Validation of Groundwater Quality Index and Proposing a Model Using Fuzzy Logic

Neha Mumtaz, Tabish Izhar, and Arshad Abbas

Abstract— **Water is the vital basis of human sustenance. Being the ultimate solvent, water carries numerous dissolved chemicals. Since groundwater travels through various layers of geological strata the probability of contamination increases resulting in the change in the water quality index. Groundwater samples were collected in the present research from commercial, residential, and industrial zones. Amongst all collected samples pH, TDS, TA, TH, Cl, SO_4, Fe, and NO_3 were determined as per IS-3025. Based on these values, the index of water quality was determined and compared with the standard. Collected samples displayed significant variations and by applying fuzzy logic, a groundwater quality model was developed which can predict the water quality status of the future and suggest optimal water management strategies.**

Index Terms— **Fuzzy Logic, Groundwater, MATLAB, Modelling, Water Quality Index**

I. Introduction

GROUNDWATER is the second largest available reservoir of freshwater [1]. Groundwater accounts for 97% of worldwide freshwater supplies and is widely extracted worldwide. The bulk of the freshwater accessible on and within Earth is trapped as ice in the polar ice caps, continental ice sheets, and glaciers. Surface waters such as rivers and lakes only account for less than 1% of the world's freshwater reserves whereas groundwater accounts for 12% of the world's freshwater resources. Unfortunately, its indiscriminate extraction and booming contamination pose a significant danger to the world's water supply.[2]

In India, groundwater is one of the most important water resources and accounts for 63% of all irrigation and over 80% of the rural and urban domestic water supplies. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Water Development Report states that India is the largest extractor of groundwater in the world. Fifty-four percent of India's groundwater wells have declined over the past seven years, and 21 major cities are expected to run out of groundwater by 2020. Therefore, India faces a dual challenge, the first to regulate the growing demand for groundwater and the second to replenish its resources at the same time. Lucknow which is the capital of Uttar Pradesh, India, and particularly known for its culture and patronage to art and literature spreads over an area of 2528 sq. km on both sides of river Gomati [3]. It is a part of Central Ganga Plain in the state of Uttar Pradesh and lies between North latitudes 26°30' and 27°10' and East longitudes 80°30'and 81°13'. Administratively the Lucknow district has been divided into 4 tehsils and 8 community development blocks [4]. According to the Central Ground Water Board [5], the elevation of the district varies between 103 and 130 meters above mean sea level showing a southeasterly slope. The drainage of the district is controlled by the river Gomati, Sai its tributaries. Surface water and groundwater are the main sources of irrigation in the district. The length of the canal in the district is 962 kilometers. The Gross irrigated area is 126607 hectares out of which 28149 hectares (22.23%) are irrigated through groundwater (77.77%) utilizing deep tube wells, shallow tube wells, private tube wells borings, etc. About 90% of the net cultivated area in the district has assured irrigation facilities while the irrigation intensity is 144.25%.

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II. Experimental Protocol

A. Study area and sampling

Groundwater quality is significantly influenced by aquifer properties and anthropogenic factors, and biogeochemical parameters play a major role [6]. In this study, the assessment of groundwater quality of different areas in Lucknow city was undertaken. Groundwater samples from areas particularly residential, commercial, and industrial were collected and tested for various groundwater quality parameters [7]. 27 water samples were collected 9 samples were collected from the residential area i.e. Aliganj. Similarly, 12 samples from the commercial i.e. Gomati Nagar, and six samples were collected from industrial area Amausi. During sampling, the notation Res 1- Res 9, Com 1-Com12, and Ind 1- Ind 6 denotes residential commercial and industrial zone respectively.

