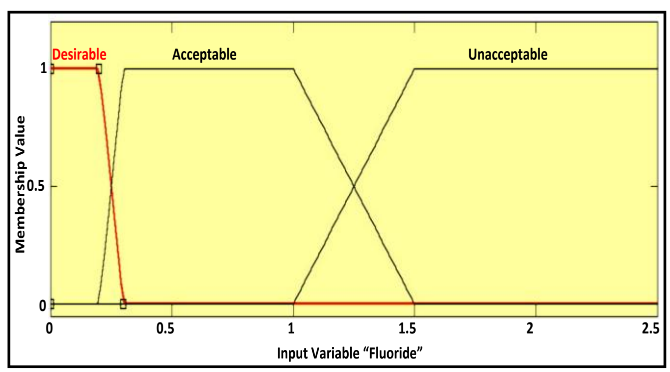

Figure.8. Fuzzy Set for Input Variable "Fluoride" (mg/l)

(4)Iron

Table.8.Membership Function for Iron

Sr. No.	Membership Function for Iron	mg/l
1	Desirable	[0,0,0.75,1.25]
2	Acceptable	[0.75,1.25,1.5,2]
3	Unacceptable	[1.5,2,3,3]

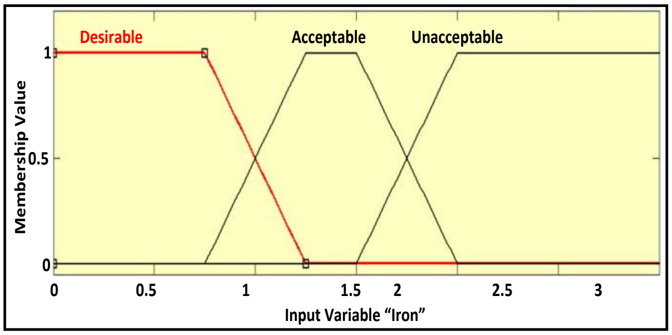

Figure.9. Fuzzy Set for Input Variable "Iron" Output Variables with their Membership Function Fuzzy Water Pollution Index (FWPI)

Table .9.Membership Function for FWPI

Sr. No.	Membership Function for FWPI	Defuzzified Index
1	Desirable	[0,0,30,40]
2	Acceptable	[30,40,60,70]
3	Unacceptable	[60,70,100,100]

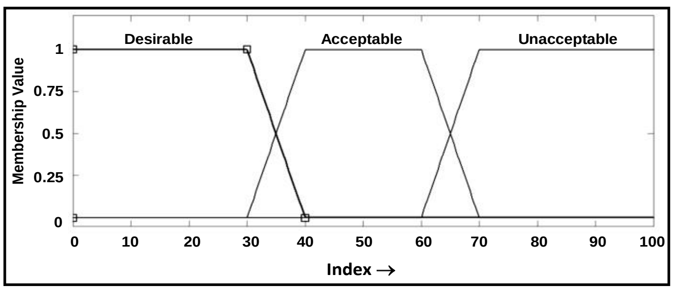

Figure.10. Fuzzy Set for Variable "FWPI"

The water quality can be defined based on concentration of any input variable. For example, based on the concentration of Fluoride, water quality can be defined as Desirable, Acceptable, and Unacceptable. It can be seen in **Figure 8** that the fuzzy set of Fluoride for Acceptable water varies from 0.2 to 1.5 mg/l. The first value (0.2 mg/l) is the minimum with zero membership value, next 0.3 mg/l with unit membership value which extends up to 1.1 mg/l and then the membership value falls down to zero at 1.5 mg/l. The membership function for this set is shown on Y axis. It is evident that the value 1.3 mg/l is in both sets: Acceptable and Unacceptable, but its degree of membership in both the set varies. This kind of classification is more pertinent for describing the water quality as it takes variability into consideration. Certainly the traditional classical set cannot take into account variability/subjectivity of information into the procedure. Similarly fuzzy set of final FWPI is shown in **Figure 10**.

Rules for FWPI

In the crisp set based WQI system, the value of index is determined by algebraic operations of individual parameter values using a derived mathematical expression, which is then transformed into informative descriptors. In a fuzzy rule based system, the numerical value of FWPI is determined by rules based on expert knowledge. Each rule has a set of antecedent's propositions comprising of attributes for input variables. Attributes are linguistic expression like Desirable, Acceptable, and Unacceptable. These linguistic descriptions are invariably imprecise keeping in view of the inadequate information on the health implication of each parameter on the consumer and the integrated effect of all the parameters on the human health. Moreover the field data measured is also subjected to errors resulting into additional uncertainty into the system (Ross, 1997). Rules are expressed in the form of natural language like: IF antecedent, THEN consequent. For example:

Rule 1: **IF** {FWPI_Gr-1 is desirable AND Total hardness is desirable AND Fluoride is desirable AND Iron is desirable}
THEN {water is desirable}.

For FWPI of selected contaminants, rules are formed using OR / AND operators to cover all possible set of combination of pH, TDS, TA (FWPI_Group-1) TH, Fluoride and Iron and are shown in **Table 10**.

