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Fuzzy Inference of Air Quality – A case study of Vadodara City

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ABSTRACT

Abstract: Air Quality Index (AQI) is derived from a series of observations of different air pollutants for reporting air quality. The severity of air pollution and its impacts on the general public are typically reported using the air quality index. Different methods have been developed by various regulatory agencies and scientists, to calculate the AQI using aggregation methods involving critical pollutants. This paper presents a comparison between conventional AQI and Fuzzy AQI. 20 sampling locations were chosen for Vadodara city in order to investigate the effects of urban air pollution, and ambient air quality was measured twice a week from October 2017 to February 2018. The Central Pollution Control Board (CPCB) method formulas were used to calculate the traditional Air Quality Index using the measured values of Coarse particulate matter (PM_{10}), Sulphur dioxide (SO_2), and Oxides of nitrogen (NO_X). Additionally, the membership functions were provided as input to the Mamdani fuzzy inference system (FIS) for the fuzzy logic system, and the fuzzy air quality index (FAQI) was calculated. The computed conventional AQI values were compared with FAQI values. A close co-relation was observed between conventional AQI and fuzzy AQI values. The application of the fuzzy inference system demonstrates its capability to manage difficult issues including data ambiguity. The findings clearly show that the FIS is capable of resolving inherent discrepancies and interpreting complex conditions.

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INTRODUCTION

Air pollution is a worldwide issue that is directly or indirectly related to human health. Various studies have indicated severe health effects resulting from higher levels of ambient air pollutants. Studies also suggest a consistent link between various respiratory, cardiovascular, and lung diseases with continual exposure to critical air pollutants (Kumar & Sharma, 2012). The problem of air pollution further worsens with the growing population, urbanization, and industrialization (Balashanmugam et al., 2012). Total suspended particulates (TSP), respiratory suspended particulate matter (RSPM), carbon monoxide (CO), sulphur dioxide (SO_2), and nitrogen dioxide (NO_x) are examples of general air pollutants, and particulates can include dust, pollen, smoke, etc (Gorai, 2012; Saini et al., 2022). Among the various air pollutants resulting from various sources, PM_{10}, SO_2, and NO_x are assumed to play a significant role in deteriorating air quality and thereby affecting human health (Balashanmugam et al., 2012). Hence, these three parameters were considered for calculating AQI for this particular study.

Globally, many cities have developed air quality networks, to constantly assess, quantify and record air pollutant concentrations. However, this simple environmental data at times is not adequate to evaluate the severity of air pollution. Additional information regarding critical levels of pollutants and potential health risks they may cause is also required. To ensure that

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the general public can understand all of this information, it is crucial to offer it in an easy-to-understand format like AQI. Air pollution indices fulfill this important need by giving a composite, single value to the overall air pollution as a single entity. This simple method of expressing pollution concentration levels is termed as Air Quality Index.

AQI combines the weighted values of several air pollutants into a distinct number that may be extensively disseminated to the public and utilised in decision-making. The fundamental goal of any air quality index is to use an acceptable aggregate approach to translate the measured air pollutant concentrations into a single numerical value. Thus, the air quality index reveals the measured pollutant concentrations in addition to the air quality perceived by the general public, for the time period it covers (Dunea et al., 2011). Hence, it can be inferred that air quality indices try to convert the air pollution data to a standard form so that they can be compared and interpreted for necessary decision-making and pollution control strategies.

Fuzzy logic is considered to be apt for solving real-life problems, with some degree of uncertainty (Lokeshappa & Kamath, 2016; Kumaravel & Vallinayagam, 2012). It uses different forms of linguistic variables like true, false, high, medium, and low (Upadhyaya & Dashore, 2010). In fuzzy theory, data sets primarily consist of inference rules and membership functions for the variables (Swarna & Nirmala, 2017). The fuzzy algorithm forms the basis of the fuzzy logic system. The basic theories of fuzzy logic were proposed by Zadeh et al, 2010. Fuzzy system application considers two inference systems namely the Mamdani system and the Sugeno system (Yadav et al., 2011; Nagendra et al., 2007).

Fuzzy set theory is one of the computational methods applied nowadays to predict air quality in cities or rural areas (Juned & Hemang, 2014; Chaudhary et al., 2013). In order to attend to real-life problems that encompass a certain degree of uncertainty, a tool like fuzzy logic is effective (Charan & Sahel, 2014). In place of usual variables, fuzzy logic employs variables like high, medium, low, etc (Chaurasia et al., 2013). In fuzzy logic, the datasets are described in terms of membership functions (Yadav et al., 2012). An explanation of the relationship between each point in the input space and a membership value between 0 and 1 is provided by a membership function (Upadhyay et al, 2014; Aggarwal et al, 2017). The prime hypothesis of a fuzzy system is a fuzzy algorithm, derived from the vital perceptions founded on fuzzy logic (Katushabe et al, 2021). The core of the fuzzy system is a straightforward rule-based system, where the knowledge encoded in the rules is derived from human experience and observation (Uthayakumar et al., 2021). The resulting rules thus show a logical connection between the inputs and outputs of the system. The fuzzifier, rule base, inference engine, and defuzzifier are the four fundamental parts of a fuzzy system (Shaffi et al., 2021; Ganesh et al., 2017; Mishra & Goyal, 2015; Javid et al., 2016)

For this particular study, Vadodara city in central Gujarat, which is a hub of petrochemicals and other integrated industries, has been taken as a case study. Mamdani inference system is used, with SO_2, NO_X, and PM_{10} as input variables and fuzzy air quality index having crisp value as output.

