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An innovative approach for determination of air quality health index

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Abstract

Fuzzy-analytical hierarchical process (F-AHP) can be extended to determine fuzzy air quality health index (FAQHI) for deducing health risk associated with local air pollution levels, and subjective parameters. The present work aims at determining FAQHI by considering five air pollutant parameters (SO₂, NO₂, O₃, CO, and PM₁₀) and three subjective parameters (population sensitivity, population density and location sensitivity). Each of the individual pollutants has varying impacts. Hence the combined health effects associated with the pollutants were estimated by aggregating the pollutants with different weights. Global weights for each evaluation alternatives were determined using fuzzy-AHP method. The developed model was applied to determine FAQHI in Howrah City, India from daily-observed concentrations of air pollutants over the three-year period between 2009 and 2011. The FAQHI values obtained through this method in Howrah City range from 1 to 3. Since the permissible value of FAQHI (as calculated for NAAQS) for residential areas is 1.78, higher index values are of public health concern to the exposed individuals. During the period of study, the observed FAQHI values were found to be higher than 1.78 in most of the day in the months of January to March, and October to December. However, the index values were below the recommended limit during rest of the months. In conclusion, FAQHI in Howrah city was above permissible limit in winter months and within acceptable values in summer and rainy months. Diurnal variations of FAQHI showed a similar trend during the three-year period of assessment.

Graphical abstract

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Conflicts of interest

The authors declare no conflicts of interest.

Keywords

Air quality health index; Fuzzy-AHP

1. Introduction

Air pollution is global environmental problem that influences mostly health of urban population. Over the past few decades, epidemiological studies have demonstrated adverse health effects due to higher ambient levels of air pollution. Studies have indicated that repeated exposures to ambient air pollutants over a prolonged period of time increases the risk of air-borne diseases like cardiovascular disease, respiratory disease, and lung cancer (WHO, 2009). Air pollution has been consistently linked to substantial burdens of ill-health in developed and developing countries (Schwartz, 1994; WHO, 1999; Bruce et al., 2000; Smith et al., 2000; Gorai et al., 2014).

Globally, many cities continuously assess air quality using monitoring networks designed to measure and record air pollutant concentrations at several points deemed to represent exposure of the population to these pollutants. Current research indicates that guidelines of recommended pollution values cannot be regarded as threshold values below which a zero adverse response may be expected (WHO, 2000; Koenig and Mar, 2000; Gent et al., 2003). Therefore, the simplistic comparison of observed values against guidelines may mislead unless suitably quantified. Again, each of the individual pollutants may have varying impacts and thus the combined health effects associated with various pollutants should be determined by aggregating the pollutants with different weights. Thus, a more sophisticated tool has been developed to communicate the health risk of ambient concentrations using air pollution index (API) or air quality index (AQI). Various air quality indices have been developed to integrate air quality variables worldwide (U.S. EPA, 1976, 1998; Malaysia, 1997; Ontario, 1991; ORAQI, 1971) but most of the methods have different characteristics not only with type of aggregation but also with number and type of pollutants.

The present research attempts to demonstrate the development of a fuzzy-analytical hierarchical process (FAHP) model for determination of fuzzy air quality health index (FAQHI). FAQHI will help to link the health risk associated with local air pollution levels,

location sensitivity, population sensitivity, and population density. Since the impact of air pollution on human health involves uncertainty, the present study also considers the uncertainty factors involved in air quality assessment.

2. Fuzzy-analytical hierarchical process (F-AHP)

Fuzzy analytical hierarchy process (F-AHP) is the extension of analytical hierarchy process (Saaty, 1980) used for structuring the problem. AHP is particularly useful for evaluating complex multi-attribute alternatives involving subjective criteria. There are few essential steps in the application of AHP viz. decomposing a general decision problem in a hierarchical fashion into sub-problems that can be easily comprehended and evaluated; determining the priorities of the elements at each level of the decision hierarchy, and synthesizing the priorities to determine the overall priorities of the decision alternatives. However, the subjective pair-wise comparison is prone to vagueness type uncertainty and hence there is a need for exploring fuzzy-based techniques. The first attempt in the integration of fuzzy-based technique with AHP is done by van Laarhoven and Pedrycz (1983) for comparison of fuzzy ratios described by triangular fuzzy numbers (TFNs) and weight computation using logarithmic least squares method. Subsequently the method has been modified by many researchers (Buckley, 1985; Boender et al., 1989; Cheng, 1999; Chang, 1996; Zhu et al., 1999; Lee et al., 1999; Deng, 1999; Leung and Cao, 2000) to improve the applicability in various fields.