Aliganj (26.9041^0N, 80.9453^0E) was a residential area, now it has become a semi-commercial area. The groundwater table in this locality is falling at an alarming rate due to innumerable groundwater extraction activities. There are various localities in the residential areas where inhabitants are completely dependent on groundwater for their day-to-day activities. Various complexes and apartments have their tube wells, which make the situation of groundwater even worse. Gomtinagar (26.8623^0N, 81.0200^0E) is an area that comprises malls and marketplaces along with housing localities. The groundwater table is also depreciating in this area because of private tube-well construction. In addition to that, the quality of groundwater is also not up to the mark because of contaminants. Amausi (26.7653°N, 80.8904°E) is considered the industrial area of Lucknow city. The area comprises various industries like the pesticide industry, metal industry, steel, and allied industry, etc. These industries use groundwater for their various manufacturing processes and sometimes expel their effluents to groundwater. This causes toxic metal to enter the groundwater and thereby possess a threat to residents nearby as well as deteriorate the quality of groundwater.

B. Standards

The standard (IS 10500:2012) shown in table 1 below describes the acceptable, permissible limit and method of test of some essential parameters considered during the study.

TABLE 1
DRINKING WATER QUALITY STANDARDS (IS 10500:2012)

Characteristics	Acceptable limit	Permissible limit in the absence of alternate sources	Method of Testing (IS 3025)
Chloride (as Cl), mg/l	250	1000	Part 32
Colour, (Hazen unit)	5	15	Part 4
Fluoride (as F), mg/l	1	1.5	Part 60
Iron (as Fe), mg/l	0.3	No relaxation	Part 53
Nitrate (as NO_3), mg/l	45	No relaxation	Part 34
Odor	Agreeable	Agreeable	Part 5
pH value	6.5-8.5	No relaxation	Part 11
Sulfate (as SO_4), mg/l	200	400	Part 24
Taste	Agreeable	Agreeable	Part 7 & 8
Total alkalinity (as $CaCO_3$), mg/l	200	600	Part 23
Total dissolved solids, mg/l	500	2000	Part 16
Total hardness (as $CaCO_3$), mg/l	200	600	Part 21
Turbidity,(NTU)	1	5	Part 10

C. Bibliometric Analysis

40 documents were reviewed from 2012-2022 using Scopus library by searching (TITLE-ABS-KEY(groundwater AND quality AND index) AND TITLE-ABS-KEY (fuzzy AND logic)). The desktop version of Mendeley was utilized for reference management. VOSviewer version 1.6.16 was used to perform the bibliometric content analysis. The co-occurrence keyword threshold was taken as 30 shown in figure 1. It is evident from the overlay visualization that groundwater quality assessment using fuzzy logic in decision-making is having great potential.

III. Analytical Interpretation

Water quality index (WQI) is defined as the rating reflecting the composite influence of different water quality parameters that were taken into consideration for the calculation purpose [8]. It provides information about water quality in a single value. It is a widely used tool for detecting and assessing water contamination. WQI indices are broadly classified into two types; they are physicochemical and biological indices [9]. The physicochemical indices are based on the values of various physicochemical parameters in a water sample, while biological indices are derived from biological information. Based on hydro chemical data, an attempt has been made to determine the water quality index of the research region [10].