MATERIALS AND METHODS

Gujarat is the fifth largest Indian state located on western coast of India. The central and eastern regions of Gujarat contain Vadodara city, that is located between latitude 22° 17' N and longitude 73° 15' E with an area of 420 square kilometres. Due to urban expansion, several previously residential neighbourhoods were transformed into commercial and industrial districts, posing a major risk of air pollution to the local residents.

The study area's geography, as well as the direction and speed of the wind, were taken into consideration while choosing the monitoring sites. The North-East wind direction was found to be the dominating wind direction during the study period from October 2017 to February 2018.

The current study is limited to the winter season because in the study area, winter is considered as worst climate scenario since dispersion of air pollutants is limited in winter season. The air quality was monitored at twenty locations as shown in Figure-1 and Table 1. The locations were identified in different parts of the city to cover the entire city area. Both the core of the city and the peripheral areas were included to give an adequate representation of all types of areas, including residential, rural, commercial, and industrial.

The sampling of various pollutants like PM_{10}, SO_2, and NO_x was carried out continuously for 24 hours using a high volume sampler and respirable dust sampler for two days in one week. The sample collection and analysis were carried out as per National Ambient Air Quality Standard methods for sampling and analysis suggested by CPCB. The particulate matter PM_{10} was found by using the gravimetric method. In this method, the air was passed through a glass fibre filter paper, for 8 or 24 hours. Gaseous pollutants, SO_2 and NO_x were collected in an absorbing solution for 4 hours using an airflow rate of 1 lit per minute. SO_2 was analysed by using the West and Geake method and NO_x was analysed by using the Jacob and Hochheiser