The present work demonstrates the application of fuzzy-AHP approach for determining the weights for air quality health index attributes, which subsequently used in determination of fuzzy air quality health index (FAQHI). Most of the existing air quality index system (AQI or PSI system of U.S. EPA, ORAQI system of Oak Ridge National Laboratory, Ontario AQI system etc.) either based on the single parameter index or do not consider the subjective parameters and thus does not reflect the combined effects due to existence of multi-pollutant and subjective parameters. The present work attempts to develop an air quality health index model by considering the multi-pollutant parameters (SO_2 , NO_2 , O_3 , CO , and PM_{10}) along with subjective parameters (population sensitivity, population density and location sensitivity). The study also considers the different weights for different attributes in determining the FAQHI. The process of the weight determination problem primarily depends upon the health impacts of the people. In case of simple AHP, it is difficult to incorporate preference scales (such as “less likely”, “more likely” etc.) in the analytical models. In fact, the scale of preference is fuzziness in nature. Therefore, using a crisp value for pair-wise comparison is not suitable because it does not accurately represents the individual semantic cognition state of the decision makers. Fuzzy logic (Zadeh, 1965) is a proven scientific technique that allows us to convert linguistic measures into crisp measure using membership functions. Membership functions define the fuzzy boundary between two measurements scales such as ‘less likely’ and ‘likely’.

3. Materials and methods

The present work builds on the application of F-AHP by incorporating the decision maker's attitude in determination of air quality health index. The flowchart of the working

methodology is shown in Fig. 1. A step-by-step description of the methodology for fuzzy air quality health index (FAQHI) model development is presented as follows:

3.1. Development of hierarchical structures

The basic risk attributes are grouped into higher-level risk factors that form a multi-stage hierarchical model of aggregative risk for air quality health index. The usage of fuzzy set techniques for air quality indexing enables the incorporation of field data (e.g. observed air quality) and soft qualitative data (e.g. expert opinion).

To develop the hierarchical model for air quality health index, all the attributes or influencing factors have to be structured into different hierarchical levels. A three level hierarchical tree is illustrated in Fig. 2. The first layer of the hierarchy corresponds to objective or goal (air quality health index), and the last layer corresponds to the evaluation alternatives (options), whereas the intermediate levels correspond to different criteria. Each criterion in the intermediate levels is influenced by the corresponding evaluation option respectively.

3.2. Weighting scheme

The proposed methodology requires information for relative importance of attributes or criteria of various parameters considered in the model. The relative importance was established using fuzzy-AHP method. The methodology is explained below in detail.

3.2.1. Pair-wise comparisons—Fuzzy pair wise comparison matrices are developed for each of the group of variables as shown in Fig. 2. The detailed method is explained in Appendix A. Matrices PI, EI, FAQHI are representing pair-wise comparison matrices for pollutant variables, exposure variables, and air quality health index variables respectively.

$$PI = \begin{matrix} & \begin{matrix} SO_2 \\ CO \\ PM_{10} \\ NO_2 \\ O_3 \end{matrix} \end{matrix} \begin{bmatrix} SO_2 & CO & PM_{10} & NO_2 & O_3 \\ \bar{1} & 1/\bar{1.5} & 1/\bar{2} & 1/\bar{2.5} & 1/\bar{3} \\ \bar{1.5} & \bar{1} & 1/\bar{1.5} & 1/\bar{2} & 1/\bar{2.5} \\ \bar{2} & \bar{1.5} & \bar{1} & 1/\bar{1.5} & 1/\bar{2} \\ \bar{2.5} & \bar{2} & \bar{1.5} & \bar{1} & 1/\bar{1.5} \\ \bar{3} & \bar{2.5} & \bar{2} & \bar{2.5} & \bar{1} \end{bmatrix};$$

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

In the above matrices, matrix PI represents the pair-wise comparison of five major pollutants (SO_2 , CO , PM_{10} , NO_2 , and O_3) whereas matrix EI represents the pair-wise comparison of the parameters population sensitivity (PS), population density (PD) and location sensitivity (LS) respectively. Matrix FAQHI represents the pair-wise comparison of the parameters pollution index (PI) and exposure index (EI).

