Available online at www.sciencedirect.com

ScienceDirect

Aquatic Procedia 4 (2015) 1023 – 1030

Aquatic Procedia

www.elsevier.com/locate/procedia

INTERNATIONAL CONFERENCE ON WATER RESOURCES, COASTAL AND OCEAN ENGINEERING (ICWRCOE 2015)

Groundwater Quality Assessment in some selected area of Rajasthan, India Using Fuzzy Multi-Criteria Decision Making Tool

R. Srinivas[a], Prashant Bhakar[a], and Ajit Pratap Singh[a,]*

[a] *Civil Engineering Department, Birla Institute of Technology and Science, Pilani, 333031, Rajasthan, India* *

Abstract

Groundwater is one of the primary sources for drinking and irrigation in Bikaner district of Rajasthan, India. However its quality is deteriorating due to population growth, agricultural runoff and urbanization. In this paper, fuzzy inference tool has been used to develop a model for assessing groundwater quality in Dungargarh block of Bikaner district in Rajasthan. Eleven water quality parameters have been considered as important indicators to evaluate water quality status in 15 groundwater wells located in the region. The model predicts status of groundwater quality along with measure of its sustainability. The ranking of the wells corresponding to both drinking and irrigation uses also provides clarity to the decision makers to formulate suitable policies for treatment processes and sustainable planning of groundwater resources in the region.

Peer-review under responsibility of organizing committee of ICWRCOE 2015

Keywords: *groundwater sustainability; water quality management; fuzzy inference system; water resources planning*

1. Introduction

Groundwater is the main source of water in the arid and semi-arid environment which fulfills the requirement of different beneficial-uses viz., drinking, domestic, and/or irrigation particularly for the rural population. With accelerated and uncontrolled development projects such as stock farming, irrigation, urbanization, and industrialization, a large quantity of waste products are being generated and discharged which ultimately

* Corresponding author. Tel.: +91-1596-515252
E-mail address: aps@pilani.bits-pilani.ac.in

2214-241X
Peer-review under responsibility of organizing committee of ICWRCOE 2015
doi:10.1016/j.aqpro.2015.02.129

contaminate both groundwater and surface water. The excessive and improper use of chemical fertilizers, animal manures, insecticides, and pesticides, improperly built or poorly located and/or maintained septic systems for household wastewater, leaking or abandoned underground storage tanks and piping, improper disposal or storage of wastes and chemical spills at local industrial sites, over exploitation and unwise use of groundwater have not only depleted groundwater availability, but also made its quality inferior and scarce. It has been contaminated by various pollutants like arsenic, fluoride, nitrate etc. It is therefore important to realize that management of groundwater does not only mean assessing groundwater quantity and its availability for different purposes but also its quality which have been impacted significantly to be precursor to various water borne epidemics. In arid and semi-arid regions, the problem has indeed become even serious and challenging which are now being recognized as a social and academic imperative by all water sectors. Hence it is necessary to put appropriate efforts in improving quality of groundwater on scientific lines by utilizing these resources in sustainable manner.