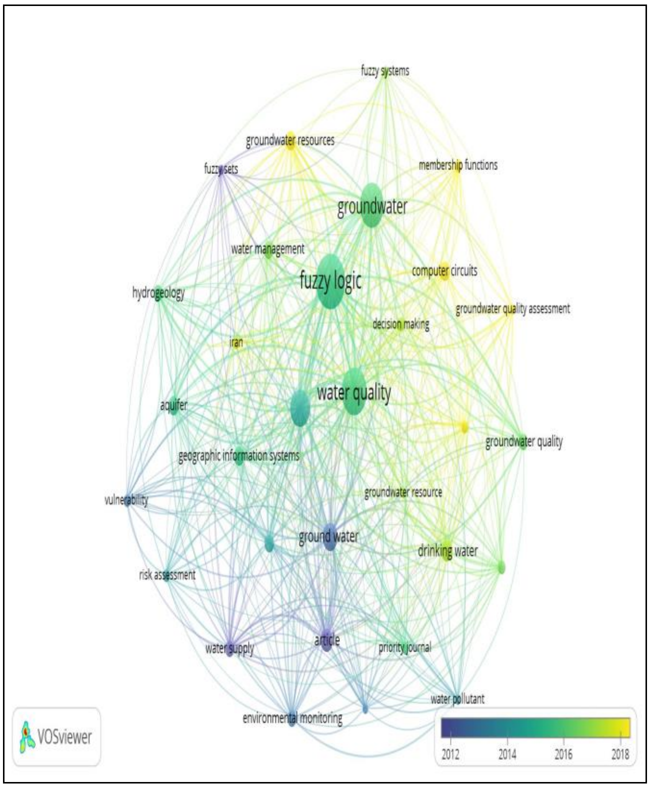

Fig 1: Bibliometric analysis overlay visualization

A. WQI Calculation

Calculation of water quality index [11] was estimated by Horton's method (1965) as follows:

$$WQI = \frac{\sum q_n W_n}{\sum W_n} \quad (1)$$

Where,
W_n = Unit weight of n^{th} water quality parameter.
q_n = Quality rating of n^{th} water quality parameter.

B. Quality rating (q_n)

Quality rating (q_n) was determined by means of the formula [12] given below:

$$q_n = \frac{V_n - V_{td}}{S_n - V_{td}} \times 100 \quad (2)$$

Where,
V_n = Estimated value of n^{th} water quality parameter at a given sample location
V_{id} = Ideal value for the n^{th} parameter in pure water.
(V_{id} for pH = 7 and 0 for all other parameters)
S_n = Standard permissible value of n^{th} water quality parameter.

C. Unit Weight (Wn)

Unit weight (W_n) is interpreted by applying the mathematical formula [13] given below:

$$W_n = \frac{K}{S_n} \qquad (3)$$

Where,
$K = [1 / (1 / S_{n=1,2.....n})]$
K = Constant of proportionality and it is calculated by using the expression
S_n = Standard permissible value of the n^{th} water quality parameter.

D. Standard Values and Unit Weights of Water Quality Parameters of the Study Area

The water quality indicators opted for had a direct impact on the deterioration of water quality for human consumption. The standards for the drinking water, recommended by the Indian Council of Medical Research (ICMR) and Indian Standards Institution (ISI) are considered for the computation of quality rating (qn) and unit weights (Wn).

For the calculation of WQI for the study area, eight water quality parameters have been selected. They have dissolved solids (TDS), pH, total alkalinity, total hardness, nitrate (NO_3), chloride (Cl), iron (Fe), and sulfate (SO_4). [14]

The values of these parameters are found high above the permissible limit in some of the samples of the study area. The higher value of these parameters would increase the WQI value. The standard values of water quality parameters and their corresponding ideal value and unit weights mention in table 2.

TABLE 2
STANDARD VALUES OF WATER QUALITY PARAMETERS AND THEIR CORRESPONDING IDEAL VALUES AND UNIT WEIGHTS.

Parameters	Standard Values (Sn)	Recommending Agency for Sn	Unit Weight (Wn)	Ideal Value
pH	6.5-8.5	IS	0.033647	7
Total dissolved solids (TDS)	500	IS	0.000572	0
Total alkalinity	120	ICMR	0.002383	0
Total hardness	300	ICMR	0.000953	0
Chloride	250	IS	0.001144	0
Sulfate	200	IS	0.00143	0
Iron	0.3	IS	0.953333	0
Nitrate	45	IS	0.006356	0

E. WQI AND STATUS:

As per the National Sanitation Foundation Water Quality Index (NSFWQI) [15], the range of WQI and their quality status along with their possible use are summarized below in table 3:

TABLE 3
WQI AND CORRESPONDING WATER QUALITY STATUS

WQI	Status	Possible Usages
0-25	Excellent	Drinking, Irrigation, and Industrial
26-50	Good	Domestic, Irrigation, and Industrial
51-75	Poor	Irrigation
76-100	Very Poor	Restricted use for Irrigation
Above 100	Unfit for Drinking (UFD)	Proper treatment required before use

The calculated water quality index (WQI) and status of the study area are mentioned in table 4.