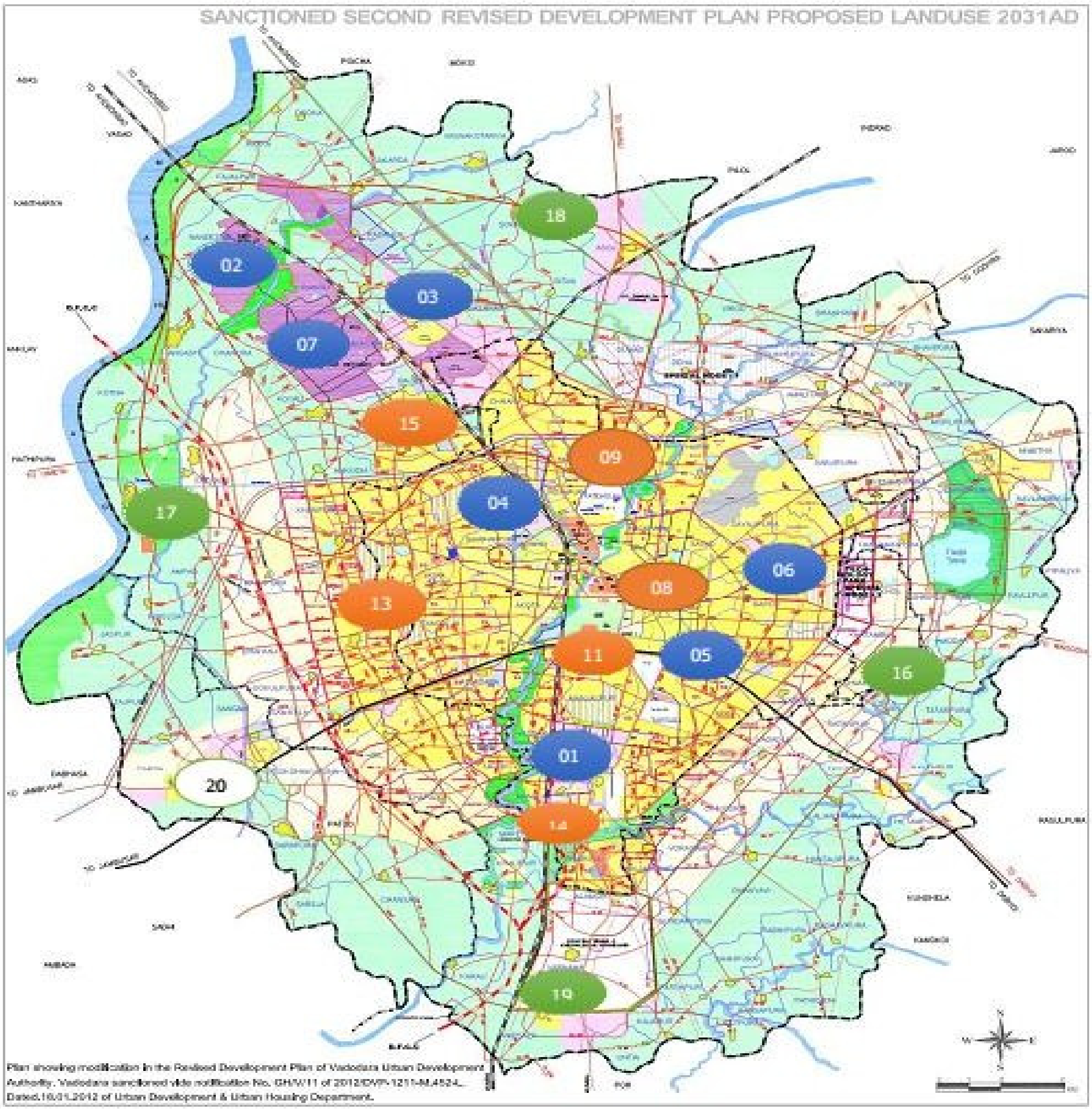

Fig. 1. Study area showing monitoring locations

Table 1. Location of monitoring stations

Station Number	Area	Location	Area details
AQ1	Industrial	GIDC Makarpura,	Engineering
AQ2		GIDC Nandesari,	Chemical
AQ3		GIDC Ranoli	Mixed
AQ4		BIDC Gorwa	Small scale
AQ5		Patel Estate, Wadi	Small scale
AQ6		Sardar Estate, Ajwa Rd	Small scale
AQ7		PCC	Petrochemicals
AQ8	Residential	Old City	Densely populated area
AQ9		Nizampura	Pure residential area
AQ10		Waghodia Road	Residential area
AQ11		Manjalpur	Residential area
AQ12		Kishanwadi	Slum Area
AQ13		Vasna-Gotri	Developing area
AQ14		Maneja	Mixed area
AQ15		Bajwa	Semi-urban
AQ16		Khatamba	East Region
AQ17		Sindhrot	West Region
AQ18	Rural	Sokhda	North region
AQ19		Varnama	South region
AQ20	Other	Padra Town	Mixed

method.

An AQI is primarily created through two steps: (i) Creation of sub-indices (for each pollutant) and (ii) Combining of sub-indices to produce an overall AQI.

Step:1 The sub-index of the individual pollutant was calculated using equation 1, shown below (Nihalani & Kadam, 2019; Nihalani et al., 2020; Pankaj et al., 2010; Saddek et al., 2014; Zadeh, 2010). The sub-index is calculated on the basis of the dose-response relationship of various pollutants, termed as breakpoint concentrations shown in Table 2.

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo} \tag{1}$$

Where I_P = Pollutant sub-index for P
C_P = concentration for pollutant P as measured
BP_{Hi}= higher breakpoint concentration for P
BP_{Lo} = lower breakpoint concentration for P
I_{Hi} = AQI corresponding to BP_{Hi}
I_{Lo} = AQI corresponding to BP_{Lo}

For example For PM_{10} reading coming at a concentration of 145 µg/m³. With reference to

Table 2. AQI values and Break-Point Concentrations

AQI value	Category	SO_2	NO_x	CO	O_3	PM_{10}
0-100	Good	0-80	0-80	0-2	0-180	0-100
101-200	**Moderate**	**81-367**	**81-100**	**2.1-12**	**180-225**	**101-150**
201-300	Poor	368-786	181-564	12.1 – 17	225-300	151-350
301-400	Very Poor	787-1572	565-1272	17.1 – 35	301-800	351-420
401-500	Severe	>1572	>1272	>35	>800	>420

Source: CPCB website

Table 3. Health effects with respect to AQI

Index Values	Color	Descriptor
0-50	Green	Good
51-100	Yellow	Moderate
101-150	Orange	Unhealthy for Sensitive Groups
151-200	Red	Unhealthy
201-300	Purple	Very Unhealthy
301-500	Maroon	Hazardous

Source: CPCB website

row2, PM_{10}, falls in the range 101-150, so higher breakpoint concentration BP_{Hi} = 150 and BP_{Lo} = 101, I_{Hi} = 200 and I_{Lo} = 101, C_p = 145. Hence, the sub index for PM_{10} would be = [{(200-101)/(150-101)} (145-101)] + 101 = 189.89. The sub-index function shows the correlation between the sub-index I_p and the pollutant concentration C_p. As the concentration of a particular pollutant changes, the sub-index I_p aims to reflect its effects on the environment.

Step:2 For any location, Air Quality Index (AQI) is determined by taking the highest individual pollutant index, or IP, out of all the detected pollutants. For this particular study, concentrations were measured for PM_{10}, SO_2, and NO_x at various sampling locations. For instance, if the sub-index of PM_{10} =189.89, SO_2 = 98, NO_x =56 then the AQI will be 189.89 which is the same as the value of the sub index of PM_{10}. Similarly, AQI for all the 20 locations was calculated using the sub-index for parameters PM_{10}, SO_2, and NO_x

In the case of India, AQI is considered to be in the range between 0 and 500. AQI having a higher value indicates elevated air pollution and points towards significant health problems (Sarella & Khambete, 2015). Table 3 presents various AQI ranges along with their consequent health effects. Based on the potential health effect caused by various pollutants, the resulting air quality is termed as clean, moderate, poor, very poor, and severe.

