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Development of Fuzzy-Based Air Quality Health Index

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Abstract
India currently uses the maximum operator-based National Air Quality Index (NAQI), which considers only the most dominant pollutant at a time. This approach oversimplifies the complex nature of air pollution and fails to account for the simultaneous exceedance of multiple pollutants over the National Ambient Air Quality Standards (NAAQS). To address this limitation, a new Fuzzy-based Air Quality Health Index (FAQHI) was developed using assessed ambient air quality at three distinct locations of Ahmedabad, Gujarat, India. This index incorporates five pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO) along with exposure parameters such as population sensitivity, location sensitivity, and population density. By applying fuzzy logic, which effectively handles uncertainty, FAQHI provides a more comprehensive assessment of air quality. A comparison with NAQI reveals that FAQHI is more stringent, especially in sensitive and densely populated areas, offering a better reflection of health risks.

Keywords: *Air Quality Health Index, Air Quality Index, Fuzzy Air Quality Index, Sensor-based Ambient Air Quality Monitoring, Air Pollutants*

INTRODUCTION

Air pollution, caused by physical, chemical, or biological contaminants, alters the natural composition of the atmosphere and poses serious health risks, including respiratory diseases and lung cancer. The WHO reports that over 99% of the global population breathes air exceeding its pollution limits (World Health Organization, n.d.). In both developed and developing countries, air pollution remains a major health concern (Lee et al., 2014). In India, key pollutants include PM_{10}, $PM_{2.5}$, NO_2, SO_2, and CO (Express, 2023). Since each pollutant affects health differently, a weighted aggregation of their impacts is essential, highlighting the need for a more advanced and comprehensive assessment tool (Gorai et al., 2015).

Ambient air quality monitoring is essential to assess pollutant levels, but raw concentrations alone cannot effectively convey overall air quality. Therefore, an index is needed. In India, the National Air Quality Index (NAQI) uses the maximum operating function, reflecting the value of the most dominant pollutant among eight considered, including PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, Pb, and NH_3 (Board, 2014). However, this method overlooks the combined effects of multiple pollutants, potentially leading to an incomplete or misleading representation of actual air quality.

Fuzzy logic, introduced by Lotfi Zadeh in 1965, deals with imprecise variables that lie between absolute values, unlike Boolean logic, which is limited to 0 or 1 (Makkar & Renu Makkar, 2018). Fuzzy variables, such as "good," "poor," or "acceptable," are useful in situations involving uncertainty, like air quality assessment. By converting vague values into quantifiable ones, fuzzy logic enables meaningful computation. This makes it well-suited for air quality indexing, where pollutant categorization is often uncertain. While previous efforts, such as those by Amit Kumar et al., applied fuzzy logic to air quality, they overlooked $PM_{2.5}$, a critical pollutant in India (Shah & Patel, 2021).

In this study, five key air pollutants: PM_{10}, $PM_{2.5}$, CO, NO_2, and SO_2 were used along with exposure parameters such as population sensitivity, location sensitivity, and population density to develop the Fuzzy-Based Air Quality Health Index (FAQHI). Each pollutant was ranked according to its relative significance and impact on air quality. Each exposure parameter is also ranked according to its significant on human health. Their concentrations were expressed through a function matrix, producing a single index value that reflects the overall air quality of the region.

MATERIALS AND METHODS

Data Collection

Ahmedabad city was selected as the study area, and three wards of Ahmedabad city: Kalupur ward, Ellisbridge ward, and Vatva GIDC area (Vatva Ward), were selected locations for monitoring of ambient air quality.

Location of Study

Ahmedabad is a metropolitan city in central Gujarat (Western India) and the 5th most populated city (Census, n.d.). It is a Tier 1 city with a population of more than 80 lakh (Ahmedabad Population 2024, n.d.). The river Sabarmati flows through the centre of the city. The city has a dry climate except for monsoons, and temperatures range between 15°C to 45°C (Mohanty et al., 2022). The city spreads over 475 sq. km of area (Mohanty et al., 2022) and comprises hybrid residential and commercial areas with industries located in the outskirts. The primary sources of pollution in the city are vehicular and industrial emissions, road dust resuspension due to vehicular movement and construction and demolition activities (Ahmedabad Municipal Corporation, 2017); (UrbanEmissions.Info, n.d.).

Location of Data Monitoring

Out of Ahmedabad's 48 municipal wards, three were selected for air quality monitoring: Kalupur, Ellisbridge, and Vatva.

I. Kalupur: Kalupur, part of the city's old town, is a densely populated commercial and residential area known for its heritage sites. Within a 1.5 km radius of the monitoring point are landmarks like Delhi Darwaja, Dariyapur Darwaja, Swaminarayan Temple, Pol Houses, and the Kalupur Railway Station. The monitoring device was installed 4.5 meters above street level on the terrace of a shop located along a narrow, high-traffic road frequented by two- and three-wheelers. The ward covers 0.89 km^2, with a population density of 35,546 people per km^2 (*GeoIQ*, 2020a).

II. Ellisbridge: Ellisbridge is a primarily commercial zone with a significant number of hospitals and some residential areas, making it a highly sensitive location. It includes major healthcare facilities such as the 1,500 beds SVP Hospital and the 500 beds VS Hospital, along with numerous private clinics. The monitoring device was placed on a balcony of a residential building, 5.5 meters above the road. It is located near Ellisbridge and the Sabarmati Riverfront roads. The ward spans 3.49 km^2 with a population density of 27,059 people per km^2 (*GeoIQ*, 2020b).

III. Vatva: The Vatva monitoring site is located in the GIDC industrial area, home to numerous small and large-scale industries, particularly in dyes and chemical manufacturing. The device was installed within a chemical factory at a height of 12.5 meters to capture emissions from industrial stacks. The area covers 10.22 km^2 with a population density of 15,701 people per km^2 (*GeoIQ*, 2020c).

The monitoring locations are illustrated in Figure 1, with detailed location data and installation photographs provided in Annexures I and II.

Figure 1: Locations of Monitoring

Data Collection and Duration of Monitoring

The air quality at the selected locations was monitored using the Polludrone, a device developed by Oizom Industries Pvt. Ltd. This device provides real-time data and measures various parameters, including Particulate Matter ($PM_{2.5}$ and PM_{10}), Carbon Monoxide (CO), Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Ambient Noise, Light, UV index, Temperature and Humidity. The sensors of the device operate using a combination of technologies such as NDIR, electrochemical analysis, optical measurement, and laser scattering (Oizom Instruments Private Limited, n.d.). Monitoring was conducted during March and April 2023. Table 1 presents the monitoring durations for each location, along with their respective latitude and longitude coordinates.

Table 1. Duration of Monitoring

Monitoring Location	Latitude	Longitude	Start Date	End Date	Monitoring Duration, days
Kalupur	23.0306	72.5909	28/02/2023	11/04/2023	40
Ellisbridge	203.0217	72.5726	28/02/2023	11/04/2023	43
Vatva	2.9606	72.6329	16/03/2023	21/04/2023	37

DATA ANALYSIS

Descriptive Analysis

Descriptive statistics of the monitoring data are presented in Table 2, with graphical representations of pollutant concentrations by location provided in Annexure III. The data indicate that the average concentrations of all pollutants remain within the NAAQS (2009) limits, except for PM_{10} and NO_2 in Kalupur and Ellisbridge. In the Vatva GIDC area, all pollutants comply with the standards except PM_{10} and $PM_{2.5}$, which exceed the prescribed limits.

Table 2. Descriptive Statistical Analysis of Monitored Data

Location		CO (mg/m^3)	$PM_{2.5}$ ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	NO_2 ($\mu g/m^3$)	SO_2 ($\mu g/m^3$)
Kalupur	Maximum	3.82	129.47	285.54	226.03	111.49
	Minimum	1.12	18.95	36.91	46.93	33.36
	Average	2.23	58.39	147.35	147.94	59.87
	Std. Dev.	0.80	23.34	53.20	39.16	22.30
Ellisbridge	Maximum	2.95	128.76	287.51	169.44	101.62
	Minimum	0.48	22.84	54.04	37.08	26.53
	Average	1.07	47.56	109.33	118.61	51.12
	Std. Dev.	0.52	22.76	48.74	23.72	20.03
Vatva	Maximum	1.93	144.70	263.04	56.73	69.64
	Minimum	0.57	42.18	91.87	11.95	0.64
	Average	0.84	72.74	152.00	26.14	19.88
	Std. Dev.	0.32	24.39	39.77	11.27	22.77

Development of Fuzzy Pair-wise Comparison Matrix

The relative importance of pollutants was assessed through a survey involving 32 experts. In this survey, the experts provided their judgments on the significance of various pollutants based on their knowledge and experience. These assessments were converted into pair-wise comparison matrices using fuzzy numbers, as detailed in Annexure IV. Any inconsistent or anomalous responses were excluded. The remaining responses were then aggregated using the geometric mean to form the final comparison matrices. The Pollutant Index (PI) reflects the relative importance of five selected pollutants. For instance, a value of $PM_{2.5}$ – SO_2 as $\bar{3}$ indicates that $PM_{2.5}$ is considered three times more important than SO_2 in the given context. The Exposure Index (EI) captures the relative importance of three factors: Location Sensitivity (LS), Population Density (PD), and Population

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Sensitivity (PS). The AQHI Matrix represents the relative contribution of the Pollutant Index (PI) and Exposure Index (EI) to overall health impact, determining how significantly each influences the final index.

$$PI = \begin{matrix} A \\ PM_{2.5} \\ PM_{10} \\ SO_2 \\ NO_2 \\ CO \end{matrix} \begin{bmatrix} PM_{2.5} & PM_{10} & SO_2 & NO_2 & CO \\ \bar{1} & \overline{3.5} & \bar{3} & \bar{2} & \overline{2.5} \\ 1/\overline{3.5} & \bar{1} & 1/\bar{2} & 1/\overline{3.5} & 1/\bar{3} \\ 1/\bar{3} & \bar{2} & \bar{1} & 1/\bar{3} & 1/\bar{2} \\ 1/\bar{2} & \overline{3.5} & \bar{3} & \bar{1} & \overline{2.5} \\ 1/\overline{2.5} & \bar{3} & \bar{2} & 1/\overline{2.5} & \bar{1} \end{bmatrix}$$

$$EI = \begin{matrix} A \\ LS \\ PD \\ PS \end{matrix} \begin{bmatrix} LS & PD & PS \\ \bar{1} & 1/\bar{3} & 1/\bar{5} \\ \bar{3} & \bar{1} & 1/\bar{3} \\ \bar{5} & \bar{3} & \bar{1} \end{bmatrix}$$

$$AQHI = \begin{matrix} A \\ EI \\ PI \end{matrix} \begin{bmatrix} EI & PI \\ \bar{1} & 1/\bar{3} \\ \bar{3} & \bar{1} \end{bmatrix}$$

3.1. Development of Fuzzy Comparison Matrix

The alpha cut (α) is used to determine the degree of uncertainty or fuzziness in the values. An alpha cut of 1 represents precise and crisp values (Yang et al., 2016). To capture this uncertainty, the pair-wise comparison matrices (PI, EI and FAQHI) are converted into new matrices (PI_f, EI_f and $FAQHI_f$). This conversion involves applying α-cut values using equations 1 and 2, which define the lower and upper limits of the fuzzy numbers.

$$\bar{x}_\alpha = [x - \alpha, x + \alpha] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (eq. 1)$$

$$\frac{1}{\bar{x}_\alpha} = [\frac{1}{(x + \alpha)}, \frac{1}{(x - \alpha)}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (eq. 2)$$

The new fuzzy matrices PI_f, EI_f and $AQHI_f$ are as follows:

$$PI_f = \begin{matrix} A \\ PM_{2.5} \\ PM_{10} \\ SO_2 \\ NO_2 \\ CO \end{matrix} \begin{bmatrix} PM_{2.5} & PM_{10} & SO_2 & NO_2 & CO \\ [1] & [2.5\ \ 4.5] & [2\ \ 4] & [1\ \ 3] & [1.5\ 3.5] \\ [0.22\ \ 0.4] & [1] & [0.33\ 1.0\ ] & [0.22\ 0.4\ ] & [0.25\ 0.5] \\ [0.25\ 0.5] & [1\ \ 3] & [1] & [0.25\ 0.5] & [0.33\ \ 1.0] \\ [0.33\ \ 1.0] & [2.5\ \ 4.5] & [2\ \ 4] & [1] & [1.5\ 3.5] \\ [0.29\ \ 0.67] & [2\ \ 4] & [1\ \ 3] & [0.29\ 0.67] & [1] \end{bmatrix}$$

$$EI_f = \begin{matrix} A \\ LS \\ PD \\ PS \end{matrix} \begin{bmatrix} LS & PD & PS \\ 1 & [0.25\ \ 0.5] & [0.17\ \ 0.25] \\ [2\ \ 4] & 1 & [0.25\ 0.5] \\ [4\ \ 6] & [2\ \ 4] & 1 \end{bmatrix}$$

$$AQHI\ f = \begin{bmatrix} EI \\ PI \end{bmatrix} \begin{bmatrix} EI & PI \\ 1 & [0.25\ 0.5] \\ [2\ 4] & 1 \end{bmatrix}$$

3.2. Conversion of Fuzzy Comparison Matrix to Crisp Comparison Matrix

The fuzzy comparison matrix is converted to a crisp matrix by using equation 3.

$$a_{ij}^{\alpha} = \lambda\, a_{iju}^{\alpha} + (1 - \lambda) a_{ijl}^{\alpha} \ldots\ldots\ldots\ldots\ldots\ldots (eq. 3)$$

a_{iju}^{α} *and* a_{ijl}^{α} = upper and lower fuzzy value of comparison element (a_{ij}).

a_{ij}^{α} = Defuzzied value and will form a crisp comparison matrix.