TABLE 4
WATER QUALITY INDEX (WQI) AND STATUS

Location	Depth(m)	∑qn Wn	∑ Wn	WQI	WQI STATUS
Res 1	60.90	41.07	0.999818	41.07	Good
Res 2	54.87	104.29	0.999818	104.31	UFD
Res 3	53.00	72.91	0.999818	72.93	Poor
Res 4	61.24	91.97	0.999818	91.99	Very Poor
Res 5	53.28	52.99	0.999818	53.00	Poor
Res 6	52.91	36.92	0.999818	36.93	Good
Res 7	58.42	113.83	0.999818	113.85	UFD
Res 8	57.12	61.26	0.999818	61.27	Poor
Res 9	58.31	67.48	0.999818	67.49	Poor
Com 1	58.12	43.95	0.999818	43.96	Good
Com 2	59.30	82.34	0.999818	82.36	Very Poor
Com 3	61.14	56.54	0.999818	56.55	Poor
Com 4	62.92	63.06	0.999818	63.07	Poor
Com5	54.86	37.78	0.999818	37.79	Good
Com 6	59.00	66.25	0.999818	66.26	Poor
Com 7	65.10	104.20	0.999818	104.21	UFD
Com 8	62.32	69.89	0.999818	69.90	Poor
Com 9	60.14	85.69	0.999818	85.70	Very Poor
Com 10	65.29	104.93	0.999818	104.95	UFD
Com 11	63.21	95.90	0.999818	95.92	Very Poor
Com 12	62.10	82.18	0.999818	92.20	Very Poor
Ind 1	65.24	54.37	0.999818	54.38	Poor
Ind 2	63.49	93.20	0.999818	93.22	Very Poor
Ind 3	59.22	93.40	0.999818	93.42	Very Poor
Ind 4	60.10	101.34	0.999818	101.36	UFD
Ind 5	55.45	115.01	0.999818	115.03	UFD
Ind 6	59.21	95.87	0.999818	95.89	Very Poor

IV. RESULT AND DISCUSSION

The analysis of results is based on a comparison of the Water Quality Index (WQI) concerning its location, groundwater quality scaling for fuzzy logic, and graphical interpretation of surface viewer of fuzzy logic.

A. Water Quality Index (WQI) Vs Location

The following inferences drawn from the water quality index (WQI) Vs Location graph are mention as follows:

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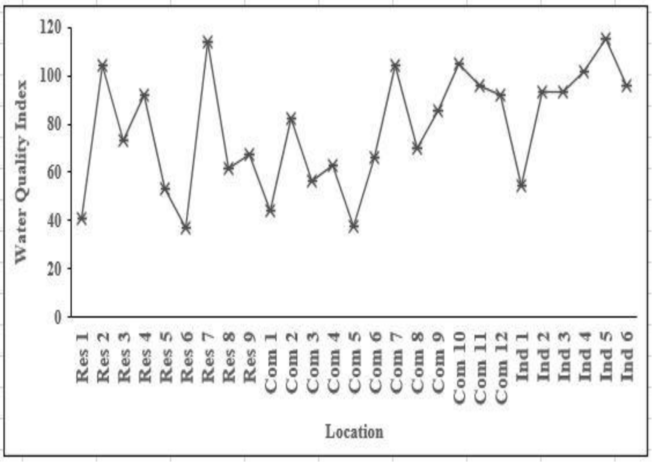

Fig 2 Variation in water quality index in residential, commercial, and industrial zones

The graph shows that the minimum water quality index (WQI) of residential area (Aliganj), commercial area (Gomti Nagar), and industrial area (Amausi) are of Res1 (26º54'28.3" N, 80º56'49.4" E) is 41.07, Com5 (26º50'52.1" N, 81º0'44.7" E) is 37.79 and Ind1 (26º45'50.6" N, 80º52'4.6" E) is 54.38 respectively.