In this study, the air quality index has been determined using fuzzy logic formalism, and comparisons with the conventional technique have been conducted. At 20 locations throughout the city, samples of the city's air pollution levels have been taken. Determinant membership functions and fuzzy rule bases were defined. Based on the Mamdani fuzzy inference method, the model was assessed using Vadodara's air pollution monitoring data. The following steps make up the process of creating the fuzzy model to predict the air quality index:

Step I: Determining the variables in the system

Identifying the system's input and output variables is the first and most crucial stage in modeling. The connections between them will define the model's goal. The Mamdani inference system can generally be used to depict the interactions between several input parameters like PM_{10}, SO_2, NO_x, and an output parameter (FAQI). One such system is the current model depicted in Figure 2 with input and output variables. This connection between inputs and outputs can be stated quantitatively as FAQI = f (PM_{10}, SO_2, NO_x)

Step II: Identifying the ranges of the input and output variables

Finding the range of input and output variables is the second step. These variables are classified as linguistic variables in fuzzy modeling, and their linguistic values are words or phrases in a real or artificial language. The language variables, their linguistic values, and the corresponding fuzzy intervals are displayed in figure 2

Step III: Choosing membership functions for inputs and output variables

This stage involves expressing linguistic values as fuzzy sets, that are represented by the membership functions. The expert defining these membership functions should take into account the degree of overlap and the structure of fuzzy sets for each input variable. Due to its computing efficiency and ease of utility, the trapezoidal membership function has been utilised. National air quality standards (NAAQS) for India served as the foundation for fuzzy set ranges.

Step IV: Development of the linguistic rules

Finally, IF-THEN rules are used to illustrate the connections between inputs and outputs. Figure 3 displays a set of rules for illustrative purposes. The Fuzzy Logic Toolbox of MATLAB7 has been used to develop the prediction model for the Air Quality Index (AQI), which is expressed as a set of straightforward IF-THEN rules (Mandal et al., 2012).

Step V: Defuzzification and fuzzy inference

Defuzzification is the process of replacing a fuzzy set with a single numerical value that best represents the set. In this investigation, the centroid defuzzification method was applied.