Table.10. Rules for FWPI

	IF							THEN
Rule	**FWPI_Gr-1**		**TH**		**Fluoride**		**Iron**	**FWPI**
1	Unacceptable	OR	Unacceptable	OR	Unacceptable	OR	Unacceptable	Unacceptable
2	Desirable	AND	Desirable	AND	Desirable	AND	Desirable	Desirable
3	Desirable	AND	Desirable	AND	Desirable	AND	Acceptable	Acceptable
4	Desirable	AND	Desirable	AND	Acceptable	AND	Not Unacceptable	Acceptable
5	Desirable	AND	Acceptable	AND	Desirable	AND	Desirable	Acceptable
6	Desirable	AND	Acceptable	AND	Desirable	AND	Acceptable	Acceptable
7	Desirable	AND	Acceptable	AND	Acceptable	AND	Not Unacceptable	Acceptable
8	Acceptable	AND	Desirable	AND	Desirable	AND	Not Unacceptable	Acceptable
9	Acceptable	AND	Desirable	AND	Acceptable	AND	Not Unacceptable	Acceptable
10	Acceptable	AND	Acceptable	AND	Not Unacceptable	AND	Not Unacceptable	Acceptable

Fuzzy numbers are operated using Mamdani type fuzzy inference system. Rule based fuzzy inference system for the FWPI model is shown in **Figure 11** and surface view is shown in **Figure 12**. The first step is to identify all the rules in which each parameter value falls. Based on these membership values and operators (OR / AND), the output fuzzy set is implicated. The implicated output from each rule is then aggregated and defuzzified to obtain the value of FWPI and its class.

Graphical View of Rule Based FWPI

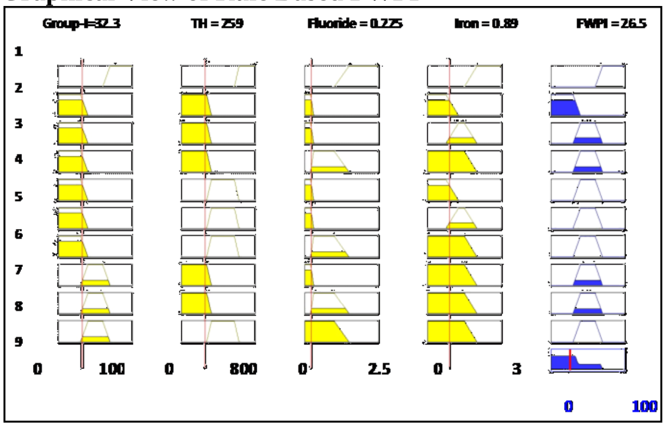

Figure .11. Rule View for Rule Based "FWPI"

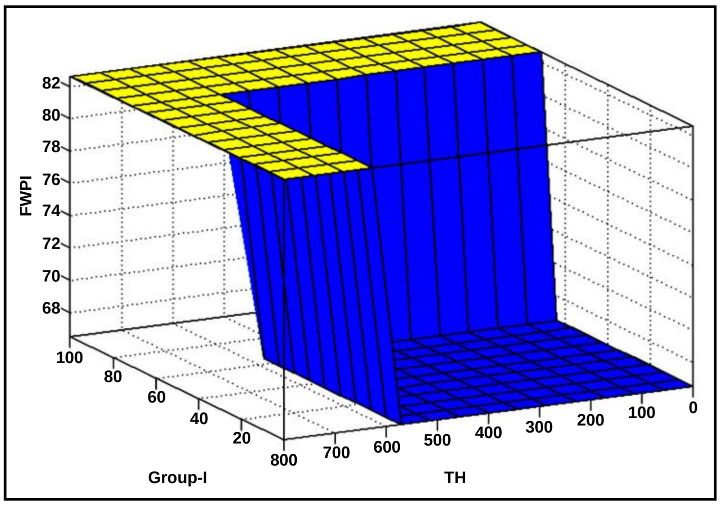

Figure.12. Surface Generated for FWPI by Rule Based Fuzzy Inference System

II. CONCLUSION

Traditionally used WQI based on crisp set theory has limitations viz., step function and eclipsing. The new methodology uses the term FWPI that overcomes these limitations. The problem of step function is eliminated by using fuzzy set and the problem of eclipsing is overcome by using rule based approach. The nomenclature of new fuzzy water pollution index (FWPI) uses the word 'pollution' instead of 'quality' as in WQI. This is done to avoid any ambiguity as increasing value of index means higher pollution levels. However the increasing value of water quality index gives a sham impression of improved water quality, which is not the case.

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Arif Khan, born in 1971, India, graduated in ’94 in Civil Engineering from Nagpur University, Nagpur, India and post-graduated in 1996 in Environmental Engineering from Gulbarga University, Gulbarga, India. Completed his doctorate in Civil and Environmental Engineering in the year 2011 from National Environmental Engineering Research Institute, NEERI, Nagpur, India. He is having more than 20 years of teaching experience at undergraduate, post- graduate and doctoral levels. He is presently working as Principal NUVA College of Engineering, Kalmeshwar, Nagpur, India. He is actively engaged in administrative work pertaining to overall management of academic institutes. His area of interest in research lies in Environmental Impact Assessment Studies (EIA), air pollution, water and wastewater engineering, with application of soft computing methods such as fuzzy set theory in the field of environmental engineering.

Dr. Arif Khan is life member of Indian Society of Technical Education, Fellow of Indian Institute of Engineers and member of Indian Water Works Association.