The value of lambda (λ) ranges from 0 to 1. The value λ=0 means an optimistic decision approach and λ=1 means a pessimistic decision approach. Thus, for maintaining neutrality, the value of λ = 0.5 is assumed (Samanta, 2016). The fuzzy comparison matrices are converted into crisp matrices (PI', EI' and FAQHI').

The value of lambda (λ) ranges between 0 and 1, where λ = 0 represents an optimistic decision-making approach, and λ = 1 corresponds to a pessimistic one. To maintain a neutral stance, a value of λ = 0.5 is typically adopted

(Samanta, 2016). The fuzzy comparison matrices (PI_f, EI_f and $FAQHI_f$) are converted into their corresponding crisp matrices (PI', EI', and FAQHI').

$$PI' = \begin{matrix} A \\ PM_{2.5} \\ PM_{10} \\ SO_2 \\ NO_2 \\ CO \end{matrix} \begin{bmatrix} PM_{2.5} & PM_{10} & SO_2 & NO_2 & CO \\ 1 & 3.5 & 3 & 2 & 2.5 \\ 0.31 & 1 & 0.67 & 0.31 & 0.38 \\ 0.38 & 2 & 1 & 0.38 & 0.67 \\ 0.67 & 3.5 & 3 & 1 & 2.5 \\ 0.48 & 3 & 2 & 0.48 & 1 \end{bmatrix}$$

$$EI' = \begin{matrix} A \\ LS \\ PD \\ PS \end{matrix} \begin{bmatrix} LS & PD & PS \\ 1 & 0.38 & 0.21 \\ 3 & 1 & 0.38 \\ 5 & 3 & 1 \end{bmatrix}$$

$$AQHI' = \begin{bmatrix} EI \\ PI \end{bmatrix} \begin{bmatrix} EI & PI \\ 1 & 0.38 \\ 3 & 1 \end{bmatrix}$$

After de-fuzzification of matrices, the consistency index (CI) and consistency ratio (CR) of the crisp matrix is checked as per Eq. 4. If CR value is less than or equal to 0.1, the matrix is consistent. Otherwise, it is inconsistent and needs to be rectified. For checking the consistency Index, the Eigen value of the matrix is calculated.

$$\text{Consistency Index} = \frac{(\lambda_{max} - n)}{(n-1)} \dots\dots\dots\dots (eq. 4)$$

λ_{max} is the maximum Eigen value of the matrix and n is the order of the matrix. The next step is to find the consistency ratio by dividing the consistency index by a random index, as shown in Eq. 5.

$$Consistency\ Ratio\ (CR) = \frac{Consistency\ Index\ (CI)}{Random\ Index\ (RI)} \dots\dots\dots (eq. 5).$$

The random index (RI) is dependent on the matrix order and is calculated by averaging multiple randomly generated reciprocal matrices. The RI values used are sourced from the table provided in Annexure V. Specifically, the random indices for 5x5 and 3x3 matrices are 1.12 and 0.58, respectively (Wedley, 1993) (Satty, 2002) (Saaty, 2008). The consistency index (CI) and consistency ratio (CR) for the crisp matrices of the Pollution Index (PI) and Exposure Index (EI) are also determined in Annexure V. The consistency ratio indicates the logical consistency of a matrix, with values closer to 0 reflecting higher consistency. The CR values for the PI and EI matrices are 0.08 and 0.10, respectively, both of which are ≤ 0.1, indicating acceptable consistency. Therefore, the matrices are considered reliable and can be used to determine individual parameter priorities and overall matrix evaluations.

Prioritization of Parameters

The relative importance (local weights) of each parameter will be calculated as shown in Table 3. This is given by the summation of one parameter's relative importance (represented in columns) and then showing each parameter's weight as a proportion of the summation, which is known as normalized matrix, as shown in Table 4. An average of all parameter weights relative to other parameters (of a row) shall lead to the local weight of the parameter as shown in Table 5. The cumulative weight of of pollutants and exposure parameters is shown in Table 6.

Table 3 Parameter Weightage of Pollution Index

PI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
$PM_{2.5}$	1.00	3.50	3.00	2.00	2.50
PM_{10}	0.31	1.00	0.67	0.31	0.38
SO_2	0.38	2.00	1.00	0.38	0.67
NO_2	0.67	3.50	3.00	1.00	2.50
CO	0.48	3.00	2.00	0.48	1.00
SUM	2.83	13.0	9.67	4.16	7.04

Table 4 Normalized Matrix of Parameter Weightage of Pollution Index

PI	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
$PM_{2.5}$	0.35	0.27	0.31	0.48	0.36
PM_{10}	0.11	0.08	0.07	0.07	0.05
SO_2	0.13	0.15	0.10	0.09	0.09
NO_2	0.24	0.27	0.31	0.24	0.36
CO	0.17	0.23	0.21	0.11	0.14

Table 5 Weights of Pollutants of Pollution Index

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
Weightage	0.35	0.08	0.12	0.28	0.17

Table 6 Individual and Cumulative Weightage of each Parameter

Parameter	Weight	Parameter	Weight	Cumulative weight
$PM_{2.5}$	0.35			0.26
PM_{10}	0.08			0.06
SO_2	0.12	PI	0.74	0.08
NO_2	0.28			0.21
CO	0.17			0.13
LS	0.11			0.03
PD	0.27	EI	0.26	0.07
PS	0.62			0.16

Development of Membership Functions

The fuzzy membership function plays a crucial role in the design of fuzzy systems. These functions, along with matrix aggregation, are used to categorize pollutants and exposure parameters into five levels: very low, low, medium, high, and very high. The membership functions for air pollutant and exposure parameters are presented in Annexure VI. In developing these functions, the applicable range is determined based on the breakpoint values provided in the National Air Quality Index of India (2014) (Board, 2014). Using the membership functions outlined in Annexure VI, ambient air quality monitoring data from all three selected locations were converted into corresponding membership degrees.

For the air quality health assessment, three exposure parameters were considered: Location Sensitivity (LS), Population Density (PD), and Population Sensitivity (PS). The rating details for these exposure index parameters are provided in Table 7. The Vatva GIDC area, being an industrial zone, was assigned a location sensitivity rating of 1. Kalupur, a mixed-use area with both commercial and residential characteristics and several heritage monuments, was given a location sensitivity rating of 3. Ellisbridge, which is also a commercial and residential area housing numerous public and private hospitals, received a location sensitivity rating of 4. Population density data for the selected locations was sourced from census information. Population Sensitivity was determined based on the proportion of individuals vulnerable to poor air quality. This includes the population under the age of 15, over the age of 60, or those with multiple chronic health conditions. Since specific data on the vulnerable population for each area was not available, city-level data for Ahmedabad was used. According to this data, 43.7% of the population in Ahmedabad falls into the vulnerable category, encompassing children, elderly, and those with chronic health issues.

Similarly, the parameter weight calculations for the Exposure Index (EI) and the Air Quality Health Index (AQHI) have been carried out and are presented in Annexure V. The local weights indicate the relative importance of each parameter. The relative importance of the Pollution Index (PI) and Exposure Index (EI) is

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0.74 and 0.26, respectively. By multiplying this relative importance with the individual weights of the corresponding internal parameters, the cumulative weights can be determined. For a better understanding, the sample ambient air quality monitoring data of Ellisbridge and the developed membership degree is given in Annexure VII.

Table 7. Ratings of Exposure Index Parameters

Parameters	Attributes	Ratings
	Vacant Area / less populated area	<1
Location Sensitivity (LS)	Industrial Area	1 - 2
	Industrial + Commercial Area	2 - 3
	Commercial + Residential Area	3 - 4
	Commercial + Residential + Sensitive area	4 - 5
	Ecological Sensitive Area	5+
Population Density (PD)	<5k	Collected Population density data directly used for membership function determination.
	5k-10k	
	10k-20k	
	20k-30k	
	30k-40k	
	40k+	
Population Sensitivity (PS)	<20%	Collected % Population sensitive data was directly used for membership function determination.
	20-40%	
	40-55%	
	55-70%	
	70-85%	
	85+%	

Aggregation and Defuzzification

After calculating the membership degrees for pollutants and exposure parameters, the membership degree matrix (R) was determined. Each row in the R matrix reflects the corresponding level of health risk associated with the pollutants and exposure parameters.

$$R = \begin{bmatrix} \mu_{PM_{2.5}}^{VL} & \mu_{PM_{2.5}}^{L} & \mu_{PM_{2.5}}^{M} & \mu_{PM_{2.5}}^{H} & \mu_{PM_{2.5}}^{VH} \\ \mu_{PM_{10}}^{VL} & \mu_{PM_{10}}^{L} & \mu_{PM_{10}}^{M} & \mu_{PM_{10}}^{H} & \mu_{PM_{10}}^{VH} \\ \mu_{SO_2}^{VL} & \mu_{SO_2}^{L} & \mu_{SO_2}^{M} & \mu_{SO_2}^{H} & \mu_{SO_2}^{VH} \\ \mu_{NO_2}^{VL} & \mu_{NO_2}^{L} & \mu_{NO_2}^{M} & \mu_{NO_2}^{H} & \mu_{NO_2}^{VH} \\ \mu_{CO}^{VL} & \mu_{CO}^{L} & \mu_{CO}^{M} & \mu_{CO}^{H} & \mu_{CO}^{VH} \\ \mu_{LS}^{VL} & \mu_{LS}^{L} & \mu_{LS}^{M} & \mu_{LS}^{H} & \mu_{LS}^{H} \\ \mu_{PD}^{VL} & \mu_{PD}^{L} & \mu_{PD}^{M} & \mu_{PD}^{H} & \mu_{PD}^{H} \\ \mu_{LS}^{VL} & \mu_{LS}^{L} & \mu_{LS}^{M} & \mu_{LS}^{H} & \mu_{LS}^{H} \end{bmatrix}$$

The membership degree matrix R is shown in Table 4 of Annexure VII for the sample ambient air quality data of Ellisbridge. Cumulative weights of parameters, as shown in Table 6 are multiplied by the membership degree matrix R, as shown in Table 8, to obtain the fuzzy evaluation matrix (u). The values of all parameters ($PM_{2.5}$ to PS) are multiplied by their respective cumulative weights.

Table 8 Matrix R multiplication with Cumulative Weights

	Very Low	Low	Medium	High	Very High		Cumulative Weights
$PM_{2.5}$	0.865	0.135	0	0	0		0.26
PM_{10}	0.698	0.302	0	0	0		0.06
SO_2	0	0.965	0.035	0	0		0.08
NO_2	0.364	0.636	0	0	0	X	0.21
CO	1	0	0	0	0		0.13
LS	0	0	0	1	0		0.03
PD	0	0	0.294	0.706	0		0.07
PS	0.00	0.755	0.245	0	0		0.16

The fuzzy evaluation matrix needs to be converted to crisp values, which is known as the defuzzification process. Defuzzification is an important step in multi-criteria evaluation. A weighted average approach is used for this research. The fuzzy values of all parameters of each range (very low to very high) are summed up, and the resultant contribution of each range (very low to very high) is calculated. A fuzzy number (unclear number having the contribution of among the 5 ranges) is converted to a single crisp value. This process is termed defuzzification. The resultant value of a field is multiplied by its level (very low = 1 to very high = 5) to obtain the value between 1 and 5, which is the Fuzzy AQHI value. The fuzzy evaluation matrix is shown as matrix u (Table 9). The FAQHI is determined by using Eq. 6.

The fuzzy evaluation matrix must be transformed into crisp values through a process known as defuzzification. This step is crucial in multi-criteria evaluation. In this study, the weighted average method is applied for defuzzification. It involves summing the fuzzy values of all parameters across each qualitative range (from very low to very high) to determine the overall contribution of each range. These fuzzy values representing varying degrees of association with the five ranges, are then converted into a single crisp value. This transformation yields a definitive numerical representation. To calculate the Fuzzy AQHI (FAQHI), the resulting crisp value is multiplied by the corresponding level weight (where very low = 1 and very high = 5), producing a final value between 1 and 5. The fuzzy evaluation matrix is denoted as matrix u (Table 9), and the FAQHI is calculated using Equation 6.

Table 9. Matrix u

	Very Low	Low	Medium	High	Very High	
$PM_{2.5}$	0.225	0.035	0	0	0	
PM_{10}	0.042	0.018	0	0	0	
SO_2	0	0.077	0.003	0	0	
NO_2	0.076	0.134	0	0	0	
CO	0.13	0	0	0	0	
LS	0	0	0	0.03	0	
PD	0	0	0.021	0.049	0	
PS	0.00	0.121	0.039	0	0	
Weightage Sum	0.473	0.385	0.063	0.079	0	Aggregation
	X 1	X 2	X 3	X 4	X 5	Defuzzification

$FAQHI = 1 * r^{VL} + 2 * r^{L} + 3 * r^{M} + 4 * r^{H} + 5 * r^{VH}$......................Eq. 6

Fuzzy AQHI = 1.748 = 1.75

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In a similar manner, the FAQHI was calculated for the ambient air quality monitoring data across all three locations, as presented in Annexure VIII. To evaluate the effectiveness of the FAQHI, the fuzzy-based index values were compared with the National Air Quality Index (NAQI), India, 2014. A detailed comparison of these two indexing methods is provided in Section 4.