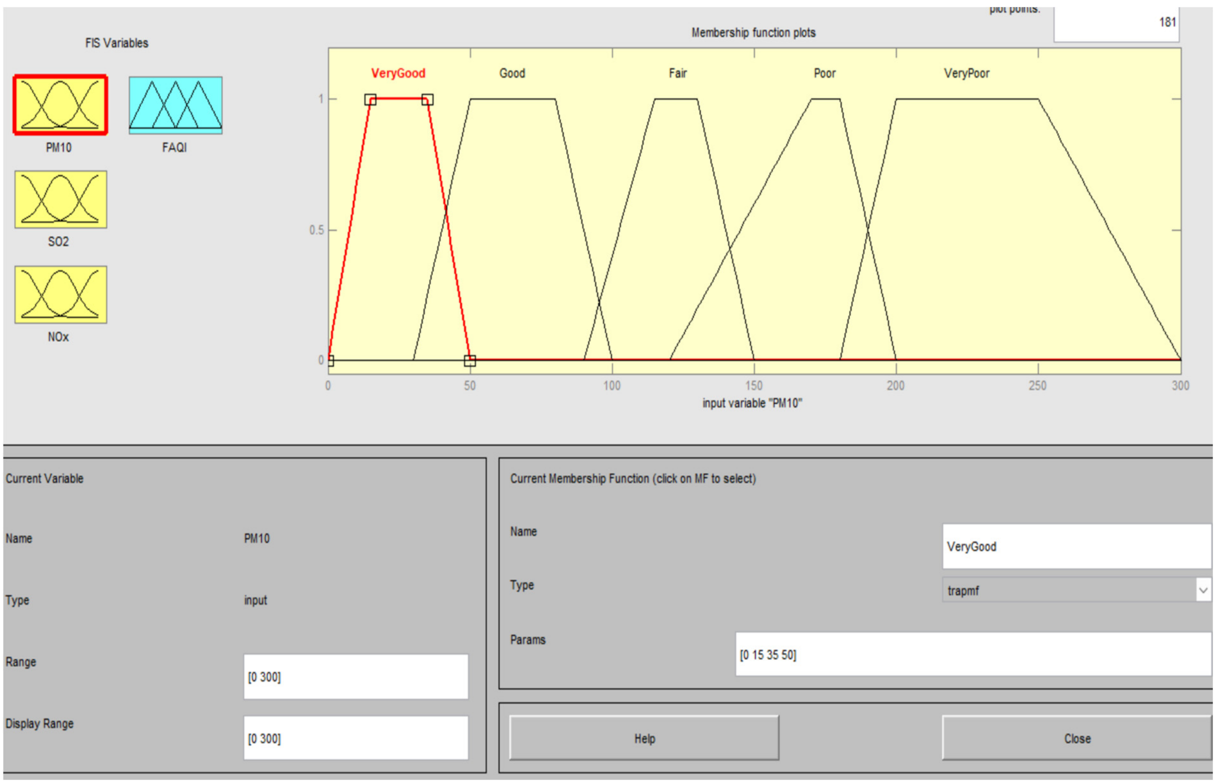

Fig. 2. Linguistic variables for input and output

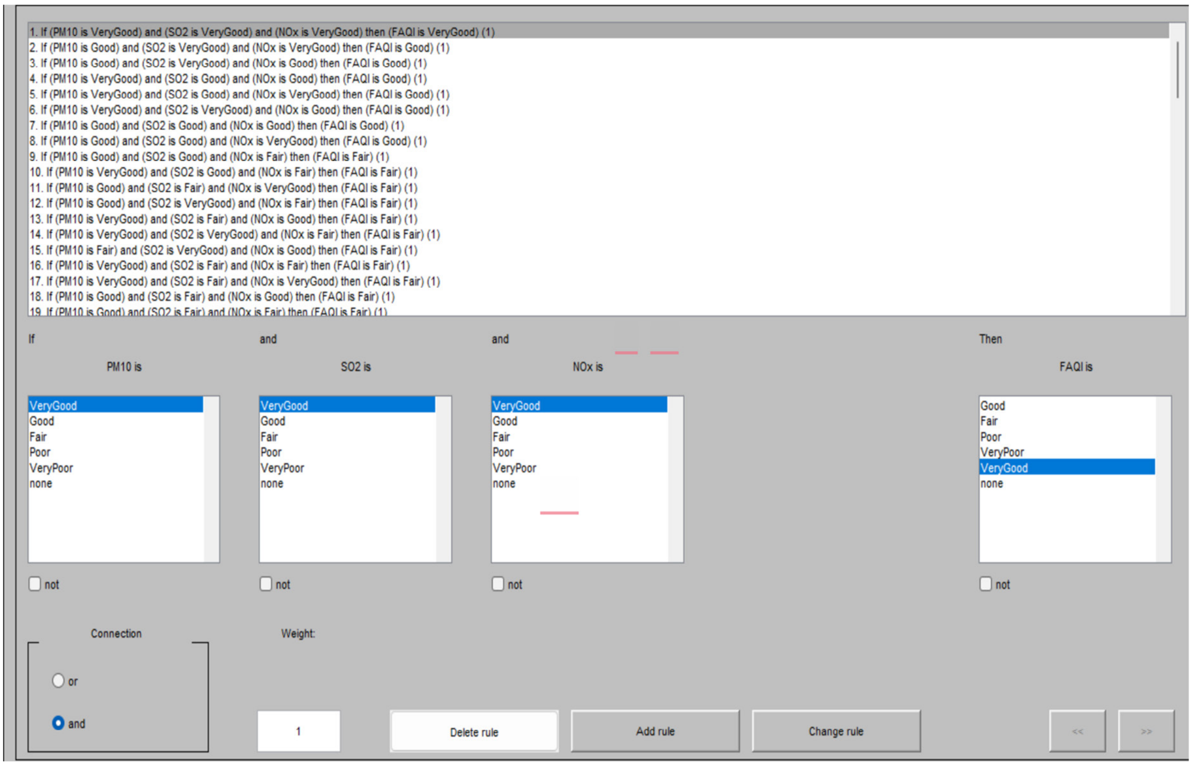

Fig. 3. Fuzzy inference rules

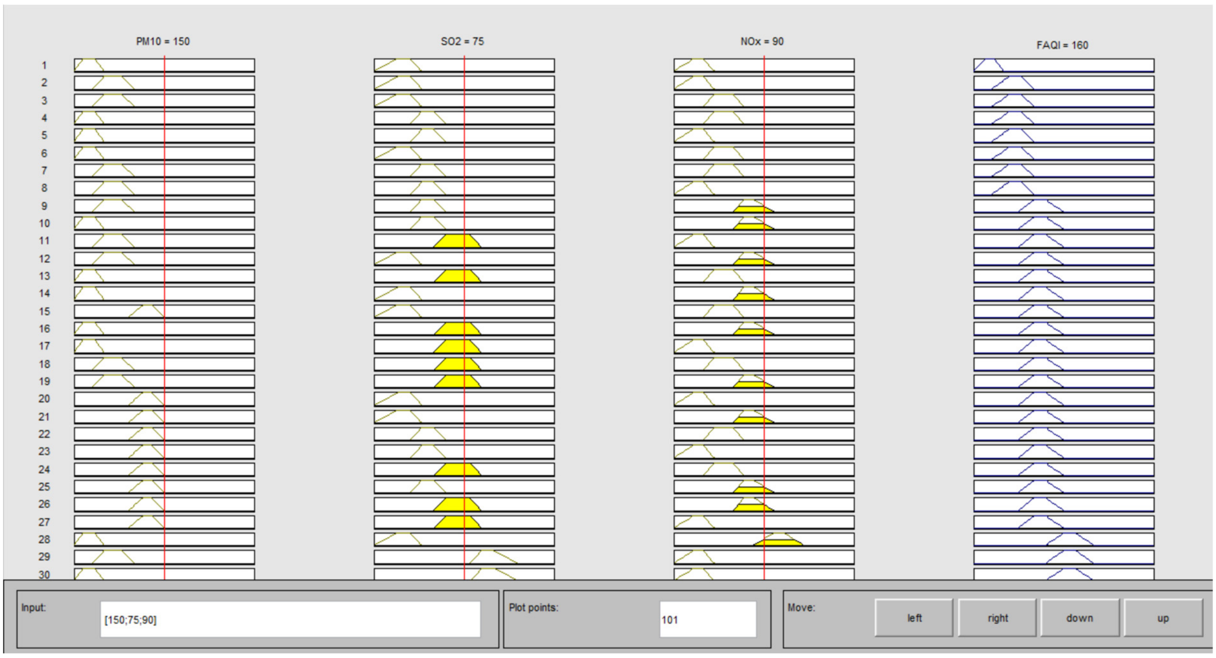

Fig. 4. Rule Viewer and Output for AQI

Based on this, all the sample findings were assessed. Figure 4 depicts the rule representation and output models. According to the rule basis, when the average concentrations of the various air pollutants are 150, 75, and 90 µg/m3, respectively, for PM_{10}, SO2, and NO_x the FAQI is observed to be around 160.