The next step is to introduce the α -cut for defining the range of uncertainty. The above pair-wise comparison matrices (PI, EI, and FAQHI) are converted into new matrices (PI_f, EI_f, and FAQHI_f) to define the lower limit and upper limit of the fuzzy numbers with respect to α -cut values by applying the following Eq. (1). That is,

$$\bar{x}_\alpha = [x - \alpha, x + \alpha]; \frac{1}{\bar{x}_\alpha} = \left[\frac{1}{x + \alpha}, \frac{1}{x - \alpha} \right]. \quad (1)$$

Here the value of α is assumed to be 1. Thus, the fuzzy comparison matrices for all the groups are as follows:

$$PI_f = \begin{matrix} SO_2 \\ CO \\ PM_{10} \\ NO_2 \\ O_3 \end{matrix} \begin{bmatrix} SO_2 & CO & PM_{10} & NO_2 & O_3 \\ [1] & [0.4 \ 2] & [0.33 \ 1] & [0.29 \ 0.67] & [0.25 \ 0.5] \\ [0.5 \ 2.5] & [1] & [0.4 \ 2] & [0.33 \ 1] & [0.29 \ 0.67] \\ [1 \ 3] & [0.5 \ 2.5] & [1] & [0.4 \ 2] & [0.33 \ 1] \\ [1.5 \ 3.5] & [1 \ 3] & [0.5 \ 2.5] & [1] & [0.4 \ 2] \\ [2 \ 4] & [1.5 \ 3.5] & [1 \ 3] & [0.5 \ 2.5] & [1] \end{bmatrix}$$

$$EI_f = \begin{matrix} LS \\ PD \\ PS \end{matrix} \begin{bmatrix} LS & PD & PS \\ [1] & [1/4 \ 1/2] & [1/6 \ 1/4] \\ [2 \ 4] & [1] & [1/4 \ 1/2] \\ [4 \ 6] & [2 \ 4] & [1] \end{bmatrix}; FAQHI_f = \begin{matrix} SI \\ PI \end{matrix} \begin{bmatrix} SI & PI \\ [1] & [1/4 \ 1/3] \\ [2 \ 4] & [1] \end{bmatrix}$$

3.2.2. Generation of crisp comparison matrix—The fuzzy comparison matrix can be converted to a crisp matrix using following Eq. (2) (Lee 1999).

$$a_{ij}^\alpha = \lambda a_{iju}^\alpha + (1 - \lambda) a_{ijl}^\alpha \quad (2)$$

Where, a_{iju}^α and a_{ijl}^α are upper and lower fuzzy value of comparison element (a_{ij}). These are giving a defuzzified value a_{ij}^α and will form crisp comparison matrix. The value of λ ranges from 0 to 1 and according to definition $\lambda = 1$ represents a pessimistic decision-making attitude. In this case, we have considered the value of λ is 0.5. Thus the fuzzy comparison matrices (PI_f, EI_f, and FAQHI_f) are converted into crisp matrices (PI', EI', and FAQHI') as follows:

$$PI' = \begin{matrix} SO_2 \\ CO \\ PM_{10} \\ NO_2 \\ O_3 \end{matrix} \begin{bmatrix} SO_2 & CO & PM_{10} & NO_2 & O_3 \\ 1 & 1.2 & 0.67 & 0.48 & 0.375 \\ 1.5 & 1 & 1.2 & 0.67 & 0.48 \\ 2 & 1.5 & 1 & 1.2 & 0.67 \\ 2.5 & 2 & 1.5 & 1 & 1.2 \\ 3 & 2.5 & 2 & 1.5 & 1 \end{bmatrix}; EI' = \begin{matrix} LS \\ PD \\ PS \end{matrix} \begin{bmatrix} LS & PD & PS \\ 1 & 0.375 & 0.21 \\ 3 & 1 & 0.375 \\ 5 & 3 & 1 \end{bmatrix};$$

$$FAQHI' = \begin{matrix} EI \\ PI \end{matrix} \begin{bmatrix} EI & PI \\ 1 & 0.375 \\ 3 & 1 \end{bmatrix}.$$