DISCUSSION AND COMPARISON BETWEEN FAQHI AND NAQI:

The Fuzzy Air Quality Health Index (FAQHI) reflects the potential health impacts of poor air quality, as it incorporates both the pollution index and the exposure index. Based on the analysis of the ambient air quality monitoring data and the corresponding FAQHI values, the classification of these values is presented in Table 10. The FAQHI produces a score ranging from 0 to 5 and can be broadly classified into categories aligned with air quality standards: Good, Satisfactory, Moderately Polluted, Poor, Very Poor, and Severe.

Table 10 Categorization of Fuzzy-based AQHI

Range	0 - 1.0	1.1 - 1.5	1.6 – 2.0	2.1 – 2.5	2.6 – 3.0	> 3.0
Class	Good	Satisfactory	Moderately Polluted	Poor	Very Poor	Severe

Both the Fuzzy-based Air Quality Health Index (FAQHI) and the National Air Quality Index (NAQI) are used to represent the air quality of a specific location. However, the numerical values and the interpretations assigned to these values may differ between the two systems. To enable a meaningful comparison, the NAQI scale (ranging from 0 to 500) has been normalized to a 0–5 scale, as shown in Table 11. Additionally, the comparison can be made by examining the air quality categories (Good to Severe) in which the values of each index fall.

Table 6 Categorization of NAQI and Fuzzy-based AQHI

NAQI Category	NAQI Range	NAQI (Converted to 0-5 Scale)	Fuzzy-based AQHI
Good	0-50	0.00-0.5	0 - 1.0
Satisfactory	51-100	0.51-1.0	1.1 - 1.5
Moderately Polluted	101-200	1.1-2.0	1.6 – 2.0
Poor	201-300	2.1-3.0	2.1 – 2.5
Very Poor	301-400	3.1-4.0	2.6 – 3.0
Severe	401-500	4.1-5.0	> 3.0

The Fuzzy-based AQHI and NAQI were calculated using data collected from three monitoring stations, and the resulting values were categorized based on the defined categories. Annexure VIII presents the location-specific ambient air quality monitoring data, along with the corresponding calculated values of the Fuzzy-based AQHI and NAQI. Table 12 summarizes the minimum, maximum, and average values of both FAQHI and NAQI for each location.

Table 7 Descriptive Statistics of FAQHI and NAQI

	Kalupur		Ellisbridge		Vatva GIDC	
	FAQHI	NAQI	FAQHI	NAQI	FAQHI	NAQI
Minimum	1.7	0.8	1.7	1.0	1.7	0.8
Maximum	3.0	3.1	2.8	3.1	3.0	3.1
Average	2.3	1.8	2.0	1.5	2.3	1.8

COMPARISON OF FUZZY-BASED AQHI AND NAQI

The key distinction between the two indexing systems lies in their approach to calculating air quality. NAQI relies on the maximum operator function, meaning its index value is determined by the highest sub-index of the pollutant. In contrast, the Fuzzy-based AQHI reflects the combined concentration of all selected pollutants that impact human health. Additionally, it takes into account factors such as location characteristics and population sensitivity. For instance, consider two areas with the same pollutant concentration: one being a densely populated, sensitive zone and the other an industrial area. While NAQI would show identical values for both, the Fuzzy-based AQHI would present a higher value for the sensitive area, recognizing the greater potential health impact. Therefore, the Fuzzy-based AQHI provides a more accurate representation of air quality in terms of health effects. Using a threshold limit of 1.5 for FAQHI and 100 for NAQI, Table 13 shows how often the monitored data from each location exceeded these respective standards.

Table 8 Number of days the Fuzzy AQHI & NAQI exceeds the Standards

	Days of Monitoring	FAQHI	NAQI
Limit		1.5 (Out of 5)	100 (Out of 500)
Kalupur	40	40	39
Ellisbridge	43	43	42
Vatva	37	27	32

COMPARISON OF FAQHI AND NAQI VALUES FOR KALUPUR

When comparing the values of FAQHI and NAQI for Kalupur, both indices exhibit similar trends in their graphical representation. However, NAQI values are generally lower than those of FAQHI. The FAQHI provides a more comprehensive reflection of air quality conditions than NAQI.

On 1st March, 7th to 13th March, 20th to 21st March, 27th March to 1st April and 3rd to 7th April 2023, two or more pollutants exceeded the National Ambient Air Quality Standards (NAAQS), 2009. During these periods, pollutant concentrations ranged from 1.2 to 1.5 times the NAAQS limits. As a result, the FAQHI classified air quality as "Poor," while the NAQI placed it in the "Moderately Polluted" category.

On 2nd and 6th March, 13th to 17th March, and 8th to 10th April, all or most pollutants exceeded the NAAQS, with concentrations often reaching twice the prescribed standards. In these cases, the FAQHI indicated a "Very Poor" air quality level, whereas NAQI categorized the same periods as either "Moderately Polluted" or "Poor."

This discrepancy arises because NAQI relies on the maximum operator function, considering only the highest sub-index for its final value. As such, it fails to reflect situations where multiple pollutants simultaneously exceed the standards, a limitation that FAQHI addresses more effectively.

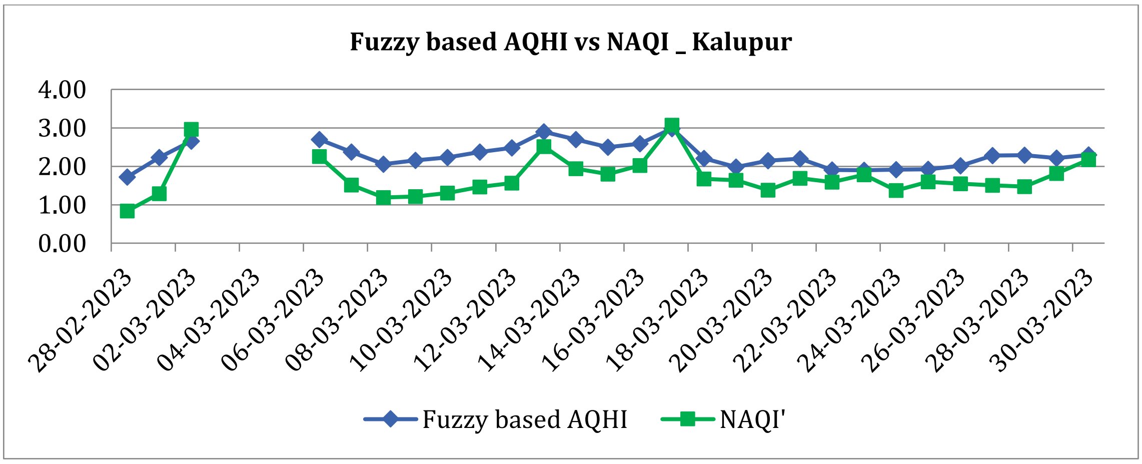

Figure 2: Fuzzy-based AQHI vs NAQI – Kalupur

4.1.2 Comparison of FAQHI and NAQI Values for Ellisbridge

When comparing FAQHI and NAQI values for Ellisbridge, both indices exhibit similar overall trends; however, the NAQI trendline shows more abrupt rises and drops compared to the smoother FAQHI trendline. This difference arises because NAQI is based solely on the sub-index of the single pollutant with the highest concentration, whereas FAQHI takes into account the concentrations of all pollutants along with additional subjective parameters.

For example, on 2nd March 2023, the concentrations of PM_{10}, $PM_{2.5}$, and CO all exceeded the NAAQS 2009 limits, with particulate matter levels reaching two to three times above the standard. As a result, the FAQHI classified air quality as "Very Poor," while NAQI rated it only as "Poor." On 3rd and 4th March, all pollutants except CO exceeded the standards; hence, FAQHI placed air quality in the "Very Poor" and "Poor" categories, respectively. In contrast, NAQI indicated a "Moderately Polluted" level on both days.

Between 11th and 16th March and again from 8th to 10th April, two or three pollutants, mainly particulate matter and NO_2, consistently exceeded NAAQS 2009 limits. During these periods, FAQHI rated the air quality as "Poor," while NAQI continued to place it in the "Moderately Polluted" category.

This difference reflects a key limitation of NAQI that it does not reflect instances where multiple pollutants simultaneously exceed standard limits, whereas FAQHI captures the cumulative impact more accurately.

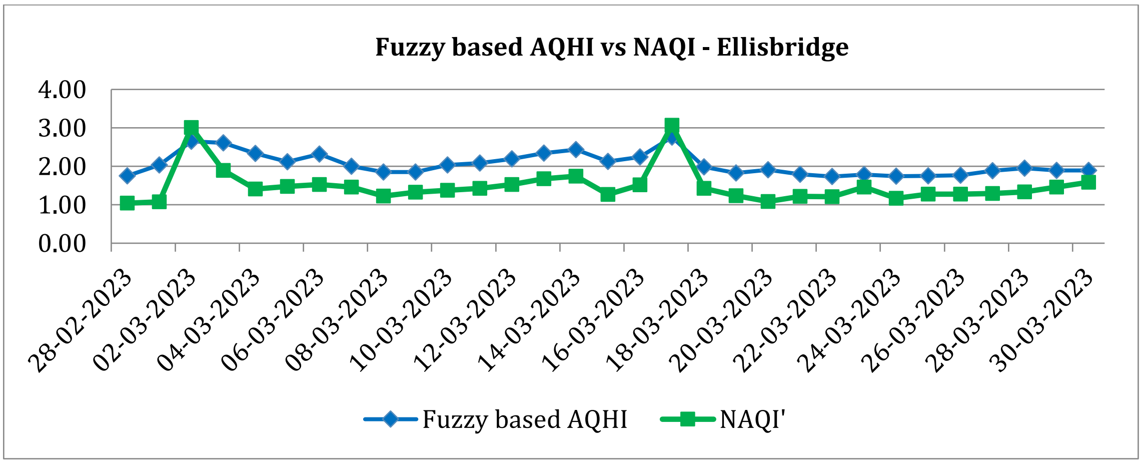

Figure 3: Fuzzy-based AQHI vs NAQI - Ellis bridge

COMPARISON OF FUZZY-BASED AQHI AND NAQI VALUES FOR VATVA

The trendlines of FAQHI and NAQI in Vatva GIDC generally follow a similar pattern; however, on certain days, NAQI values were higher than those of FAQHI. For most monitoring days, PM_{10} concentrations exceeded the NAAQS, 2009, resulting in both indices typically falling within the "Moderately Polluted" category.

In this industrial area, NAQI values tend to be higher than FAQHI values. This difference may be attributed to the lower location sensitivity assigned to industrial zones like Vatva GIDC, in contrast to more sensitive areas such as Ellisbridge and Kalupur, which are more densely populated and therefore given higher consideration in the FAQHI calculation.

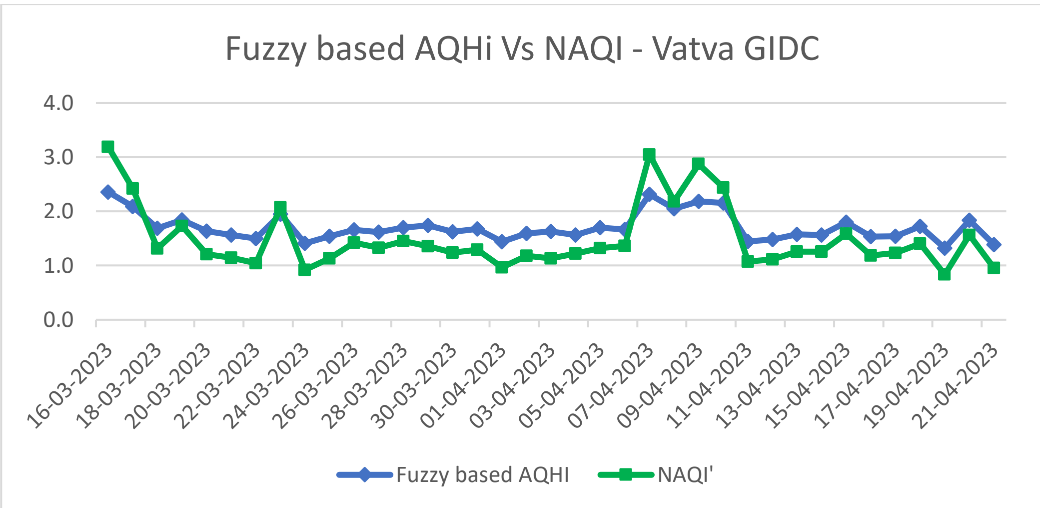

Figure 4: Fuzzy-based AQHI vs NAQI – Vatva GIDC

Annexure IX presents graphical representations of the date-wise percentage contribution of pollutants and exposure parameters to the FAQHI, along with the minimum and maximum percentage contributions. It also includes location-wise percentages of the FAQHI and NAQI categories. The graphs indicate that in Ellisbridge and Kalupur, both densely populated and location-sensitive areas, the exposure parameters contribute the most to the FAQHI, with an average contribution exceeding 30%, followed by $PM_{2.5}$, NO_2, CO, PM_{10} and SO_2. In these areas, the FAQHI is more stringent than the NAQI, as reflected in the pie charts showing the distribution of FAQHI and NAQI categories. In contrast, in Vatva, an industrial area with lower population density, the highest contribution to FAQHI comes from $PM_{2.5}$, followed by exposure parameters: NO_2, PM_{10}, CO and SO_2.