The measurement of the groundwater quality parameters has always been important especially at regular intervals. In Rajasthan context, the prominent studies on groundwater exploration and augmentation efforts have been carried out by Rathore (2005). The hydro-chemical investigations and correlation-analysis of ground water quality of Jaipur city has also been performed which essentially characterizes the status of quality of groundwater in a simple and a comparable manner (Tatawat and Chandel, 2007). Many authors have also emphasized the significance of knowledge of hydrochemistry in assessing the ground water quality corresponding to different beneficial uses (Latha 2012; Singh and Singh 2002; Srinivas et al. 2013). Tietenberg (1984) suggested that sustainability should be dealt by keeping in view that future generations remain, at least, as well off as current generations''. However, there is no measuring gauge or standard against which sustainability is measured and accordingly policies are formulated (Hinterberger et al., 1997; Phillis and Andriantiatsaholiniaina, 2001). Expressing sustainability in mathematical terms gives a clear picture to the decision makers to plan the suitable policies. The vagueness and complexity involved in sustainability not just makes it difficult to define or measure it but also demands to apply concepts of fuzzy logic. Ayres (1996) did statistical measurement of sustainability. Fuzzy logic is not just capable of imitating experts but also gives a systematic approach to express vagueness and impreciseness. Fuzzy multi-criteria decision making tool can be used to assess the quality of water (Singh and Srinivas, in press). A systematic model can be developed using MATLAB fuzzy logic tool box. The inputs of such a model are the quantitative sustainability objectives and output will be the measure of sustainability. Brink (1991) have presented a useful tool for establishing sustainable development. He suggested that a model should (a) give a clear indication as to whether objectives of sustainability are met; (b) express the system as a whole; (c) have a quantitative character; (d) be understandable to non-scientists; and (e) contain parameters which can be used for periods of one or more decades.

In this paper, the focus of the study is to assess the groundwater suitability for Dungargarh block of Bikaner district, Rajasthan which has population about 50,000 (as per 2011 census) for different beneficial uses especially for irrigation and domestic uses. Suitability of groundwater has been evaluated with reference to standards prescribed by Bureau of Indian Standards (BIS). Water quality of 15 groundwater wells of this block has been analyzed and sustainability of these wells has been assessed though initially 38 wells were sampled. These wells are located at Bana, Bigga, Biramsar, Dhirdesar chotiya, Dhirdesar purohitan, Dholiya, Dungargarh, Gusainsar, Kitasar, Kotasar, Kunpalsar, Ladhariya, Lakhsar, Punrasa, and Sawantsar villages. Water quality analysis has been performed using by applying concepts of fuzzy logic in MATLAB tool (version 8.0.0.783 (R2012b)) and sustainability of groundwater wells has been assessed corresponding to given beneficial uses so that the water requirements for present generation are met without compromising the needs of the future generations.

2. Materials and Methods

The complexity and ambiguity involved in sustainability can be handled effectively using fuzzy logic reasoning. (Zimmermann, 1991). A very popular fuzzy inference technique called Mamdani method has been used in this study which consists of four basic steps a) fuzzification of the input variables, b) rule evaluation (inference), c) aggregation of the rule outputs (composition), and d) defuzzification. The process of transforming real data values into linguistic values by performing operations is called fuzzification. The given information or data is represented by IF–THEN linguistic rules. A linguistic rule consists of an IF-THEN statement (IF–part is called the antecedent, while the THEN–part is called the consequent) which is formed with the help of linguistic values of the linguistic variables under expert opinion. In order to obtain a final crisp value, defuzzification methods are applied. An illustration of IF–THEN fuzzy approximate reasoning is the assessment of drinking water quality based on concentration of Total dissolved solids (TDS), pH, Total hardness (TH), Nitrate (NO^-_3) and Fluoride (F). Choosing TDS, pH, TH, NO^-_3 and F as the primary factors deciding the drinking water quality, the fuzzy rules can be

- IF TDS is 'excellent' AND pH is 'excellent' AND TH is 'bad' AND NO^-_3 is 'excellent' AND F is 'excellent', THEN drinking water quality is 'satisfactory'.
- IF TDS is 'excellent' AND pH is 'excellent' AND TH is 'acceptable' AND NO^-_3 is 'excellent' AND F is 'acceptable', THEN drinking water quality is 'good'.

'Acceptable', 'Bad' and 'Excellent' are linguistic values of the linguistic variables TDS, pH, TH, NO^-_3 and F; they correspond to the fuzzification of their data value (concentration in mg/l or meq/l). 'Very bad', 'Bad', 'Satisfactory', 'Good' and 'Very good' corresponds to the linguistic values of drinking water quality. Defuzzification of their linguistic values provides a crisp measurement of drinking water quality. MATLAB based Fuzzy Inference System (FIS) consists of combination of these rules which serve as input to the model being developed. In this way, a mathematical model is developed which not just defines groundwater sustainability as a function of number of various parameters but also gives a numerical value of sustainability.