As a function of PM_{10}, SO_2, and NO_x, FAQI in the model has been calculated. Mamdani inference method was used to implement the model. The model explicitly shows that as PM_{10} rises, the FAQI follows suit. The air quality index scale is therefore reducing, meaning that a higher value of the AQI implies poor air quality in the location and vice versa. Similar to this, it is possible to explain the prediction model for FAQI using various combinations of inputs and related default variables.

RESULTS AND DISCUSSIONS

The concentration of various pollutants as measured in the study area is illustrated in Figure-5. The mean PM_{10} concentration ranged between 66 to 177 µg/m^3. The highest concentration of PM_{10} was observed at location 8, old city area, and the lowest concentration was observed as 66 µg/m^3 at location 15, Khatamba. The concentration of PM_{10} at all the locations except locations 15 (Bajwa), 16 (Khatamba), 17 (Sindhrot), and 20 (Padra) is observed to exceed the NAAQS standard of 100 µg/m^3. The average SO_2 concentration in the study area was determined to be between 9-26 µg/m^3. The highest concentration of SO_2 was observed to be 26.2 µg/m^3 at location 6, Sardar estate, and the lowest concentration of 8.5 µg/m^3 was observed at location 16 (Khatamba).

The average NO_x concentration in the study area was determined to be between 20 to 44 µg/m^3. The highest concentration of NO_x was 43.9 µg/m^3 at location2 (GIDC) and the lowest concentration was 19.9 µg/m^3 at location 17 (Sindhrot). The values of SO_2 and NO_x at all 20 locations were much lower than the NAAQS standard of 80 µg/m^3 for both SO2 and NOx.

Using the ambient air quality concentrations of PM_{10}, SO_2, and NO_x, the values of AQI have been computed using the CPCB method. The AQI values for the study area are shown in Figure 6. The bar with green colour shows AQI less than 50 and in the good range. The bars with colour yellow depict AQI less than 100 and in moderately polluted range whereas bars with the colour orange represent AQI in the range unhealthy for sensitive groups. The goal of the current study is to calculate air pollution concentrations for different locations in Vadodara. AQI index is highest showing a value of 130, at location 8 (Old City area) owing to congestion. The lowest