CONCLUSIONS

FAQHI values offer a more realistic representation of air quality conditions, as this indexing system incorporates not only the concentrations of all selected pollutants but also subjective factors such as location sensitivity, population sensitivity, and population density. In contrast, NAQI does not account for these contextual parameters. FAQHI effectively highlights situations where multiple pollutants simultaneously exceed the NAAQS (2009), whereas NAQI, being based on the maximum operator function, only reflects the pollutant with the highest sub-index value.

Although the trend lines of FAQHI and NAQI across all three selected locations generally follow a similar pattern, the FAQHI provides a more refined and stringent assessment, particularly in sensitive and densely populated areas. One limitation of this study is that ideally, the permissible FAQHI thresholds should vary depending on the type of monitoring location, considering local sensitivity and population characteristics. However, implementing location-specific standards at the national level may not be practical.

The fuzzy air quality health indexing system is inherently more complex than the current national system (NAQI), but its broader range of output values and more comprehensive approach demonstrate its superiority. To address the complexity and ensure consistent application, the FAQHI system should be developed into a programmed tool for easier calculation and deployment. Overall, the comparison indicates that FAQHI is a more stringent and informative index than NAQI, especially for vulnerable urban environments.

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CONFLICT Of INTEREST

The authors declare that there are no conflicts of interest.

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Annexure - I

Location details

Location	Latitude and Longitude	Location Sensitivity	Population Density (persons/sq. km)	Population Sensitivity (portion of population < 19 years of age or > 60 years of age) (%)
Kalupur	23°01'42"N, 72°35'25"E	Medium (Residential Commercial Zone with Heritage Buildings in the vicinity)	35546	43.7 %
Ellisbridge	23°01'18"N, 72°34'20"E	High (Number of hospitals in the vicinity)	27059	43.7 %
Vatva	22°58'08"N, 72°38'12"E	Low (Industrial Zone with chemical factories)	15701	43.7 %

Note: Population Density and Sensitivity calculated from GeoIQ (*GeoIQ*, 2020a) (*GeoIQ*, 2020b) (*GeoIQ*, 2020c).

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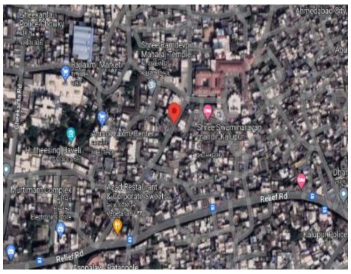
Annexure - II

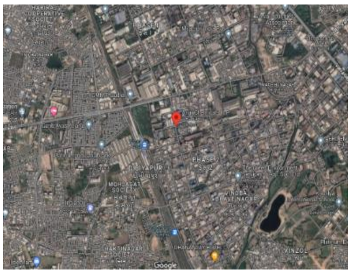
Monitoring Location and Photos Showing Installation of Monitoring Device

Location on map	Photograph of context	Photograph of Polludrone Device installed
		

Kalupur Ward

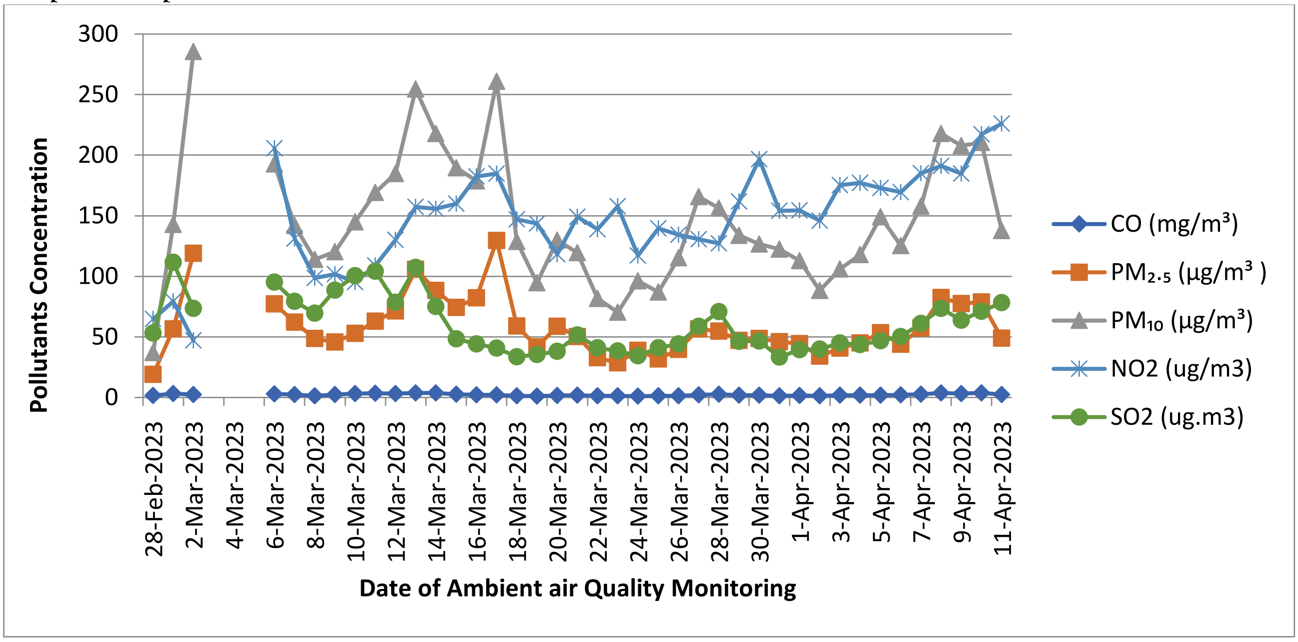
		

Ellisbridge Ward

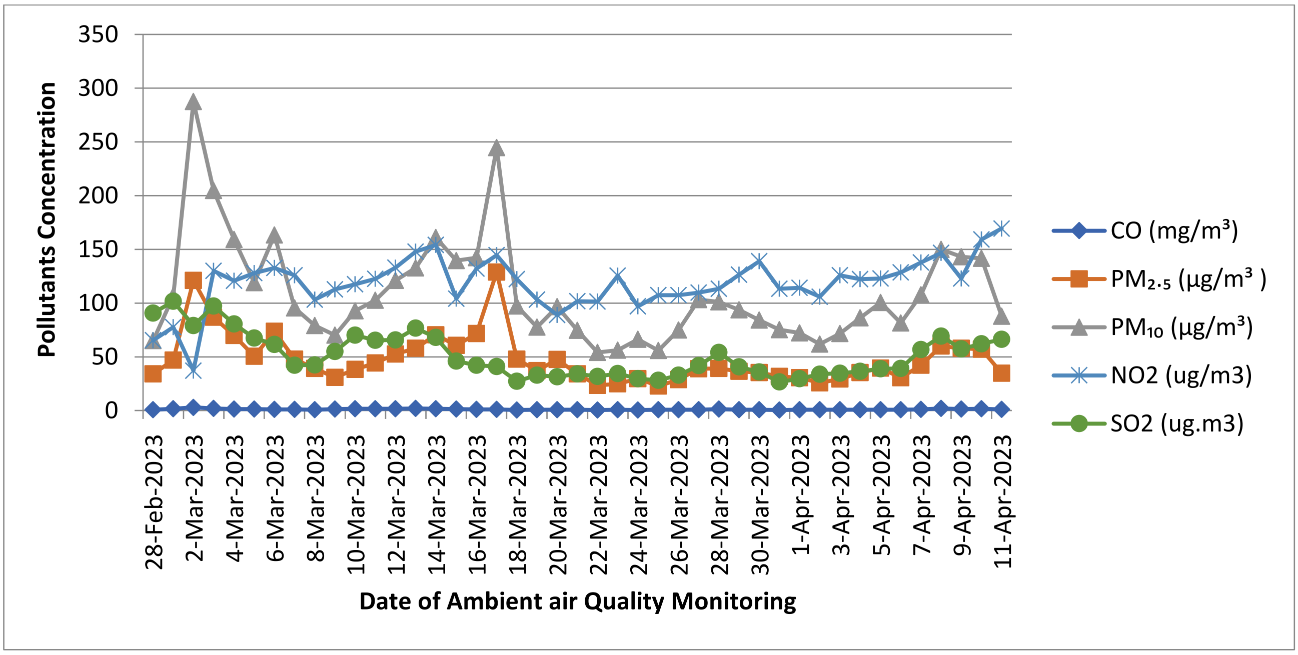
		

Annexure – III

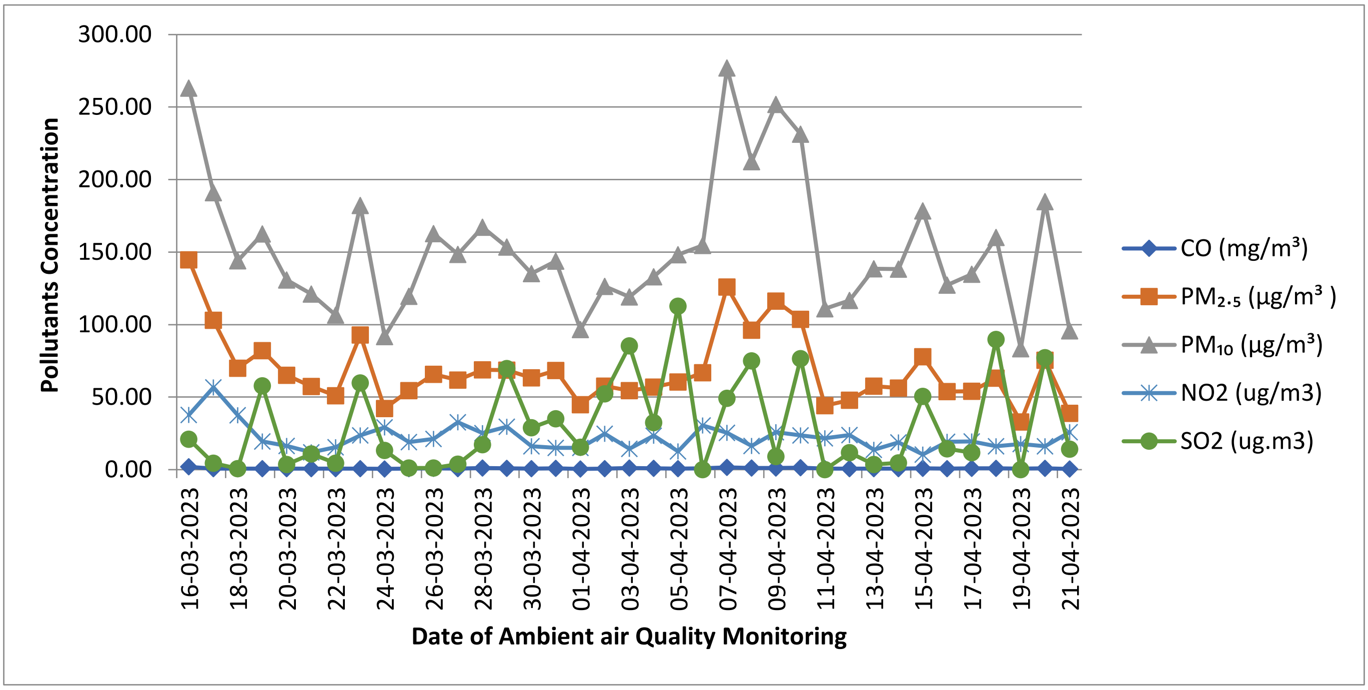
Graphical Representation of Ambient Concentrations of Air Pollutants



Ambient Concentrations of Air Pollutants _ Kalupur



Ambient Concentrations of Air Pollutants _ Ellisbridge



Ambient Concentrations of Air Pollutants _ Vatva

Annexure - IV

Fuzzy-Based Pairwise Comparison Matrix

A survey was conducted where 32 experts were asked for their opinions on the relative importance of pollutants. In the fuzzy AHP model, instead of discrete numbers (1 - 9), the fuzzy numbers ($\bar{1}$-$\bar{9}$) are used to capture the subjectivity or vagueness of the pair-wise preferences of fuzzy air quality health index attributes. The table below shows the fuzzy number, its definition and explanation.

Relative Importance	Fuzzy Scale[a]	Definition[b]	Explanation
$\bar{1}$	(1, 1, 1)	Equal importance	Two activities contribute equally to the objective.
$\bar{3}$	$(3 - \alpha), 3, (3 + \alpha)$	Weak importance	Experience and judgement slightly favour one activity over another.
$\bar{5}$	$(5 - \alpha), 5, (5 + \alpha)$	Essential or strong importance	Experience and judgement strongly favour one activity over another.
$\bar{7}$	$(7 - \alpha), 7, (7 + \alpha)$	Demonstrated importance	Experience and judgement strongly favour one activity over another.
$\bar{9}$	$(9 - \alpha), 9, (9 + \alpha)$	Extreme importance	One activity is strongly favoured and demonstrated in practice.
$\bar{2}, \bar{4}, \bar{6}, \bar{8}$	$(x - \alpha), x, (x + \alpha)$	Intermediate values between two adjacent judgements	The evidence favouring one activity over another is of the highest possible order of affirmation.

α is a fuzzification factor.

[a] The intensity of importance definition is in accordance with the description proposed by Saaty (1977, 1980).