2.1. Sampling wells

In this study, a total of fifteen important sampling groundwater wells are chosen from the Dungargarh block of Bikaner district of Rajasthan (Figure 1b). These wells are located in Bana (W1), Bigga (W2), Biramsar (W3), Dhirdesar chotiya (W4), Dhirdesar purohitan (W5), Dholiya (W6), Dungargarh (W7), Gusainsar (W8), Kitasar (W9), Kotasar (W10), Kunpalsar (W11), Ladhariya (W12), Lakhsar (W13), Punrasa (W14), and Sawantsar (W15). Each groundwater well has been represented as the groundwater system at that location and sustainability of these wells are assessed in context to domestic and irrigation usages using fuzzy logic concepts.

2.2. Water quality parameters considered for the study

The quality of water varies with time and space depending on concentration of different water quality parameters. Based on the water quality, user can decide the optimal use of the water at a particular location. Authors have identified appropriate water quality parameters based on the earlier work (CGWB, 2009; Singh and Ghosh, 1999; Singh et al. 2007) and also on the basis of opinion of the experts on requirements of domestic and agricultural usages. The combined effect of these parameters for a particular beneficial-use has been evaluated to measure sustainability for each groundwater well. The important parameters considered for domestic purposes are Total Dissolved Solids (TDS), pH, Total Hardness (TH), Nitrate (NO^{-3}), and Fluoride (F). Similarly, the water quality parameters for irrigation purpose are considered as Electrical Conductivity (E.C.), pH, Sodium (Na^+), Calcium (Ca^{2+}), Chloride (Cl^-), and Bicarbonate (HCO_3^-).

2.3. Normalization of data values

In this study, sustainability assessment is formulated by decomposing appropriate elements at different hierarchical levels (Figure 1a). The top most level deals with the selection of the groundwater well on the basis of its optimal sustainability for a given designated-use. The intermediate levels correspond to criteria (i.e. domestic and irrigation) and sub-criteria representing the suitable water quality parameters for different beneficial uses. The bottom most level corresponds to fifteen sampling groundwater wells chosen from the study area of Dungargarh block of Bikaner district in Rajasthan.

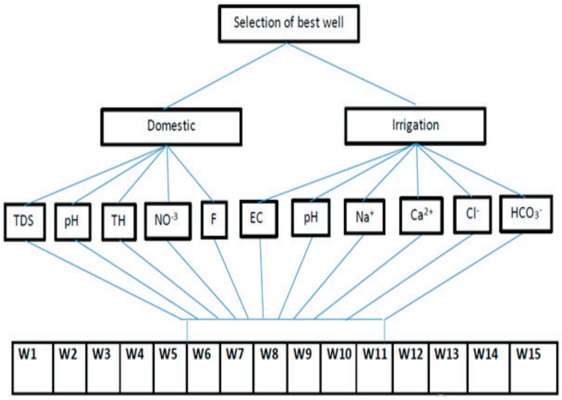

Fig. 1a. Hierarchical structure of the objective, criteria, sub-criteria and decision alternatives considered in the study