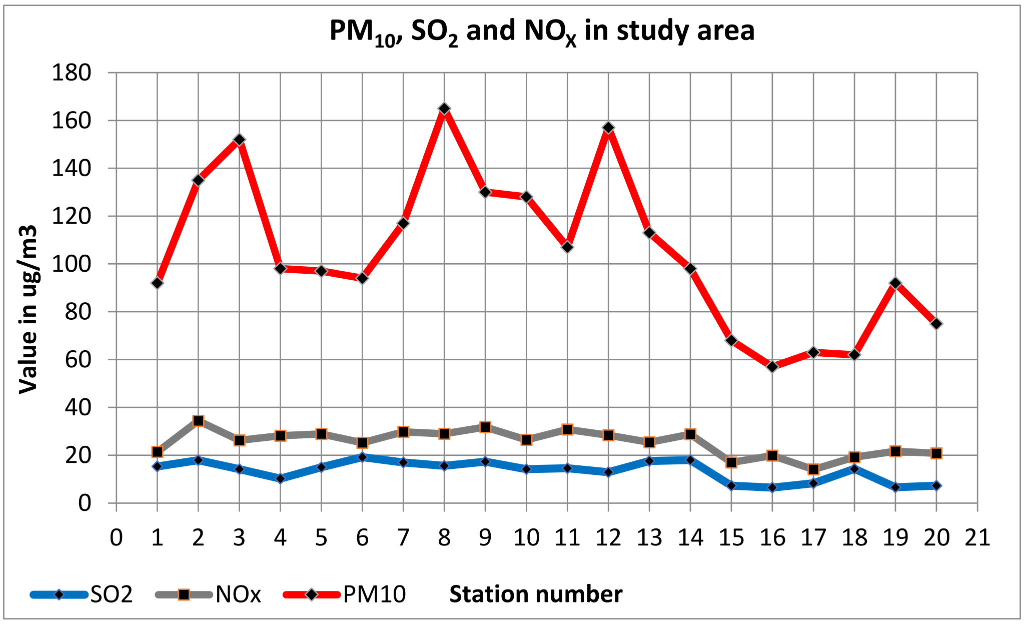

Fig. 5. PM_{10}, SO_2, NO_x in the study area

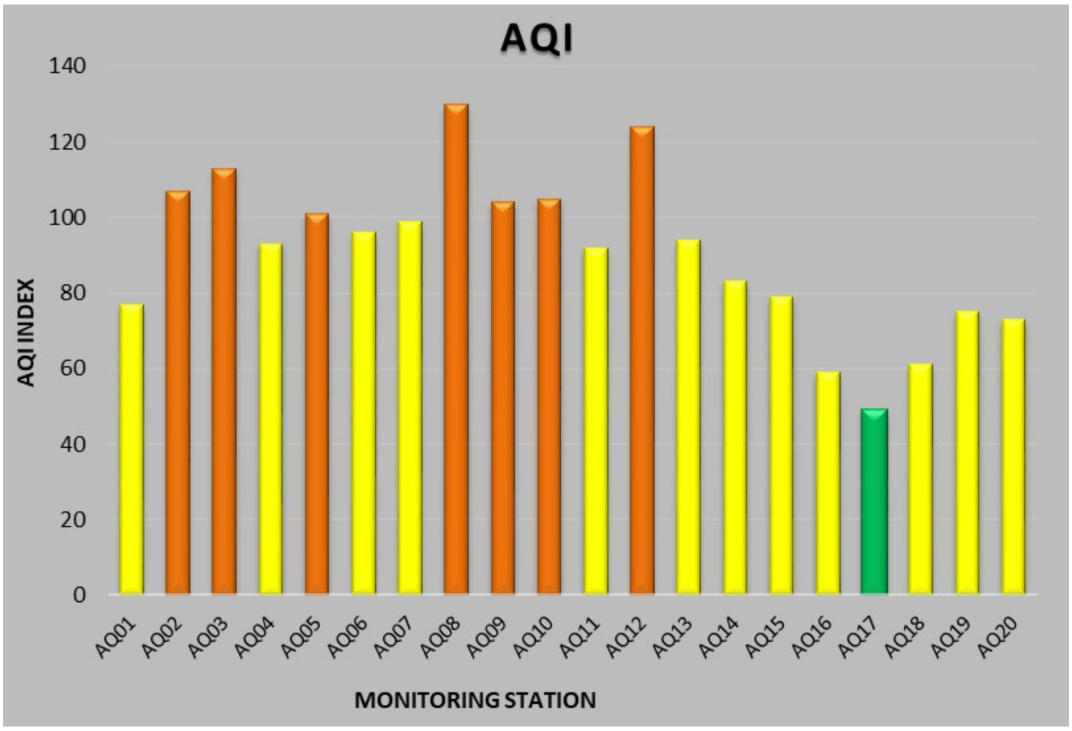

Fig. 6. Air Quality Index in the study area

Table 4. AQI and FAQI in the study area

Stn. No	PM_{10}	IP for PM10	SO_2	Ip for SO2	NOx	Ip for NO2	AQI		FAQI		Percent difference
	$\mu g/m^3$		$\mu g/m^3$		$\mu g/m^3$						%
AQ01	92.00	92.00	15.30	19.13	21.40	26.75	92.00	Good	74.1	Good	19.46
AQ02	135.00	169.69	17.90	22.38	34.40	43.00	169.69	Moderate	130	Moderate	23.39
AQ03	152.00	204.04	14.20	17.75	26.20	32.75	204.04	Poor	160	Moderate	21.58
AQ04	98.00	98.00	10.20	12.75	28.20	35.25	98.00	Good	102	Moderate	4.08
AQ05	97.00	97.00	15.00	18.75	28.90	36.13	97.00	Good	97.1	Good	0.10
AQ06	94.00	94.00	19.20	24.00	25.20	31.50	94.00	Good	82.6	Good	12.13
AQ07	117.00	133.33	17.00	21.25	29.80	37.25	133.33	Moderate	112	Moderate	16.00
AQ08	165.00	230.31	15.60	19.50	29.00	36.25	230.31	Poor	160	Moderate	30.53
AQ09	130.00	159.59	17.30	21.63	31.80	39.75	159.59	Moderate	123	Moderate	22.93
AQ10	128.00	155.55	14.20	17.75	26.40	33.00	155.55	Moderate	122	Moderate	21.57
AQ11	107.00	113.12	14.60	18.25	30.80	38.50	113.12	Moderate	112	Moderate	0.99
AQ12	157.00	214.14	12.90	16.13	28.40	35.50	214.14	Poor	160	Moderate	25.28
AQ13	113.00	125.24	17.60	22.00	25.40	31.75	125.24	Moderate	112	Moderate	10.58
AQ14	98.00	98.00	18.00	22.50	28.80	36.00	98.00	Moderate	102	Moderate	4.08
AQ15	68.00	68.00	7.30	9.13	17.00	21.25	68.00	Good	66	Good	2.94
AQ16	57.00	57.00	6.50	8.13	19.90	24.88	57.00	Good	66	Good	15.79
AQ17	63.00	63.00	8.30	10.38	14.10	17.63	63.00	Good	66	Good	4.76
AQ18	62.00	62.00	14.30	17.88	19.20	24.00	62.00	Good	67	Good	8.06
AQ19	92.00	92.00	6.60	8.25	21.70	27.13	92.00	Moderate	75	Good	18.48
AQ20	75.00	75.00	7.30	9.13	20.80	26.00	75.00	Good	66	Good	12.00

AQI value is 49 at location 17 (Sindhrot).