[b] Minimum, most likely, and maximum values.

Annexure - V

Determination of Consistency Index and Consistency Ratio

Random Index Values for Determination of Consistency Ratio

Degree of matrix	1	2	3	4	5	6
Random Index Values	0	0	0.58	0.9	1.12	1.24

Determination of Consistency Index and Consistency Ratio for Pollution Index

Crisp Matrix of Pollution Index

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
$PM_{2.5}$	1.00	3.50	3.00	2.00	2.50
PM_{10}	0.31	1.00	0.67	0.31	0.38
SO_2	0.38	2.00	1.00	0.38	0.67
NO_2	0.67	3.50	3.00	1.00	2.50
CO	0.48	3.00	2.00	0.48	1.00

Column Addition

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
$PM_{2.5}$	1.00	3.50	3.00	2.00	2.50
PM_{10}	0.31	1.00	0.67	0.31	0.38
SO_2	0.38	2.00	1.00	0.38	0.67
NO_2	0.67	3.50	3.00	1.00	2.50
CO	0.48	3.00	2.00	0.48	1.00
Sum	2.83	13.00	9.67	4.16	7.04

Normalized Matrix

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
$PM_{2.5}$	0.35	0.27	0.31	0.48	0.36
PM_{10}	0.11	0.08	0.07	0.07	0.05
SO_2	0.13	0.15	0.10	0.09	0.09
NO_2	0.24	0.27	0.31	0.24	0.36
CO	0.17	0.23	0.21	0.11	0.14

Calculation of Priorities: Row Averages

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Priority
$PM_{2.5}$	0.35	0.27	0.31	0.48	0.36	0.35
PM_{10}	0.11	0.08	0.07	0.07	0.05	0.08
SO_2	0.13	0.15	0.10	0.09	0.09	0.11
NO_2	0.24	0.27	0.31	0.24	0.36	0.28
CO	0.17	0.23	0.21	0.11	0.14	0.17

Weights of Pollutants of Pollution Index

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
Weightage	0.35	0.08	0.12	0.28	0.17

Prioritization of Results

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Priority
$PM_{2.5}$	1.00	3.50	3.00	2.00	2.50	0.35
PM_{10}	0.31	1.00	0.67	0.31	0.38	0.08
SO_2	0.38	2.00	1.00	0.38	0.67	0.11
NO_2	0.67	3.50	3.00	1.00	2.50	0.28
CO	0.48	3.00	2.00	0.48	1.00	0.17

Priorities as Factors

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
Criteria Weights	0.35	0.08	0.11	0.28	0.17
$PM_{2.5}$	1.00	3.50	3.00	2.00	2.50
PM_{10}	0.31	1.00	0.67	0.31	0.38
SO_2	0.38	2.00	1.00	0.38	0.67
NO_2	0.67	3.50	3.00	1.00	2.50
CO	0.48	3.00	2.00	0.48	1.00

Calculation of Weighted Columns

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
$PM_{2.5}$	0.35	0.27	0.34	0.56	0.43
PM_{10}	0.11	0.08	0.08	0.09	0.06
SO_2	0.13	0.15	0.11	0.11	0.11
NO_2	0.24	0.27	0.34	0.28	0.43
CO	0.17	0.23	0.23	0.13	0.17

Calculation of Weighted Sum

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Weighted Sum
$PM_{2.5}$	0.35	0.27	0.34	0.56	0.43	1.96
PM_{10}	0.11	0.08	0.08	0.09	0.06	0.42
SO_2	0.13	0.15	0.11	0.11	0.11	0.62
NO_2	0.24	0.27	0.34	0.28	0.43	1.56
CO	0.17	0.23	0.23	0.13	0.17	0.94

Calculation of λ_{max}

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Weighted Sum	Priority	λ
$PM_{2.5}$	0.35	0.27	0.34	0.56	0.43	1.96	0.35	5.55
PM_{10}	0.11	0.08	0.08	0.09	0.06	0.42	0.08	5.42
SO_2	0.13	0.15	0.11	0.11	0.11	0.62	0.11	5.41
NO_2	0.24	0.27	0.34	0.28	0.43	1.56	0.28	5.54
CO	0.17	0.23	0.23	0.13	0.17	0.94	0.17	5.42
						λ_{max}		5.47

Determination of Consistency Index (CI)

$$\text{Consistency Index (CI)} = \frac{(\lambda_{max}\text{-n})}{(\text{n-1})} = \frac{(5.47\text{-}5)}{(5\text{-}1)} = 0.1$$

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} = \frac{0.1}{1.12} = 0.08$$

Determination of Weights of Parameters, Consistency Index and Consistency Ratio for Exposure Index

Crisp Matrix of Exposure Index

	LS	PD	PS
LS	1.00	0.38	0.21
PD	3.00	1.00	0.38
PS	5.00	3.00	1.00

Column Addition

	LS	PD	PS
LS	1.00	0.38	0.21
PD	3.00	1.00	0.38
PS	5.00	3.00	1.00
Sum	9.00	4.38	1.59

Normalized Matrix

	LS	PD	PS
LS	0.11	0.09	0.13
PD	0.33	0.23	0.24
PS	0.56	0.69	0.63

Calculation of Priorities: Row Averages

	LS	PD	PS	Priority
LS	0.11	0.09	0.13	0.11
PD	0.33	0.23	0.24	0.27
PS	0.56	0.69	0.63	0.62

Weights of Parameters of Exposure Index

	LS	PD	PS
Weightage	0.11	0.27	0.62

Prioritization of Results

	LS	PD	PS	Priority
LS	0.11	0.09	0.13	0.11
PD	0.33	0.23	0.24	0.27
PS	0.56	0.69	0.63	0.62

Priorities as Factors

	LS	PD	PS
Criteria Weights	0.11	0.27	0.62
LS	1.00	0.38	0.21
PD	3.00	1.00	0.38
PS	5.00	3.00	1.00

Calculation of Weighted Columns

	LS	PD	PS
LS	0.11	0.10	0.13
PD	0.33	0.27	0.24
PS	0.55	0.81	0.62

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Calculation of Weighted Sum

	LS	PD	PS	Weighted Sum
LS	0.11	0.10	0.13	0.34
PD	0.33	0.27	0.23	0.84
PS	0.55	0.81	0.62	1.98

Calculation of λ_{max}

	LS	PD	PS	Weighted Sum	Priority	λ
LS	0.11	0.10	0.13	0.34	0.11	3.09
PD	0.33	0.27	0.23	0.84	0.27	3.11
PS	0.55	0.81	0.62	1.98	0.62	3.19
					λmax	3.13

Determination of Consistency Index (CI)

$$\text{Consistency Index (CI)} = \frac{(\lambda_{max}\text{-n})}{(\text{n-1})} = \frac{(3.13\text{-}3)}{(3\text{-}1)} = 0.06$$

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} = \frac{0.06}{0.58} = 0.1$$

Determination of Weights of Parameters, Consistency Index and Consistency Ratio for AQHI

Crisp Matrix of AQHI

	EI	PI
EI	1.00	0.38
PI	3.00	1.00

Column Addition

	EI	PI
EI	1.00	0.38
PI	3.00	1.00
Sum	4.00	1.38

Normalized Matrix

	EI	PI
EI	0.25	0.27
PI	0.75	0.73

Calculation of Priorities: Row Averages

	EI	PI	Priority
EI	0.25	0.27	0.26
PI	0.75	0.73	0.74

Weights of Parameters of AQHI Index

	EI	PI
Weightage	0.26	0.74

Prioritization of Results

	EI	PI	Priority
EI	0.25	0.27	0.26
PI	0.75	0.73	0.74

Priorities as Factors

	EI	PI
Criteria Weights	0.26	0.74
EI	1	0.38
PI	3	1

Calculation of Weighted Columns

	EI	PI
EI	0.26	0.28
PI	0.78	0.74

Calculation of Weighted Sum

	EI	PI	Weighted Sum
EI	0.26	0.28	0.54
PI	0.78	0.74	1.52

Calculation of λ_{max}

	EI	PI	Weighted Sum	Priority	λmax
EI	0.26	0.28	0.54	0.26	2.07
PI	0.78	0.74	1.52	0.74	2.05
				λmax	2.06

Determination of Consistency Index (CI)

$$\text{Consistency Index (CI)} = \frac{(\lambda_{max}\text{-n})}{(\text{n-1})} = \frac{(2.06\text{-}2)}{(2\text{-}1)} = 0.06$$

Annexure - VI

Membership Function of Air Pollutant and Exposure Parameters

MEMBERSHIP FUNCTION OF AIR POLLUTANT PARAMETERS

Pollutants	Range of applicability	Membership to Very Low	Membership to Low	Membership to Medium	Membership to High	Membership to Very High
$PM_{2.5}$	<30	1	0	0	0	0
	31-60	$\frac{(60-x)}{(60-30)}$	$\frac{(x-30)}{(60-30)}$	0	0	0
	61-90	0	$\frac{(90-x)}{(90-60)}$	$\frac{(x-60)}{(90-60)}$	0	0
	91-120	0	0	$\frac{(120-x)}{(120-90)}$	$\frac{(x-90)}{(120-90)}$	0
	121-250	0	0	0	$\frac{(250-x)}{(250-120)}$	$\frac{(x-120)}{(250-120)}$
	250+	0	0	0	0	1
PM_{10}	<50	1	0	0	0	0

	51-100	$\frac{(100-x)}{(100-50)}$	$\frac{(x-50)}{(100-50)}$	0	0	0
	101-200	0	$\frac{(200-x)}{(200-100)}$	$\frac{(x-100)}{(200-100)}$	0	0
	201-300	0	0	$\frac{(300-x)}{(300-200)}$	$\frac{(x-200)}{(300-200)}$	0
	301-400	0	0	0	$\frac{(400-x)}{(400-300)}$	$\frac{(x-300)}{(400-300)}$
	400+	0	0	0	0	1
SO_2	<40	1	0	0	0	0
	80	$\frac{(80-x)}{(80-40)}$	$\frac{(x-40)}{(80-40)}$	0	0	0
	81-380	0	$\frac{(380-x)}{(380-80)}$	$\frac{(x-80)}{(380-80)}$	0	0
	381-800	0	0	$\frac{(800-x)}{(800-380)}$	$\frac{(x-380)}{(800-380)}$	0
	801-1600	0	0	0	$\frac{(1600-x)}{(1600-800)}$	$\frac{(x-800)}{(1600-800)}$
	1600+	0	0	0	0	1
NO_2	<40	1	0	0	0	0
	41 - 80	$\frac{(80-x)}{(80-40)}$	$\frac{(x-40)}{(80-40)}$	0	0	0
	81-180	0	$\frac{(180-x)}{(180-80)}$	$\frac{(x-80)}{(180-80)}$	0	0
	181-280	0	0	$\frac{(280-x)}{(280-180)}$	$\frac{(x-180)}{(280-180)}$	0
	281-400	0	0	0	$\frac{(400-x)}{(400-280)}$	$\frac{(x-280)}{(400-280)}$
	400+	0	0	0	0	1
CO	<1	1	0	0	0	0
	1-2	$\frac{(2-x)}{(2-1)}$	$\frac{(x-1)}{(2-1)}$	0	0	0
	2.1-10	0	$\frac{(10-x)}{(10-x)}$	$\frac{(x-2)}{(10-2)}$	0	0
	10-17	0	0	$\frac{(17-x)}{(17-10)}$	$\frac{(x-10)}{(17-10)}$	0
	17-34	0	0	0	$\frac{(34-x)}{(34-17)}$	$\frac{(x-34)}{(34-17)}$
	34+	0	0	0	0	1

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MEMBERSHIP FUNCTION OF EXPOSURE PARAMETERS

Exposure Parameters	Range of applicability	Membership to Very Low	Membership to Low	Membership to Medium	Membership to High	Membership to Very High
Location Sensitivity	<1	1	0	0	0	0
	1-2	$\frac{(2-x)}{(2-1)}$	$\frac{(x-1)}{(2-1)}$	0	0	0
	2-3	0	$\frac{(3-x)}{(3-2)}$	$\frac{(x-2)}{(3-2)}$	0	0
	3-4	0	0	$\frac{(4-x)}{(4-3)}$	$\frac{(x-3)}{(4-3)}$	0
	4-5	0	0	0	$\frac{(4-x)}{(5-4)}$	$\frac{(x-4)}{(5-4)}$
	5+	0	0	0	0	1
Population Density	<5k	1	0	0	0	0
	5k-10k	$\frac{(10k-x)}{(10k-5k)}$	$\frac{(x-5k)}{(10k-5k)}$	0	0	0
	10k-20k	0	$\frac{(20k-x)}{(20k-10k)}$	$\frac{(x-10k)}{(20k-10k)}$	0	0
	20k-30k	0	0	$\frac{(30k-x)}{(30k-20k)}$	$\frac{(x-20k)}{(30k-20k)}$	0
	30k-40k	0	0	0	$\frac{(40k-x)}{(40k-30k)}$	$\frac{(x-30k)}{(40k-30k)}$
	40k+	0	0	0	0	1
Population Sensitivity	<20	1	0	0	0	0
	20-40	$\frac{(40-x)}{(40-20)}$	$\frac{(x-20)}{(40-20)}$	0	0	0
	40-55	0	$\frac{(55-x)}{(55-40)}$	$\frac{(x-40)}{(55-40)}$	0	0
	55-70	0	0	$\frac{(70-x)}{(70-55)}$	$\frac{(x-55)}{(70-55)}$	0
	70-85	0	0	0	$\frac{(85-x)}{(85-70)}$	$\frac{(x-70)}{(85-70)}$
	85+	0	0	0	0	1