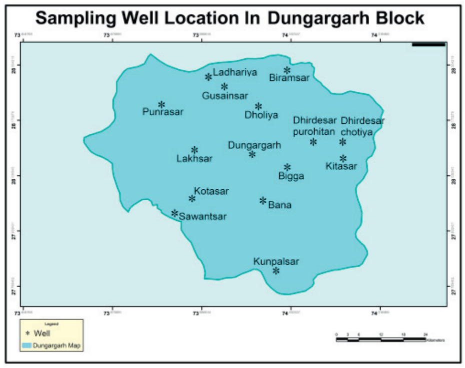

Fig 1b. Locations of Sampling wells in Dungargarh block, Bikaner

The status of water quality for a given usage have been expressed using linguistic variables. They are bad (=B), acceptable (=A), and excellent (=E). These linguistic variables have been expressed by the membership functions of the input and outputs variables as shown in Figure 2a and Figure 2b. The sustainability of groundwater wells corresponding to domestic and irrigation have been expressed in linguistic terms such as very bad (=VB), bad (=B), satisfactory (=S), good (=G), and very good (=VG). Trapezoidal membership functions are chosen for both input and output variables as they can represent the uncertainties and ambiguities in a much better way (Zimmermann, 1991). In each figure, the horizontal axis represents the normalized scores of sustainability ranging at interval [0, 1], whereas the vertical axis represents membership grades at interval [0, 1]. In the present study, groundwater quality was monitored to assess sustainability effects with respect to irrigation and domestic uses. In order to evaluate overall score at a given sampling well, there is a need to evaluate the rating of all the parameters on the same scale because all parameters associated with assessment of sustainability may have different measurement units. This requires linear normalization of the actual measured values with some standard values. The normalized rating of these parameters can be obtained by introducing a simple linear transformation function (or utility function) as expressed in equation (1). If C_0 is the observed data value of the water quality parameter for a particular usage of a given well and C_{min} and C_{max} be the minimum and maximum values of the parameter, C_t be the target value; then its normalized value C_N is calculated as follows:

If Target Value C_t corresponds to an interval [min C_t, max C_t]:

$$
\begin{aligned}
C_N &= \frac{C_0 - C_{min}}{\min C_t - C_{min}}; \text{ for } C_0 \le C_t \\
C_N &= 1; \text{ for } C_0 \in [\min C_t, \max C_t], \text{ and} \\
C_N &= \frac{C_{max} - C_0}{C_{max} - \max C_t}; \text{ otherwise}
\end{aligned}
\tag{1}
$$

In this paper, equation (1) has been used because target values for each parameters lies within the range of permissible limit. For example, the permissible range for pH corresponding to domestic purposes varies between 6.5 (min C_t) to 8.5 (max C_t) as shown in Table 1. Table 1 summarizes the normalized values of all parameters for sampling groundwater well located at *Bana*. Similarly, normalized values of all other parameters have been calculated at all sampling wells.