The above mentioned WQI of Res1and Com5 belong to the good category of WQI status so groundwater from these locations can be used for domestic, irrigation, and industrial purposes whereas the WQI of Ind1 lies between the poor category of WQI status, therefore, water from this location can only be used for irrigation purposes.

The above-mentioned WQI belongs to the UFD (Unfit for drinking) category of the WQI status therefore groundwater from these locations requires proper treatment before use. Out of the 27-groundwater samples collected from the residential, commercial, and industrial areas of Lucknow city, only four belong to the good category of WQI status.

Therefore, it can be used for domestic, irrigation, and industrial purposes. From the groundwater samples of Lucknow city nine samples, WQI lies between poor categories of WQI status.

Hence, groundwater from these locations can only be used for irrigation purposes. Eight samples of WQI belong to the very poor category of WQI status. The groundwater from these locations is restricted for the use of irrigation. Six samples of WQI belong to the UFD (Unfit for drinking) category of WQI status. Therefore, proper treatment of the groundwater before use is required.

B. Groundwater Quality Scale for Fuzzy Logic

Groundwater consumption has risen dramatically in India as a result of fast population expansion, industrialization, and urbanization [16]. From the groundwater quality scale we can assess the following points of the fuzzy logic system [17] tabulated in table 5:

1. If the groundwater quality lies between 0-25, then the water quality is excellent and possesses no risk at all to the population concerned.
2. If the groundwater quality lies ranging from 26-50, then it is good and the quality is acceptable but possesses some health problems to the sensitive group of consumers.
3. If the groundwater quality lies ranging from 51–75, then the quality of water is harmful and the sensitive groups may be likely to experience some health problems.
4. If the groundwater quality lies ranging 76–100, then the water is very harmful and everyone in the community may experience some health problems.
5. If the groundwater quality lies above 100, then the water is hazardous to the community concerned and everybody can experience some severe health problems.

TABLE 5
GROUNDWATER QUALITY SCALE FOR FUZZY LOGIC

WQI	Status	
Above 100	150	Hazardous
76 - 100	100	Very Harmful
51 - 75	75, 50	Harmful
26 - 50	25	Good
0 - 25	0	Excellent

C. Surface Viewer of Fuzzy Logic System

The Surface viewer [18] is invoked using surf view ('a') is a GUI tool that generates a three-dimensional output surface where 8 of the inputs vary but two of the inputs must be held constant because computer monitor cannot display a five-dimensional shape mentioned in figure 3, 4, 5, and 6.

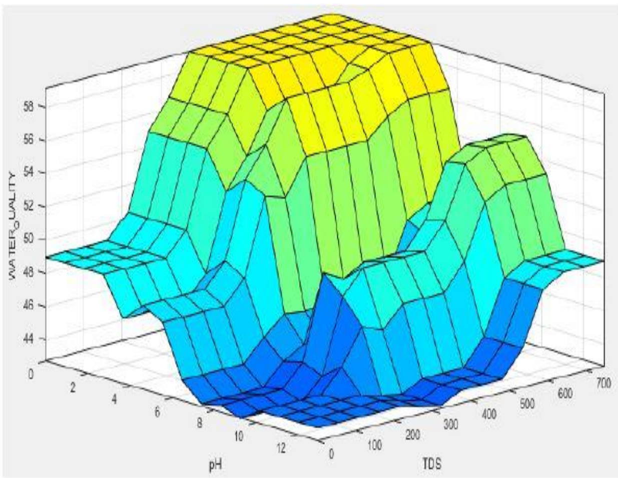

Fig 3. Case I (X-axis – pH; Y-axis – Water Quality; Z-axis – TDS)

The surf view image of the study area represents the fuzzy interface system design [19]. In case I, pH and TDS are the determining water quality variables. In case II, total alkalinity and pH are studied. In Case III, Total hardness and pH are determining factors of water quality. In case IV, total dissolved solids and total hardness are major variables against changing water quality.