Annexure - VII

Determination of Air Quality Health Index

Location : Ellisbridge

Monitoring Date: 28/02/2023

TABLE 1 AMBIENT AIR QUALITY MONITORING DATA

	Unit of Measurement	Concentration
$PM_{2.5}$	$\mu g/m^3$	34.1
PM_{10}	$\mu g/m^3$	65.1
SO_2	$\mu g/m^3$	90.5
NO_2	$\mu g/m^3$	65.4
CO	mg/m^3	0.8

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TABLE 2 MEMBERSHIP DEGREE FOR THE MONITORED AMBIENT AIR QUALITY DATA

Pollutants	Range of applicability	Membership to Very Low	Membership to Low	Membership to Medium	Membership to High	Membership to Very High
$PM_{2.5}$ = 34.05 µg/m^3	31-60	$\frac{(60-34.1)}{(60-30)}$	$\frac{(34.1-30)}{(60-30)}$	0	0	0
PM_{10} = 65.09 µg/m^3	51-100	$\frac{(100-65.1)}{(100-50)}$	$\frac{(65.1-50)}{(100-50)}$	0	0	0
SO_2 = 90.53 µg/m^3	81-380	0	$\frac{(380-90.5)}{(380-80)}$	$\frac{(90.5-80)}{(380-80)}$	0	0
NO_2 = 65.44 µg/m^3	41- 80	$\frac{(80-65.4)}{(80-40)}$	$\frac{(65.4-40)}{(80-40)}$	0	0	0
CO = 0.84 mg/m^3	<1	1	0	0	0	0

TABLE 2A MEMBERSHIP DEGREE FOR THE MONITORED AMBIENT AIR QUALITY DATA

Pollutants	Range of applicability	Membership to Very Low	Membership to Low	Membership to Medium	Membership to High	Membership to Very High
$PM_{2.5}$ = 34.05 µg/m^3	31-60	0.86	0.14	0	0	0
PM_{10} = 65.09 µg/m^3	51-100	0.70	0.30	0	0	0
SO_2 = 90.53 µg/m^3	81-380	0	0.96	0.04	0	0
NO_2 = 65.44 µg/m^3	41- 80	0.36	0.64	0	0	0
CO = 0.84 mg/m^3	<1	1	0	0	0	0

TABLE 3 MEMBERSHIP FUNCTION OF EXPOSURE PARAMETERS

Exposure Parameters	Range of applicability	Membership to Very Low	Membership to Low	Membership to Medium	Membership to High	Membership to Very High
Location Sensitivity (LS) = 4	3-4	0	0	0	1	0
Population Density (PD) = 27059	20k-30k	0	0	0.294	0.706	0
Population Sensitivity (PS) = 43.68	40-55	0	0.755	0.245	0	0

TABLE 4 THE MEMBERSHIP DEGREE MATRIX R

$$R = \begin{bmatrix} & VL & L & M & H & VH \\ PM_{2.5} & 0.865 & 0.135 & 0 & 0 & 0 \\ PM_{10} & 0.698 & 0.302 & 0 & 0 & 0 \\ SO_2 & 0 & 0.965 & 0.035 & 0 & 0 \\ NO_2 & 0.364 & 0.636 & 0 & 0 & 0 \\ CO & 1 & 0 & 0 & 0 & 0 \\ LS & 0 & 0 & 0 & 1 & 0 \\ PD & 0 & 0 & 0.294 & 0.706 & 0 \\ PS & 0 & 0.755 & 0.245 & 0 & 0 \end{bmatrix}$$

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Annexure - VIII
Concentrations and Fuzzy based AQHI values

Kalupur	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Fuzzy based AQHI	NAQI	NAQI'
Sample data for each category	30	50	40.00	40.00	1	1.5	50	0.50
	60	100	80.00	80.00	2	2.2	100	1.00
	90	250	380.00	180.00	10	3.0	200	2.00
	120	350	800.00	280.00	17	3.7	300	3.00
	250	430	1600.00	400.00	34	4.4	400	4.00
	251	435	1650.00	420.00	35	4.4	500	5.00
28/2/23	19.0	36.9	53.2	64.8	1.7	1.7	83.7	0.8
1/3/23	56.5	142.7	111.5	79.4	3.1	2.2	128.7	1.3
2/3/23	119.0	285.5	73.5	46.9	2.3	2.7	296.7	3.0
6/3/23	77.3	192.6	95.1	205.6	3.0	2.7	225.6	2.3
7/3/23	62.1	142.1	79.3	131.1	2.5	2.4	151.1	1.5
8/3/23	48.7	114.0	69.4	98.7	1.4	2.1	118.7	1.2
9/3/23	45.9	120.3	88.5	101.7	2.4	2.2	121.7	1.2
10/3/23	52.8	145.0	100.5	95.3	3.0	2.2	130.2	1.3
11/3/23	63.0	169.2	104.1	109.0	3.4	2.4	146.3	1.5
12/3/23	71.3	184.9	78.4	130.1	3.1	2.5	156.7	1.6
13/3/23	105.7	254.7	107.3	157.2	3.7	2.9	251.3	2.5
14/3/23	88.2	217.9	75.0	155.7	3.7	2.7	193.9	1.9
15/3/23	74.3	189.6	48.5	159.9	2.6	2.5	179.9	1.8
16/3/23	82.1	178.8	44.1	182.4	2.2	2.6	202.4	2.0
17/3/23	129.5	260.9	40.7	184.7	2.2	3.0	307.5	3.1
18/3/23	59.1	128.7	33.6	147.0	1.4	2.2	167.0	1.7
19/3/23	41.8	94.6	35.5	143.5	1.1	2.0	163.5	1.6
20/3/23	58.8	129.9	38.1	118.1	1.5	2.1	138.1	1.4
21/3/23	50.3	119.5	51.5	149.0	1.8	2.2	169.0	1.7
22/3/23	32.7	81.6	41.1	138.7	1.3	1.9	158.7	1.6
23/3/23	28.6	70.5	38.3	157.8	1.2	1.9	177.8	1.8
24/3/23	38.8	96.3	34.5	117.1	1.2	1.9	137.1	1.4
25/3/23	31.6	87.1	40.9	139.6	1.4	1.9	159.6	1.6
26/3/23	39.6	115.3	44.3	134.4	1.4	2.0	154.4	1.5
27/3/23	56.6	165.9	58.6	130.5	2.0	2.3	150.5	1.5
28/3/23	54.7	156.2	70.8	127.2	2.5	2.3	147.2	1.5
29/3/23	47.0	133.7	46.3	161.7	1.9	2.2	181.7	1.8
30/3/23	48.5	126.7	46.5	196.8	2.0	2.3	216.8	2.2
31/3/23	46.1	122.4	33.4	154.2	1.4	2.1	174.2	1.7
1/4/23	44.4	112.8	39.5	154.5	1.7	2.1	174.5	1.7
2/4/23	34.0	88.4	39.8	146.0	1.4	2.0	166.0	1.7
3/4/23	40.7	106.0	45.1	175.4	1.7	2.1	195.4	2.0
4/4/23	44.9	117.9	43.5	177.0	1.9	2.2	197.0	2.0
5/4/23	53.3	149.0	46.8	172.9	1.9	2.3	192.9	1.9
6/4/23	44.0	125.2	50.3	169.5	2.0	2.2	189.5	1.9

7/4/23	57.2	157.8	61.1	185.1	2.7	2.4	205.1	2.05
8/4/23	82.5	217.8	73.4	191.1	3.8	2.7	211.1	2.1
9/4/23	77.3	207.8	63.6	184.7	3.3	2.6	204.7	2.0
10/4/23	78.9	210.4	71.0	217.3	3.8	2.7	237.3	2.4
11/4/23	48.9	137.8	78.1	226.0	2.4	2.4	246.0	2.5

Ellisbridge	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Fuzzy based AQHI	NAQI	NAQI'
28/2/23	34.1	65.1	90.5	65.4	0.8	1.8	104.2	1.0
1/3/23	47.0	106.6	101.6	77.5	1.5	2.0	107.8	1.1
2/3/23	120.9	287.5	79.1	37.1	3.0	2.7	300.9	3.0
3/3/23	86.9	204.7	97.3	130.0	1.9	2.6	189.2	1.9
4/3/23	69.9	159.1	80.7	120.9	1.3	2.3	140.9	1.4
5/3/23	50.6	119.0	67.5	128.0	1.2	2.1	148.0	1.5
6/3/23	73.7	163.3	61.4	132.6	1.0	2.3	152.6	1.5
7/3/23	47.7	95.6	42.0	125.7	1.1	2.0	145.7	1.5
8/3/23	39.1	79.2	42.4	103.1	0.6	1.9	123.1	1.2
9/3/23	30.7	70.2	55.0	112.6	1.3	1.9	132.6	1.3
10/3/23	38.2	92.8	70.2	117.6	1.7	2.0	137.6	1.4
11/3/23	44.3	102.5	65.2	122.6	1.6	2.1	142.6	1.4
12/3/23	52.5	121.1	65.8	133.0	1.6	2.2	153.0	1.5
13/3/23	58.1	132.7	76.7	148.0	2.0	2.3	168.0	1.7
14/3/23	70.6	161.0	67.9	154.0	1.7	2.4	174.0	1.7
15/3/23	60.7	139.6	46.0	103.9	1.2	2.1	126.7	1.3
16/3/23	71.7	142.3	42.1	132.2	0.9	2.2	152.2	1.5
17/3/23	128.8	244.6	40.9	144.6	1.0	2.8	307.0	3.1
18/3/23	47.8	97.2	27.3	122.3	0.5	2.0	142.3	1.4
19/3/23	37.1	77.6	33.0	103.3	0.6	1.8	123.3	1.2
20/3/23	47.4	96.6	31.5	88.9	0.7	1.9	108.9	1.1
21/3/23	34.2	74.5	34.1	101.6	0.6	1.8	121.6	1.2
22/3/23	23.3	54.0	31.8	101.3	0.5	1.7	121.3	1.2
23/3/23	24.8	56.3	34.2	125.6	0.6	1.8	145.6	1.5
24/3/23	29.7	66.2	29.5	96.9	0.6	1.7	116.9	1.2
25/3/23	22.8	55.9	28.0	107.5	0.6	1.7	127.5	1.3
26/3/23	28.8	74.8	32.9	107.3	0.6	1.8	127.3	1.3
27/3/23	38.7	103.3	41.9	109.6	0.7	1.9	129.6	1.3
28/3/23	39.1	101.2	54.2	113.2	1.2	1.9	133.2	1.3
29/3/23	36.5	93.7	40.8	126.4	0.8	1.9	146.4	1.5
30/3/23	35.1	84.2	35.8	138.9	0.7	1.9	158.9	1.6
31/3/23	31.8	75.2	26.5	113.4	0.5	1.8	133.4	1.3
1/4/23	30.6	72.2	29.7	114.1	0.6	1.8	134.1	1.3
2/4/23	25.8	61.7	33.8	105.8	0.7	1.8	125.8	1.3
3/4/23	29.4	71.6	34.8	125.9	0.6	1.8	145.9	1.5
4/4/23	35.3	86.2	36.5	122.3	0.8	1.9	142.3	1.4
5/4/23	39.4	100.6	38.9	123.0	0.7	1.9	143.0	1.4

6/4/23	30.5	81.3	39.0	128.4	0.8	1.8	148.4	1.5
7/4/23	42.2	107.6	56.7	137.7	1.1	2.0	157.7	1.6
8/4/23	60.1	150.0	69.3	146.8	1.8	2.3	166.8	1.7
9/4/23	58.0	143.2	57.5	122.9	1.4	2.2	142.9	1.4
10/4/23	56.9	141.7	62.2	159.2	1.7	2.3	179.2	1.8
11/4/23	34.7	87.8	66.3	169.4	1.0	2.0	189.4	1.9