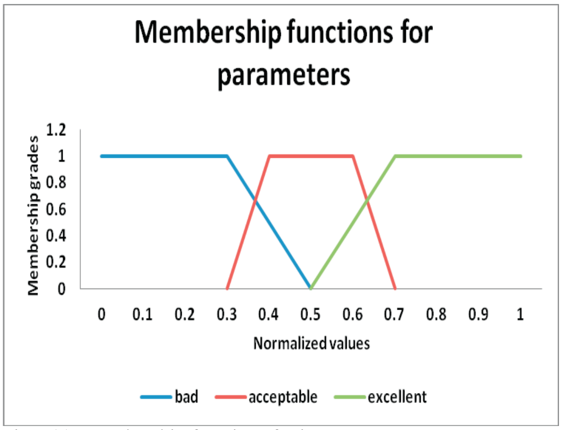

Fig. 2(a). Membership functions for input parameters

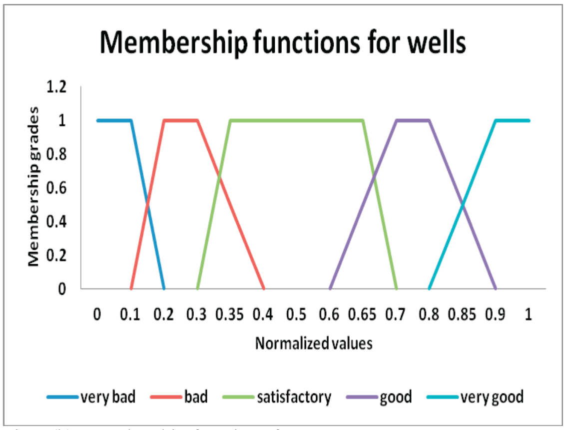

Fig. 2(b). Membership functions for output parameters

Table 1. Normalized values of parameters for Bana well

	Bana					
Parameters	C_0	C_{max}	C_{min}	Min C_t	Max C_t	C_N
E.C.(x 10^6µ siemens/ cm)	1150.000	7200.000	690.000	250.000	1500.000	1.000
TDS(mg/l)	652.000	4963.000	390.000	500.000	2000.000	1.000
pH	8.600	8.900	7.200	6.500	8.500	0.750
Na^+(meq/l)	7.375	50.511	3.478	0.000	2.174	0.892
Ca^{+2}(meq/l)	1.072	10.792	0.418	1.600	4.800	0.553
Cl^-(meq/l)	5.820	46.516	3.400	1.400	3.944	0.956
HCO^-_3(meq/l)	3.622	9.506	1.911	0.820	1.970	0.781
NO^-_3(meq/l)	1.056	34.702	0.000	0.726	1.613	1.000
F(mg/l)	0.680	2.320	0.000	1.000	1.500	0.680
TH(mg/l)	187.000	995.000	83.000	300.000	600.000	0.479

2.4. Fuzzy inference rules using fuzzy operators

The overall sustainability of the specific well for a particular usage is evaluated using fuzzy inference rules, popularly known as IF-THEN rules. These IF and THEN statements are connected with a fuzzy operator (AND or OR) which is used to obtain a single number for the fuzzy evaluation. These rules are formed after consulting the fuzzy experts using fuzzy logic toolbox of MATLAB. Generally, the maximum number of rules for a given usage (R) can be formulated as R = [number of linguistic variables]$^{\text{(number of parameters)}}$. For example, if there are three linguistic variables (i.e. bad, acceptable and excellent) for 5 input parameters associated with domestic purposes, there will be 3^5 = 243 rules can be formulated to determine the sustainability of a groundwater well. The important rules that are being used in this study with specific reference to domestic purposes are shown in Table 2.

3. Application of MATLAB Based Fuzzy Inference System

The methodology used in this model has been explained in six simple steps as shown in Figure 3. For illustration, sustainability measure of the groundwater well located at Bana village with respect to domestic usage has been briefly explained. The same procedure has been applied for remaining groundwater wells. The main steps of the process are as follows: (a) the membership grades for input variables (i.e. water quality parameters) have been defined in MATLAB FIS framework, (b) the membership grades are also defined for the sustainability measure of groundwater well, say at Bana for domestic purposes as the output variable. (c) Fuzzy inference rules are defined using AND operator with the help of experts, (d) Normalized values of all water quality parameters have been derived as shown in Table 1 and aggregation values have been evaluated under fuzzy inference rules to get the final measure of sustainability of the well. Thus the sustainability measure of a well located at Bana for domestic purposes is 0.644 which has been expressed as 64.4 %. It indicates that a well located at Bana demonstrates "good" sustainability condition as can be seen from Figure 2. Similarly sustainability measures of all the wells have been evaluated and classified with respect to both domestic and irrigation usages as shown in Tables 3 and 4.

Table 2. Fuzzy inference rules used for domestic purposes

Description	Inputs					Output	Description	Inputs					Output
Operators→	IF	AND	AND	AND	AND	THEN	Operators →	IF	AND	AND	AND	AND	THEN
Parameters→	TDS	pH	TH	NO^-_3	F	Result	Parameters→	TDS	pH	TH	NO^-_3	F	Result
Rule 1	E	E	B	E	E	S	Rule 8	E	E	B	B	B	B
Rule 2	E	E	A	E	A	G	Rule 9	E	E	E	E	A	VG
Rule 3	E	B	E	E	B	B	Rule 10	E	E	B	E	A	S
Rule 4	E	B	E	E	A	S	Rule 11	A	E	B	A	A	S
Rule 5	E	E	E	E	B	S	Rule 12	E	B	E	E	E	S
Rule 6	A	E	E	B	E	G	Rule 13	B	E	B	B	E	VB
Rule 7	E	E	B	E	E	S	Rule 14	B	E	B	A	B	VB