High AQI here can be attributed to the use of non-cleaner fuels and congestion or overcrowding. AQI for industrial areas is highest followed by residential areas and least in rural areas (Deshpande et al., 2014). Out of all the 20 locations, only location 17 (sindhrot) falls under the category of good. Fourteen locations out of 20 fall under the moderately polluted

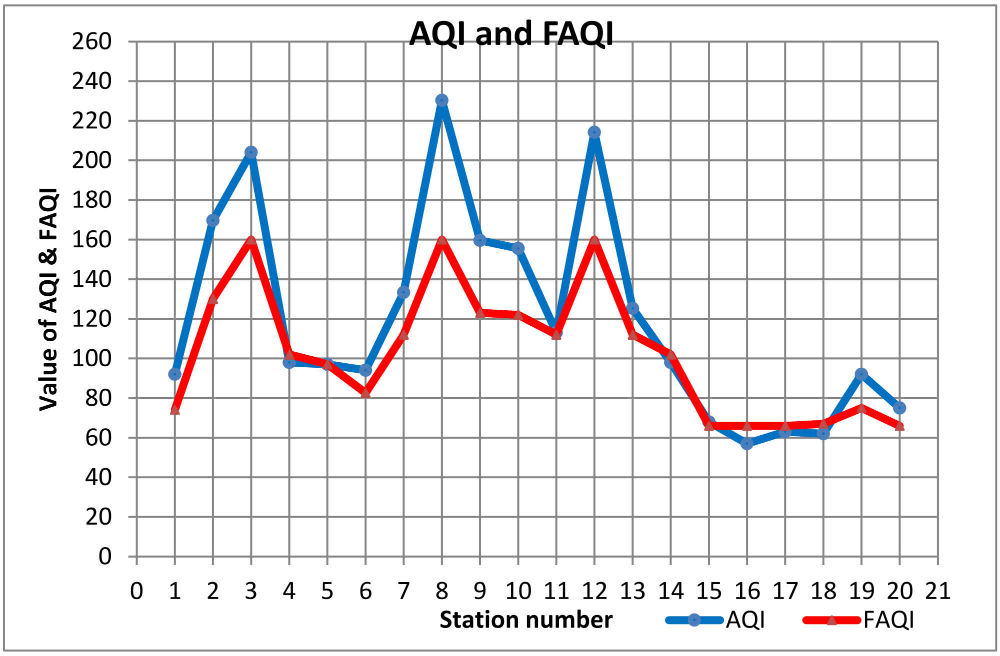

Fig. 7. AQI and FAQI comparison

category and 7 seven locations that are location no 2, 3 5, 8, 9, 10, and 12 fall under the category unhealthy for sensitive groups.

The FAQI index has been used to evaluate the air quality in the city of Vadodara. Twenty locations were used to monitor the air quality from October 2017 to February 2018, and a fuzzy inference system (FIS) was used to determine the projected FAQI values. By computing each pollutant index first, the three pollutants' (PM10, SO2, and NOx) maximum values are then combined to create the overall station index in the traditional calculation of the AQI. By feeding the input values (concentration levels for each input parameter) into the constructed model, the output value (FAQI) may be predicted. Thus, acquired FAQI output values were compared with those of the traditional AQI. The Table 4, below shows sampling locations with respective mean values of all parameters, AQI, FAQI and their percent difference.

Figure 7 shows a comparison of conventional AQI and FAQI for the study area. The conventional AQI is shown by blue line. The FAQI computed by using Mamdani fuzzy inference system is shown by red line. The trend line of FAQI is closely following the trend of AQI determined by conventional AQI. Except for Stations 3, 8 and 12, the difference between AQI and FAQI is less. It can be inferred from the results, that whenever the pollutant considered for AQI calculation or AQI crosses the mark of 200, the difference between AQI and FAQI increases. The input range for variables and membership functions can be refined more to handle this difference.

CONCLUSIONS

The CPCB-recommended approach for determining conventional AQI is used. For the comparison and model validation, the FAQI and conventional AQI for each monitoring period's data have been determined. The trend of the lines for the FAQI and traditional AQI shows that the proposed fuzzy model can be utilised to predict the air quality index, and the fuzzy aggregation mechanism for calculating the air quality index provides a better representation than the current aggregation approach. The fuzzy air quality index is a powerful decision-making tool for managing air quality that is used in this paper. It has been proven that using linguistic phrases when computing within FIS increases one's tolerance for inaccurate data. It is thought that the new FAQI index will help decision-makers by reporting the state of air quality and looking into spatial and temporal variations. The authors claim that when used logically, fuzzy logic principles could be a helpful tool for resolving issues with environmental policy. Further to this study, other soft computing approaches like neural network, decision tree, regression etc can be applied to forecast AQI and the results can be compared with FAQI.

ABBREVIATIONS

Abbreviation	*Extended Form*
AQI	Air Quality Index
CPCB	Central Pollution control Board
NAAQS	National Ambient Air quality standards
GIDC	Gujarat Industrial Development Corporation
FIS	Fuzzy Inference system
FAQI	Fuzzy Air quality index
TSP	Total suspended particulates
RSPM	Respirable suspended particulate matter
PM10	Particulate matter with aerodynamic diameter <= 10 um
SO2	Sulphur dioxide
NOx	Oxides of nitrogen
CO	Carbon monoxide

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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