Vatva	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	Fuzzy based AQHI	NAQI	NAQI'
16/3/23	144.7	263.0	21.0	37.9	1.9	2.4	319.2	3.2
17/3/23	103.0	191.0	4.5	56.7	0.7	2.1	242.1	2.4
18/3/23	69.9	144.1	0.6	37.6	0.8	1.7	131.5	1.3
19/3/23	82.1	162.6	57.7	19.5	0.7	1.8	173.1	1.7
20/3/23	65.0	130.8	3.7	16.3	0.6	1.6	120.8	1.2
21/3/23	57.3	121.2	10.9	12.0	0.6	1.6	114.4	1.1
22/3/23	51.0	106.5	4.6	15.4	0.7	1.5	104.7	1.0
23/3/23	92.8	182.2	59.8	23.7	0.8	2.0	207.3	2.1
24/3/23	42.2	91.9	13.2	29.1	0.6	1.4	91.9	0.9
25/3/23	54.5	119.5	1.1	19.0	0.7	1.5	113.3	1.1
26/3/23	65.7	162.7	1.2	21.3	0.9	1.7	142.0	1.4
27/3/23	61.8	148.4	3.8	32.6	0.8	1.6	132.5	1.3
28/3/23	68.9	167.2	17.3	25.1	1.1	1.7	145.0	1.4
29/3/23	68.7	153.5	69.6	29.7	0.9	1.7	135.9	1.4
30/3/23	63.4	135.3	28.9	16.3	0.7	1.6	123.8	1.2
31/3/23	68.5	143.7	35.1	15.1	0.9	1.7	129.4	1.3
1/4/23	44.9	96.7	15.5	15.0	0.6	1.4	96.7	1.0
2/4/23	57.5	126.4	52.3	24.8	0.7	1.6	117.9	1.2
3/4/23	54.4	119.2	85.3	14.4	1.0	1.6	113.1	1.1
4/4/23	56.9	133.0	32.4	23.4	0.9	1.6	122.3	1.2
5/4/23	60.5	148.1	112.7	12.5	0.7	1.7	132.3	1.3
6/4/23	66.9	154.6	0.0	30.5	0.9	1.7	136.6	1.4
7/4/23	125.9	276.9	49.3	25.3	1.7	2.3	304.7	3.0
8/4/23	96.1	212.3	75.0	16.4	1.2	2.1	218.5	2.2
9/4/23	116.3	251.8	9.0	26.0	1.2	2.2	287.4	2.9
10/4/23	103.6	231.3	76.5	23.7	1.4	2.2	244.1	2.4
11/4/23	44.1	111.0	0.0	21.6	0.8	1.4	107.6	1.1
12/4/23	48.0	116.8	11.7	23.8	0.8	1.5	111.5	1.1
13/4/23	57.6	138.6	3.5	13.7	0.7	1.6	126.0	1.3
14/4/23	56.3	138.3	4.7	18.9	0.8	1.6	125.8	1.3
15/4/23	77.9	178.4	50.6	10.5	0.9	1.8	158.7	1.6
16/4/23	53.8	127.4	14.3	19.3	0.8	1.5	118.5	1.2
17/4/23	54.1	134.8	11.7	19.5	0.9	1.5	123.4	1.2
18/4/23	63.2	160.1	89.7	16.2	0.9	1.7	140.3	1.4
19/4/23	32.9	83.3	0.0	17.8	0.6	1.3	83.3	0.8
20/4/23	75.5	184.7	77.3	16.2	0.9	1.8	156.6	1.6
21/4/23	38.9	95.8	14.1	25.7	0.6	1.4	95.8	1.0

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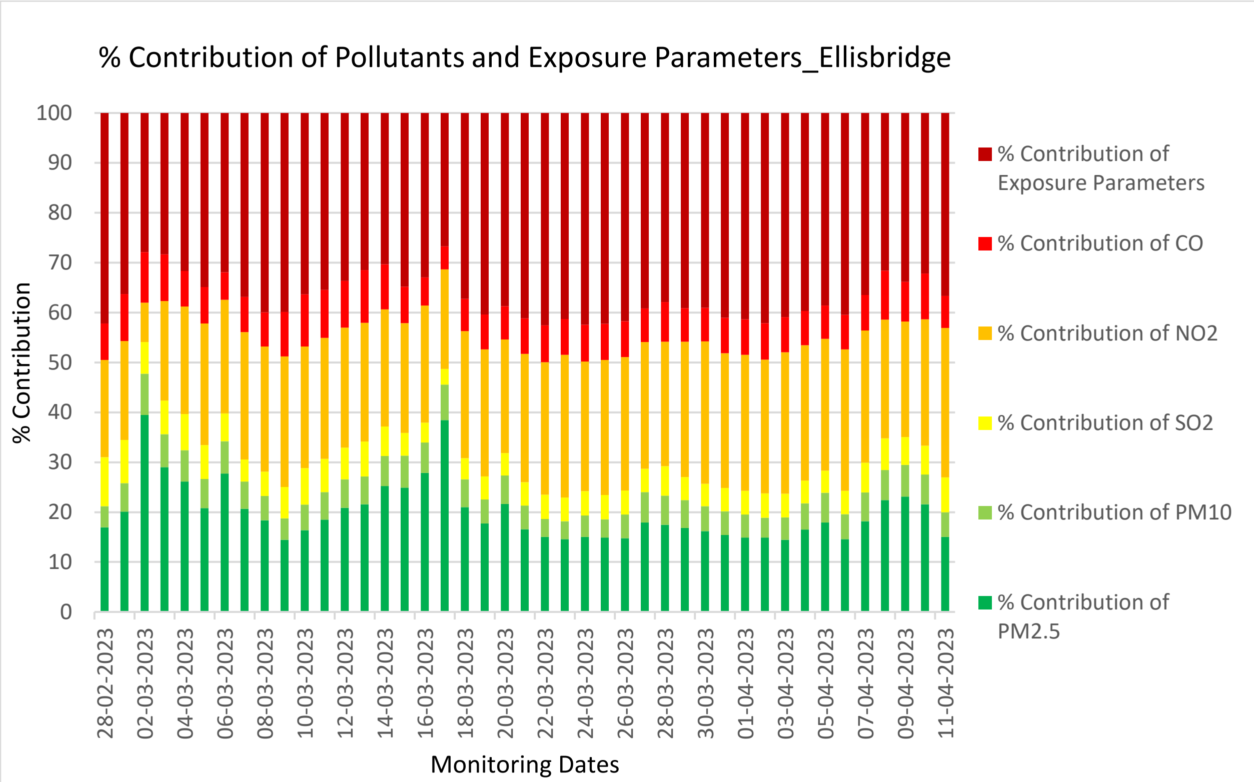
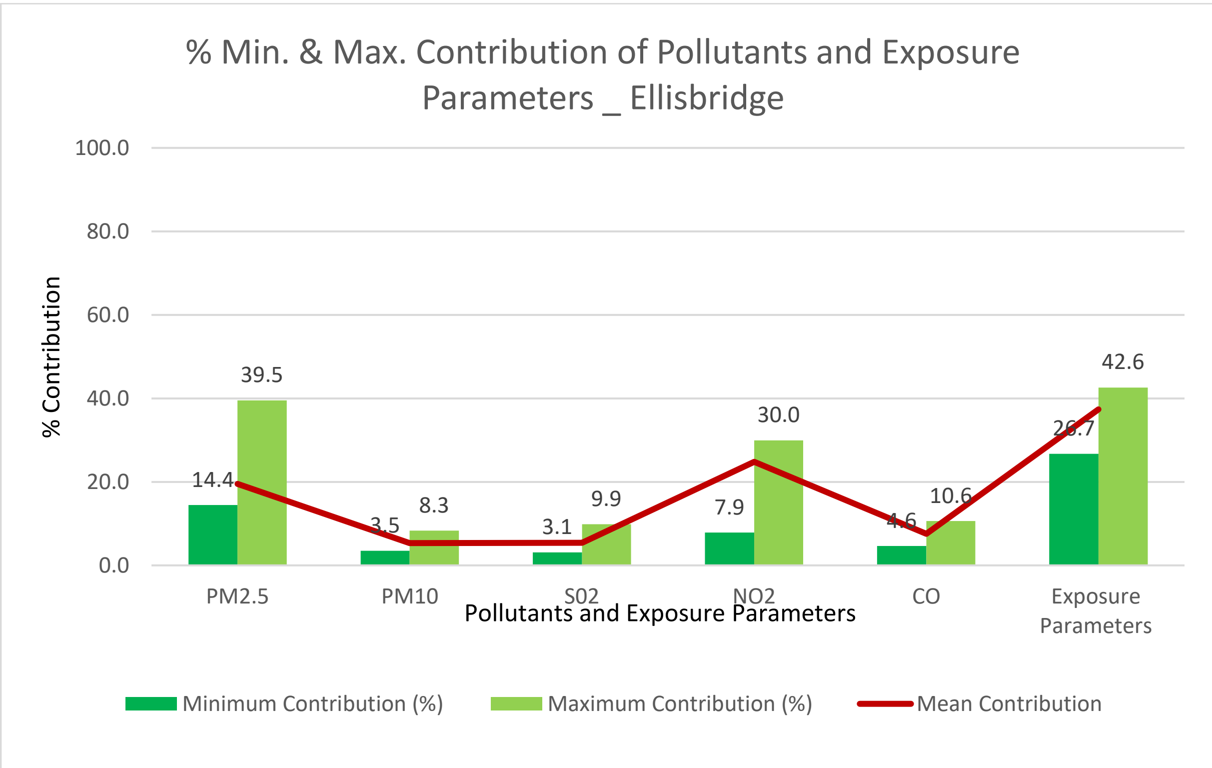
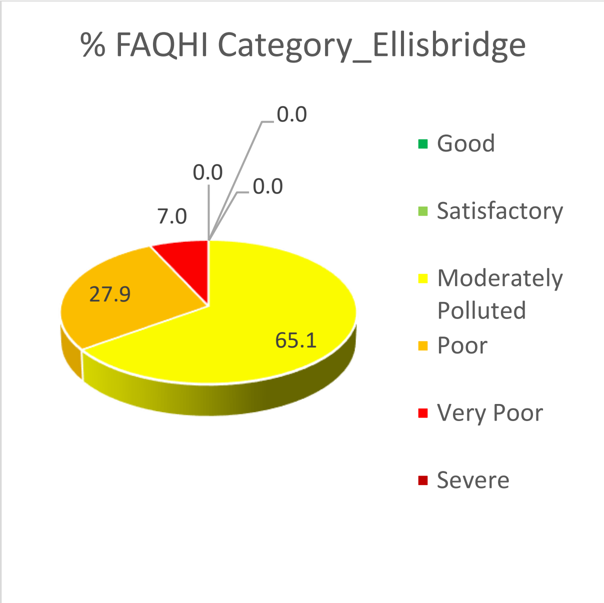
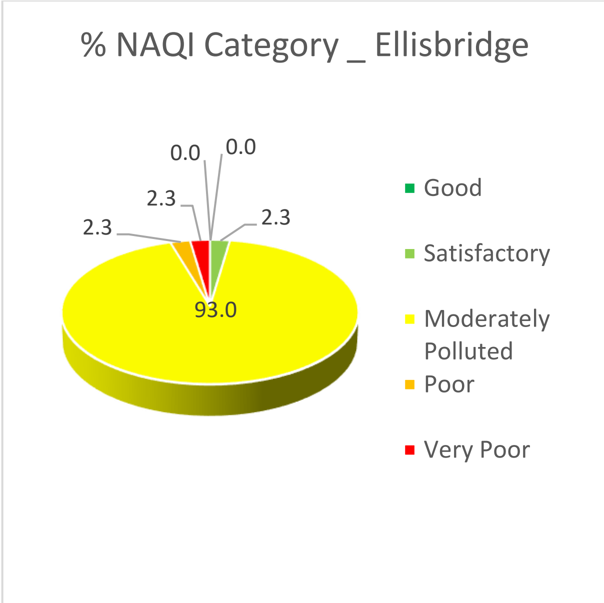
Annexure - IX
Graphical representation of Fuzzy-based AQHI characteristics, % Minimum and Maximum Contribution of Pollutants and Exposure Parameters, % FAQHI and % NAQI Category
Location - Ellisbridge