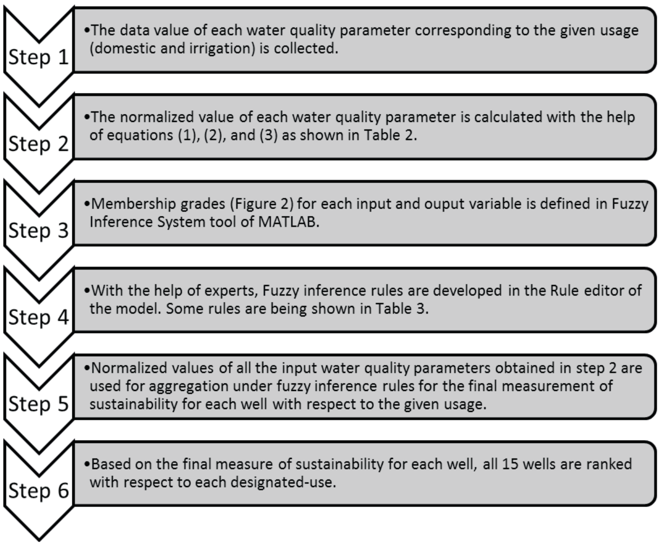

Fig. 3. Methodology applied to obtain sustainability measure of well

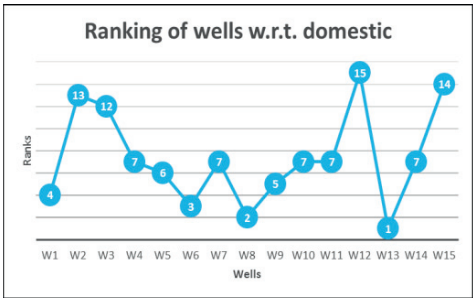

Fig. 4a. Rankings of wells with respect to domestic usage

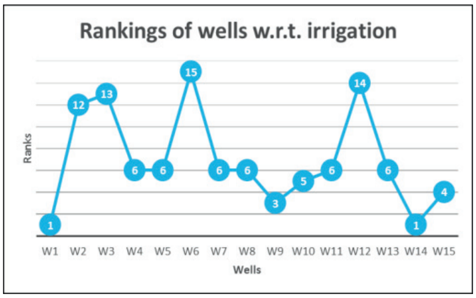

Fig. 4b. Rankings of wells with respect to irrigation usage

4. Results and discussions

The scores of all 15 groundwater wells with respect to both the beneficial uses have been shown in Tables 3 and Table 4. Figure 4(a) and 4(b) depict the ranking of these wells according to their sustainability scores for domestic and irrigation purposes. The abscissa (X-axis) of the plot represents the groundwater wells and ordinate (Y-axis) represents the final ranks that are calculated using the proposed methodology.

Table 3. Sustainability score at groundwater wells for domestic usage

	Domestic														
Parameters	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
TDS	1.000	1.000	0.873	1.000	1.000	0.620	1.000	1.000	0.999	0.645	1.000	0.000	1.000	1.000	0.000
pH	0.750	0.000	0.250	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.250	1.000	1.000	1.000	1.000
TH	0.479	0.770	1.000	1.000	0.286	1.000	0.378	1.000	0.638	0.194	1.000	0.000	1.000	1.000	0.382
NO^{-}_{3}	1.000	1.000	0.951	0.988	0.962	0.430	0.222	1.000	0.917	0.430	0.836	0.000	0.955	1.000	0.585
F	0.680	0.200	0.488	0.200	0.760	1.000	0.680	0.488	0.341	0.680	0.780	0.920	0.680	0.240	0.360
Final Score	0.644	0.250	0.490	0.500	0.587	0.750	0.500	0.869	0.618	0.500	0.500	0.075	0.907	0.500	0.084