3.2.3. Check for consistency—The consistencies of the above crisp matrices are checked using the consistency ratio (CR) values. The detailed method is explained in Appendix B. The values of CR are listed in Table 1. Consistency ratio of each matrix was calculated and found within the recommended limit (0.1) (Saaty, 2005). It indicates that matrices are consistent.

3.2.4. Determination of fuzzy weights—The present study uses the eigen vector computation for estimating the weights. The eigen values and eigen vectors of crisp matrices was calculated using MATLAB 7.10.0 version software. The detailed method is explained in Appendix C. The fuzzy weights are determined as follows:

$$PI_v = \begin{bmatrix} SO_2 & CO & PM_{10} & NO_2 & O_3 \\ 0.23 & 0.31 & 0.41 & 0.53 & 0.63 \end{bmatrix};$$

$$EI_v = \begin{bmatrix} LS & PD & PS \\ 0.16 & 0.38 & 0.91 \end{bmatrix};$$

$$FAQHI_v = \begin{bmatrix} EI & PI \\ 0.33 & 0.94 \end{bmatrix}.$$

Matrices PI_v , EI_v and $FAQHI_v$ are representing eigen vector of crisp matrix PI' , EI' and $FAQHI'$. Normalization of eigen vector represents the local weights of individual parameters. These are represented by matrices PI_w , EI_w and $FAQHI_w$ respectively.

$$PI_w = \begin{matrix} SO_2 \\ CO \\ PM_{10} \\ NO_2 \\ O_3 \end{matrix} \begin{bmatrix} 0.11 \\ 0.15 \\ 0.19 \\ 0.25 \\ 0.30 \end{bmatrix}; EI_w = \begin{matrix} LS \\ PD \\ PS \end{matrix} \begin{bmatrix} 0.11 \\ 0.26 \\ 0.63 \end{bmatrix}; FAQHI_w = \begin{matrix} EI \\ PI \end{matrix} \begin{bmatrix} 0.26 \\ 0.74 \end{bmatrix}$$

3.2.5. Determination of global weight—The local priorities at each level are aggregated to obtain final preferences of the alternative. After determining the relative importance at each hierarchical level, the overall weight of parameter is to be determined. The importance depicted in above matrices (PI_w , EI_w , and $FAQHI_w$) has been used to calculate the cumulative weight of individual parameters. The detailed method is explained in Appendix D. The cumulative weights of each parameter are listed in Table 2.

3.3. Data collection and analysis

The procedure described in Section 3.2 was applied to case studies in the Howrah City region of India. Howrah is an industrial city situated on west bank of the Hoogli River in West Bengal, India. Howrah district lies between $22^{\circ}48' \text{ N}$ and $22^{\circ}12' \text{ N}$ latitudes and between $88^{\circ}23' \text{ E}$ and $87^{\circ}50' \text{ E}$ longitudes. As per 2011 population census, the total population of Howrah district was 4,273,099. The population growth rate in Howrah district was found to be lower (13.31%) as compared to national growth rate (21.15%) in the last decade (2001 to 2011). Howrah district administers 1467 km² of areas. The district of Howrah once occupied the prime position and was considered to be one of the highly industrialized districts in West Bengal. A number of industries like engineering, casting, steel fabrication, ship building, consumer goods industries, construction pressure die casting, forging, electric installations, manufacturing of industrial electrical goods accessories etc. had a large concentration in the district. Howrah city continues to defile ambient air quality due to dense conglomerate of small scale industries without air pollution management, huge traffic congestion and human settlement.