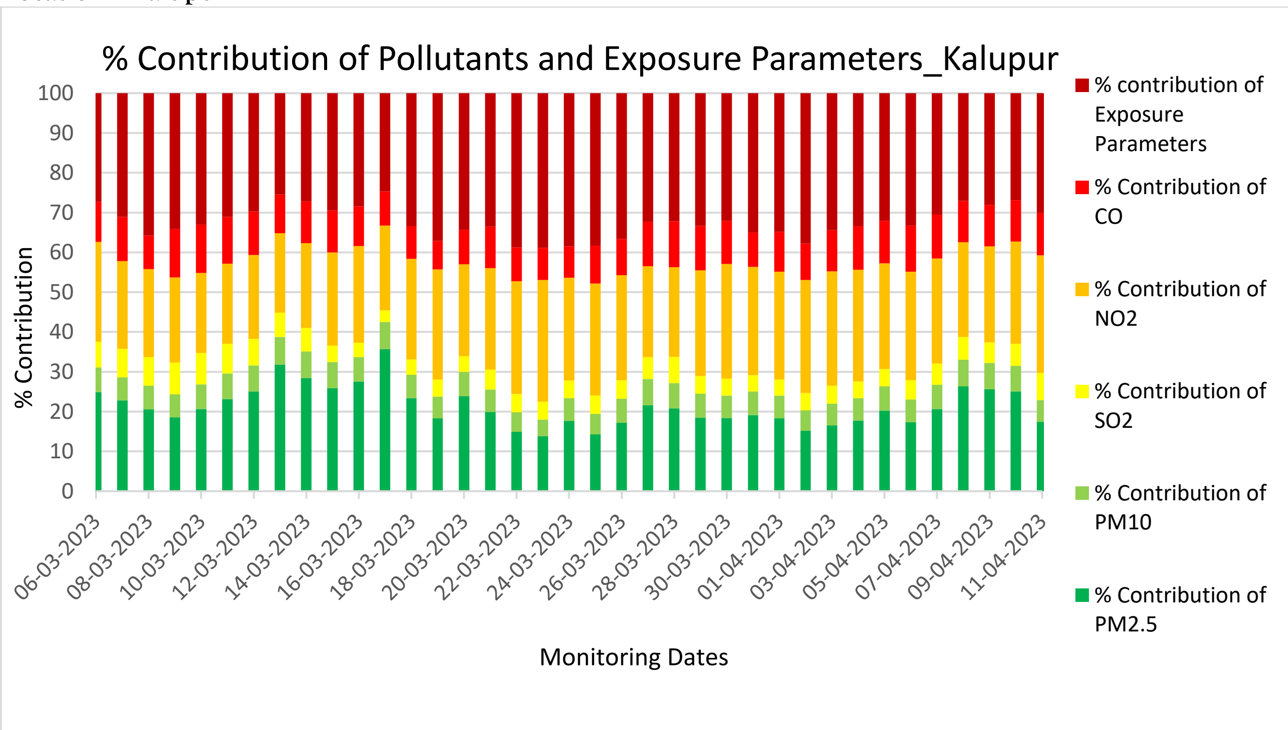


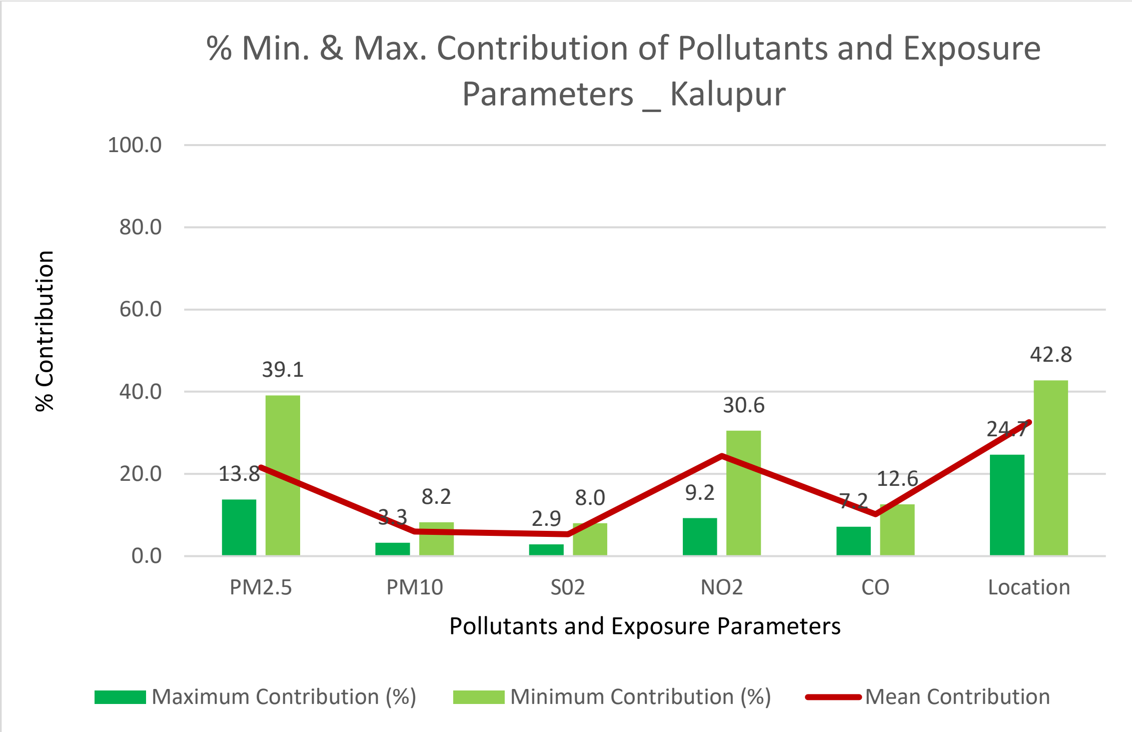




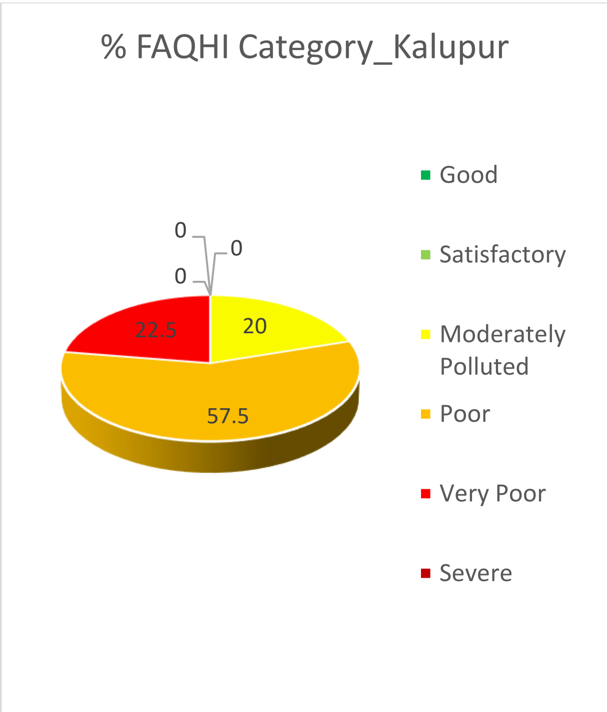


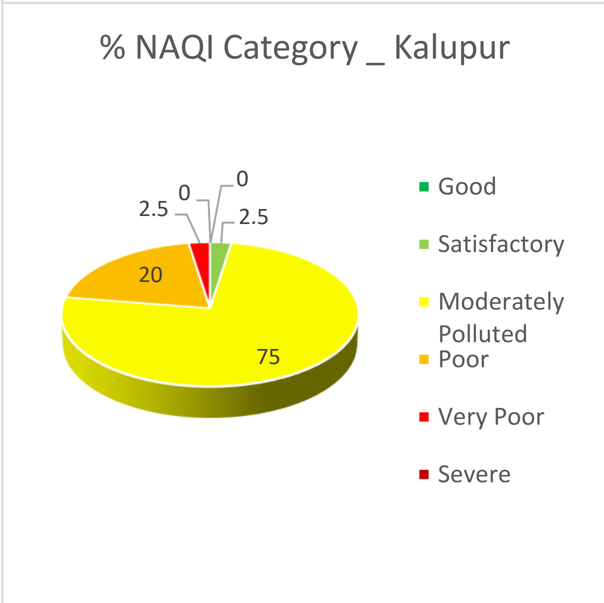
Location - Kalupur

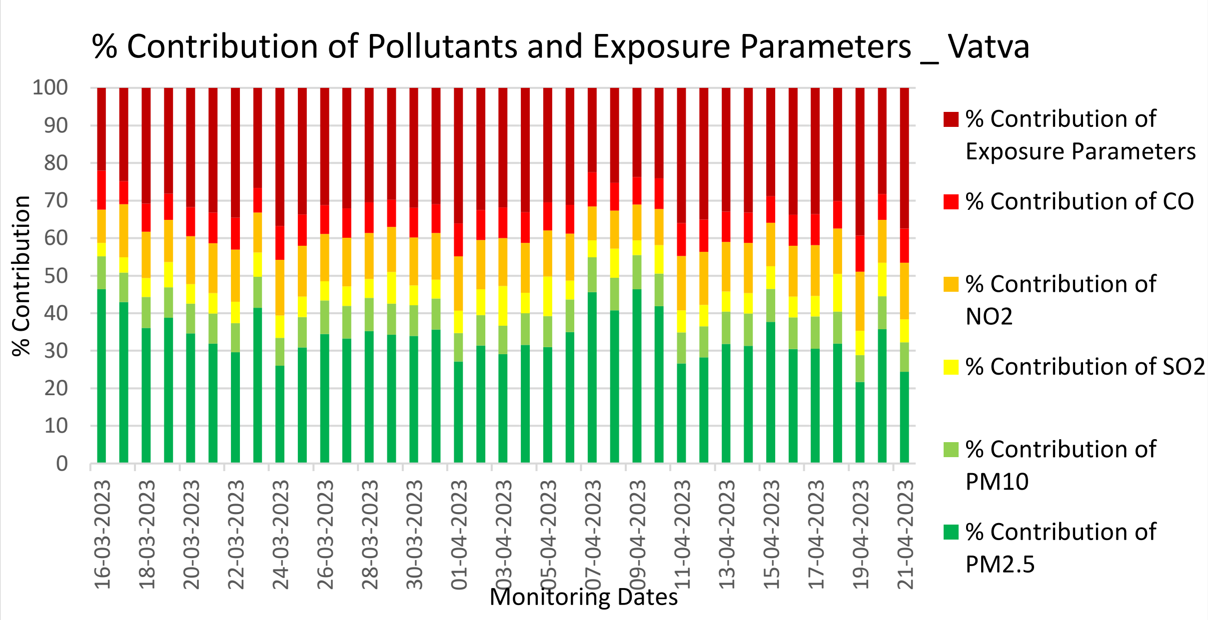


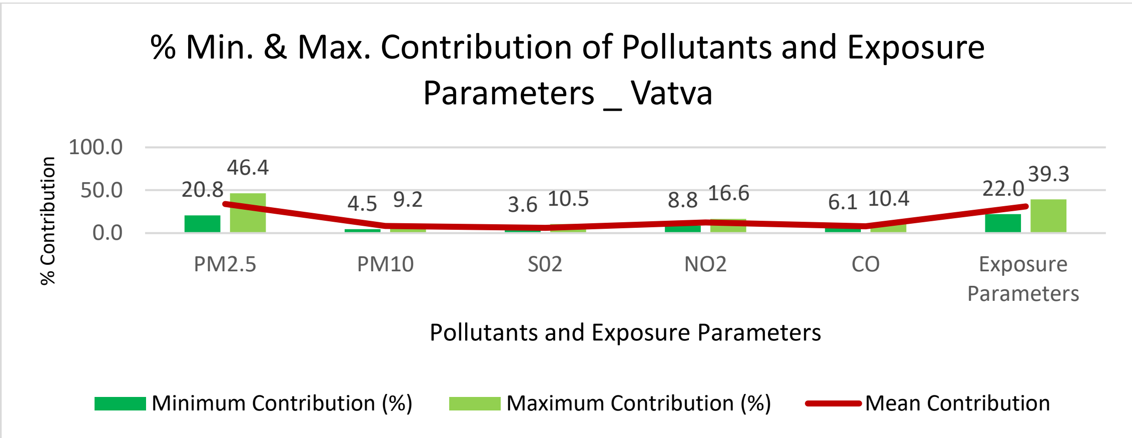


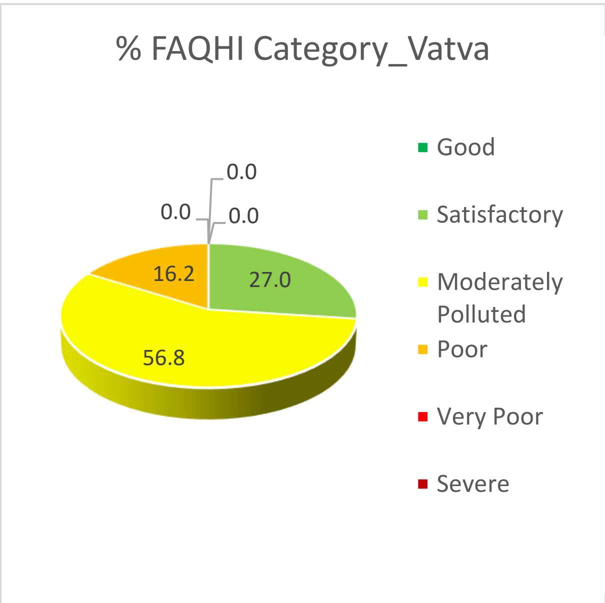
Location – Vava GIDC






% Contribution of Pollutants and Exposure Parameters _ Vatva
% Contribution
Monitoring Dates
% Contribution of Exposure Parameters
% Contribution of CO
% Contribution of NO2
% Contribution of SO2
% Contribution of PM10
% Contribution of PM2.5


% Min. & Max. Contribution of Pollutants and Exposure Parameters _ Vatva
% Contribution
20.8 46.4
4.5 9.2
3.6 10.5
8.8 16.6
6.1 10.4
22.0 39.3
PM2.5
PM10
S02
NO2
CO
Exposure Parameters
Pollutants and Exposure Parameters
Minimum Contribution (%)
Maximum Contribution (%)
Mean Contribution


% FAQHI Category_Vatva
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0.0
16.2
27.0
56.8
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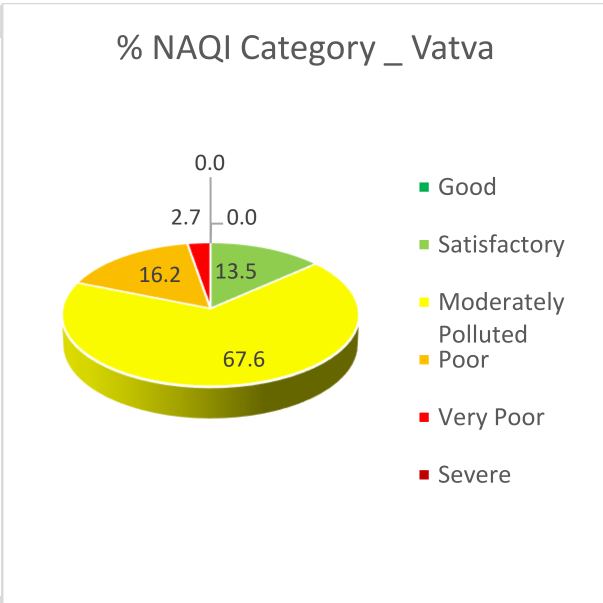
Satisfactory
Moderately Polluted
Poor
Very Poor
Severe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0.0
16.2
13.5
67.6
Good
Satisfactory
Moderately Polluted
Poor
Very Poor
Severe