As, it can be seen from Figure 4(a) that well no. 13 (W13) located at Lakhsar secures rank 1 with the highest measure of sustainability i.e. 90.7% corresponding to domestic purposes. This is because data values of all water quality parameters lie in the permissible range of the Target values with TDS, pH, TH and NO_3 having excellent as their linguistic variable and F has acceptable value. However well no. 12 located at Ladhariya has the least measure of sustainability 7.5 % as most of the important water quality parameters are below permissible range. As far as utilization of these wells for domestic and irrigation purposes is concerned, the wells having sustainability of 50 % or above are considered as best. On the basis of the scores, only 40 percent of the wells are considered best for domestic usages. This gives systematic information to the planners to decide which well's quality is best to be used for household purposes and what all measures or policies should be obtained to improve the sustainability of the wells securing low ranks. Similarly, from Table 4 and Figure 4(b) it can be inferred that well no. 14 (W14) located at Punrasa secures rank 1 with the highest measure of sustainability i.e. 92.5% corresponding to irrigation purpose as observed values of all water quality parameters lie within the permissible limit of the target values. However well no. 6 located at Dholiya has the least measure of sustainability with a sustainability score of just 7.5 % due to the fact that most of the important water quality parameters are below the permissible limit. Only, 33 percent of the wells are considered best for irrigation. Hence, more than 50 percent of the groundwater wells of this region are unfit for both drinking and irrigation. The results indicate that groundwater of this region needs immediate attention from the controlling agencies.

Table 4. Sustainability score at groundwater wells for irrigation usage

	Irrigation														
Parameters	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
E.C.	1.000	1.000	0.579	1.000	0.972	0.193	1.000	0.789	0.649	1.000	0.877	0.000	0.772	0.965	1.000
pH	0.750	0.000	0.250	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.250	1.000	1.000	1.000	1.000
Na^{+}	0.892	0.856	0.406	0.923	0.750	0.000	0.829	0.622	0.622	0.924	0.748	0.935	0.608	0.803	0.954
Ca^{+2}	0.553	0.682	1.000	0.000	0.000	1.000	0.273	1.000	1.000	0.350	0.814	1.000	1.000	1.000	0.355
Cl^{-}	0.956	0.888	0.364	0.956	0.956	0.000	0.938	0.609	0.508	1.000	0.869	0.383	0.605	0.753	1.000
HCO^{-}_{3}	0.781	0.808	0.687	0.888	0.202	0.800	0.630	0.247	0.908	0.681	1.000	0.380	1.000	0.941	0.861
Final Score	0.925	0.471	0.250	0.500	0.500	0.075	0.500	0.500	0.832	0.603	0.500	0.084	0.500	0.925	0.612

5. Conclusions

In this paper, measures of groundwater sustainability in terms of water quality parameters have been derived for two primary beneficial uses namely domestic and irrigation. The crisp values of groundwater sustainability have been evaluated using MATLAB based fuzzy logic tool box. Overall sustainability of all the wells under study is computed using five water quality parameters for domestic usage and six water quality parameters for irrigation purpose. The fuzzy inference rules are developed using MATLAB by fuzzy AND, OR, and IF–THEN operators. The rules are linguistic and express the interdependencies amongst the essential parameters determined for measuring sustainability of a particular groundwater well. To manage issues concerning maximizing sustainability on a small scale like farming in a particular piece of land might be simpler, however, when the scale of assessment goes up to regional level as in this study, management of sustainability becomes difficult and confusing. Consequently, politicians, decision makers and implementation agencies need a systemic tool to deal with sustainability. In this regard, the fuzzy approach provides best quantitative answers pertaining to sustainability. The mathematical model developed in this paper is flexible and accommodative in the sense that it allows inclusion, elimination or modification of parameters according to their degree of impact on the final result. It also gives room to the operators to build different fuzzy rules and choose crucial sustainability parameters depending on their interests and condition of the system. It is emphatic to note that the computer version of this model is interactive and the user is able to adjust the inputs of the model according to the data at hand. This flexibility of the model is one of its advantages over other existing static methods. The number of parameters used to evaluate each linguistic variable of sustainability of a particular beneficial usage may be changed according to need.