The air pollution data of Howrah city during the period 2009 to 2011 was used for the determination of air quality health index. The data used for assessment was taken from the West Bengal Pollution Control Board (WBPCB) website (Source: <http://emis.wbpcb.gov.in/airquality/citizenreport.do>). The monitoring station of WBPCB is located in Howrah municipal corporation area. The pollution concentrations of five major air pollution parameters (SO₂, NO₂, PM₁₀, O₃, and CO) were selected to represent air quality health index. The diurnal average (24 h) concentrations of SO₂, NO₂, PM₁₀ and maximum daily 8 hourly average concentrations O₃, and CO during 2009, 2010, and 2011 are represented in Fig. 3(a)–(e). The descriptive statistics of the pollutant concentration variations is represented in Table 3. The annual average of PM₁₀ concentration in 2011 ($160.01 \pm 117.32 \mu\text{g}/\text{m}^3$) was found to be lower than 2010 ($175.66 \pm 138.52 \mu\text{g}/\text{m}^3$). The annual average PM₁₀ concentration level in 2010 was found to be lower than 2009 ($185.57 \pm 121.16 \mu\text{g}/\text{m}^3$). This clearly indicates that the annual average concentration of PM₁₀ has been decreased during 2009 to 2011. Similar trend was observed for CO concentration. The annual average of 8 h average CO concentration in 2011 ($0.939 \pm 0.632 \text{ mg}/\text{m}^3$) was found to be lower than 2010 ($1.344 \pm 0.961 \text{ mg}/\text{m}^3$). The annual average of 8 h average concentration of CO in 2010 was found to be lower than 2009 ($1.59 \pm 0.72 \text{ mg}/\text{m}^3$). Fig. 3(d) clearly reveals that the 8 h average concentration of CO exceeded the permissible limit [National Ambient Air Quality Standard (NAAQS) for CO is $2 \text{ mg}/\text{m}^3$ (8 h. average) in India] during winter months in every observed years. But, the reverse trend was observed for SO₂ and NO₂. The annual average concentration of SO₂ was increased from $17.68 \mu\text{g}/\text{m}^3$ (2009) to $43.048 \mu\text{g}/\text{m}^3$ (2011). The best thing is that the annual average concentration of SO₂ was within the permissible limit ($50 \mu\text{g}/\text{m}^3$) in each of the observed year. But, Fig. 3(a) indicates that the diurnal average concentration of SO₂ exceeded the permissible limit ($80 \mu\text{g}/\text{m}^3$) during winter months. The annual average concentration of NO₂ has been increased from $63.87 \mu\text{g}/\text{m}^3$ (2009) to $78 \mu\text{g}/\text{m}^3$ (2011). The worst thing is that the annual average concentration of NO₂ exceeded the permissible limit ($40 \mu\text{g}/\text{m}^3$). Fig. 3(b) indicates that the diurnal average concentration of NO₂ exceeded the permissible limit ($80 \mu\text{g}/\text{m}^3$) during winter months. The annual average of 8 h average concentration of ozone was found to decrease

from 0.033 ppm in 2009 to 0.0213 ppm in 2010, whereas it increased to 0.078 ppm in 2011. Thus, no uniform trend was observed in ozone concentration. Fig. 3(e) clearly indicates that the 8 h average concentration of ozone was within the permissible limit (0.0509) in every season of each observed years except one occasion in 2011. This is because ozone is secondary pollutant and the formation and destruction of ozone depends on many factors like NO_x concentration, solar radiation, volatile organic compounds (VOC's) concentration etc. Table 3 also clearly reveals that the fluctuation of SO₂, NO₂ and O₃ concentration during the observed years, which has increased continuously as the standard deviation value has been increased. But there was no uniform trend in variation (standard deviation) for PM₁₀ and CO concentration.