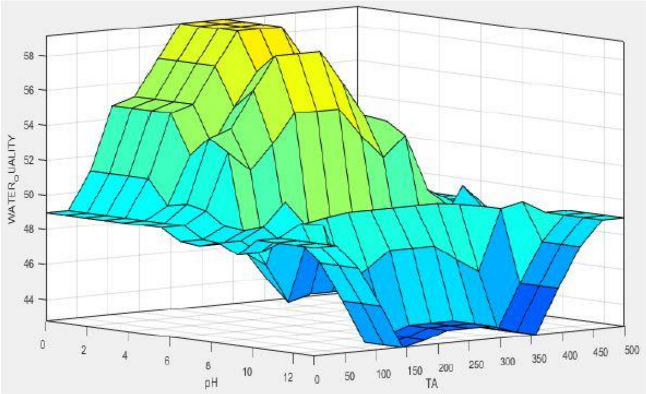

Fig 4 Case II (X-axis – pH; Y-axis – Water Quality; Z-axis – Total alkalinity)

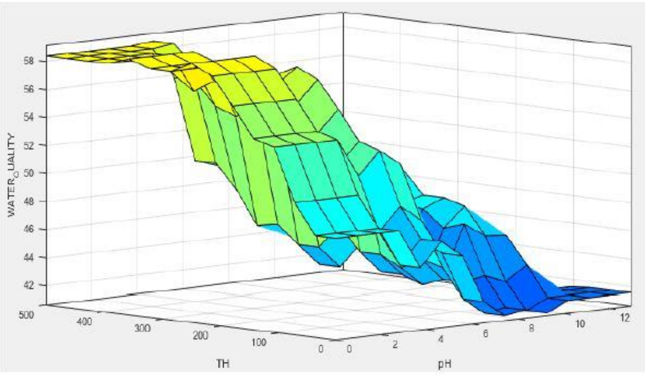

Fig 5. Case III (X-axis – Total hardness; Y-axis – Water Quality; Z-axis - pH)

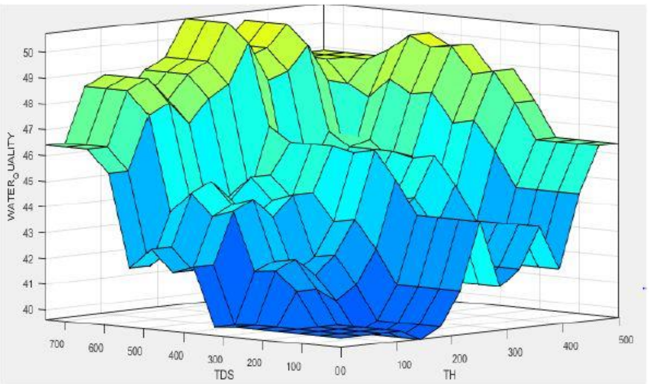

Fig 6. Case IV (X-axis – Total dissolved solids; Y-axis – Water Quality; Z-axis – Total hardness)

V. Conclusion

As the study was conducted by collecting 27 groundwater samples from the residential, commercial and industrial areas out of which none of the samples belong to the excellent category of the WQI status which means that groundwater contamination has already started and has reached its peak position in some of the areas. In all nine samples, WQI lies between the poor categories of the WQI status, which belong to the Aliganj (residential area) and Gomti Nagar (commercial area) in particular. This shows that groundwater quality in these areas is also being contaminated by the interference of groundwater pollutants from the activities such as improper sewage disposal, leachate problem. Out of the total groundwater sample collected, 8 samples WQI lie between the very poor category of the WQI status. The highest among these is from Amausi (industrial area). Here the main cause of groundwater pollution is due to improper disposal of effluents from the industries such as the pesticide industry, metal industry, and steel and allied industry. 6 samples of WQI lie between UFD (Unfit for Drinking). Out of which one is from aliganj, two from Gomti Nagar, and three from Amausi. This means that groundwater at these locations requires proper treatment for their domestic, irrigation, and industrial usage. The overall result indicates that most of the groundwater samples of Lucknow city taken in this study are not satisfactory and require treatment of one or the other form for their consumption and usage.

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