The approach presented in this paper has very essential scope, as it can be used to predict the percentage measure of sustainability for generations ahead. For example, if we have data values of the essential parameters for next ten years, then the data values can be predicted for coming twenty years with the help of tools like artificial neural networks. And thus using those values, one can predict the sustainability measure in percentage for next twenty years. The model proposed in this paper exhibits three essential characteristics. First, it allows the combination of various aspects of sustainability with different units of measurement with the help of normalizing technique. Second, the methodology being flexible is easy to use and interpret. Third, it can predict the sustainability in mathematical terms. Therefore, the model has the potential to become a practical tool to policy-makers, treatment agencies and scientists involved in the field of sustainability measurement.

References

Ayres, R.U., 1996. Statistical measures of sustainability. Ecol. Econ. 16, 236–255.

Brink, B.J.E.T., 1991. The AMOEBA approach as a useful tool for establishing sustainable development. In: Kuik, O., Verbruggen, H. (Eds.), In Search of Indicators of Sustainable Development. Kluwer Academic Publishers, The Netherlands, p. 126.

CGWB, 2009, Groundwater scenario. Central Ground Water Board, Bikaner, Rajasthan.

Hinterberger, F., Luks, F., Schmidt-Bleek, F., 1997. Material flows vs. ‘natural capital’: what makes an economy sustainable. Eco. Eco. 23, 1–14.

Phillis, Y.A., and Andriantiatsaholiniaina, L.A., 2001. Sustainability: an ill-defined concept and its assessment using fuzzy logic. Ecological Economics 37, 435-456.

Rathore M.S., 2005. Groundwater exploration and augmentation efforts in Rajasthan, Institute of Development Studies, Jaipur.

Singh, A. P., Srinivas, R., Kumar, S. and Chakrabarti S. (in press). Water quality assessment of a river basin under Fuzzy Multi-Criteria Framework. Int. J. Water.

Singh, A.P., Ghosh, S.K., 1999. Water Quality Index of River Yamuna. Pollution Research; 18(4): 435-439.

Singh, A.P., Ghosh, S.K., Sharma, P., 2007. Water quality management of a stretch of river Yamuna: An interactive fuzzy multi-objective approach. Water Resour Manage; 21: 515–532. doi 10.1007/s11269-006-9028-0.

Singh, Dhirendra Kumar, and Anil Kumar Singh. Groundwater situation in India: Problems and perspective. International Journal of Water Resources Development 18.4 (2002): 563-580.

Srinivas Y, Hudson Oliver D, Stanley Raj A, Chandrasekar N (2013). Evaluation of groundwater quality in and around Nagercoil town, Tamil Nadu, India: an integrated geochemical and GIS approach. Appl Water Sci 3:631–651

Swarna Latha P, Nageswara Rao K (2012) An integrated approach to assess the quality of groundwater in a coastal aquifer of Andhra Pradesh, India. J Environ Earth Sci 66:2143–2169.

Tatawat, R.K., and Chandel, C.P.S. Hydrochemical, 2007.Investigations and correlation-Analysis of ground water quality of Jaipur city, Rajasthan (India). Journal of environ. Science and Engg. Vol. 49, No. 3, pp. 229-234.

The MathWorks Inc., 2012. Fuzzy Logic Toolbox User’s Guide. 24 Prime Parkway, Natick, MA 01760-1520; http://www.mathworks.com.

Tietenberg, T., 1984. Environmental and Natural Resource Economics. Scott Foresman, Glenview.

Zimmermann, H.J., 1991. Fuzzy Set Theory and Its Applications. Kluwer, Boston, p. 399.