3.4. Development of membership functions

The fuzzy membership function (MF) is a key concept in designing fuzzy systems. In addition to fuzzy rules construction, constructing a suitable MF has been a challenge for three decades. Membership Functions (MFs) characterize the fuzziness in a fuzzy set in a graphical form for eventual use in the mathematical formalisms of the fuzzy set theory. This illustrates whether the functions are discrete or continuous. Three linguistic variables (fuzzy subsets) are defined using triangular fuzzy numbers (TFNs) for exposure and air pollution parameters. In the present study, three fuzzy subsets [low (μ_L), medium (μ_M), high (μ_H)] were considered to maintain simplicity in the analysis.

It is already mentioned in earlier sections that five pollutants and three exposure parameters were considered for the air quality health assessment. Air pollution parameters included — CO, NO₂, PM₁₀, O₃ and SO₂. Exposure parameters included location sensitivity (LS), population density (PD), and population sensitivity (PS). Table 4 defines the equations of TFNs of five pollutants (CO, NO₂, PM₁₀, O₃ and SO₂) for each of the linguistic variable [low (μ_L), medium (μ_M), high (μ_H)]. The membership function (μ) for each linguistic variable was defined on the basis of various regulatory values (listed in Table 5). The observed pollutant concentration levels were converted into the membership degree viz. low (μ_L), medium (μ_M) and high (μ_H) using the corresponding equation (listed in Table 4) for each day of observed data (2009 to 2011).

Three types of subjective parameters [location sensitivity (LS), population density (PD) and population sensitivity (PS)] were considered for the study. Table 6 provides details of three exposure parameters — location sensitivity (LS), population density (PD), and population sensitivity (PS). The LS refers to the importance of various areas (residential, commercial, industrial) with respect to their potential use. A scale is defined over a range of 1–3. The higher the score the more sensitive is the area. For example, hospitals and nursing homes are rated highly sensitive locations and assigned a value of 3. A value of 1 is assigned to an industrial location and 2 for residential areas. The population density refers to population per unit area and this is a quantified variable and hence used direct value to develop the membership function. Higher population density refers to higher values as an exposure parameter and vice-versa. This is because the number of people affected will be more in highly dense populated area as comparison to the less dense populated areas. Population sensitivity is also defined over a range of 1–3. The highest value of 3 is assigned to a

population with more than 50% vulnerable inhabitants (population of age group below 18 and/or above 60 years). Whereas a rating value of 1 is assigned to a population with less than 25% vulnerable habitants and a rating value of 2 is assigned to population with 25–50% of vulnerable habitants. These numerical values for various exposure parameters are converted into linguistic variables—low (μ_L), medium (μ_M), high (μ_H) using the corresponding equation listed in Table 7. Each linguistic variable is defined by TFN. The study area is partially commercial and partial residential and thus it was considered a zone of medium sensitivity. The rank assigned to medium zone sensitivity is ‘2’ on the basis of Table 6. According to 2001 census the average population density of Howrah Municipal Corporation was 19,473 people per sq. km (Source: http://www.howrah.gov.in/Templates/Area_popu.htm). Considering the same population density in 2009, 2010 and 2011, the membership values for population density are $\mu_L = 0$, $\mu_M = 0.06$, and $\mu_H = 0.94$. This indicates the study area is highly sensitive on the basis of population density. As per the 2011 census data of Government of India (Source: http://www.censusindia.gov.in/2011census/population_enumeration.aspx), the populations in the State of West Bengal was recorded as 9,12,76,115. The share of this population in the age group either below 18 or above 60 was 42% (3,86,60,608). Assuming the same proportion of sensitive population in 2009, 2011, and 2011 in the study area due to unavailability of data the corresponding rating for population sensitivity in the study area is ‘2’. Thus the membership value corresponding to rating ‘2’ of population sensitivity are $\mu_L = 0$, $\mu_M = 2$, and $\mu_H = 0$.

3.5. Aggregation

After determining the membership degree of every assessment variable, the membership degree matrix (R) was established where each row represents levels of health risk due to various pollutant and exposure factors. As described before, risk in each case is defined by three partitions — low (μ_L), medium (μ_M), and high (μ_H).

$$R = \begin{bmatrix} \mu_{PM_{10}}^L & \mu_{PM_{10}}^M & \mu_{PM_{10}}^H \\ \mu_{SO_2}^L & \mu_{SO_2}^M & \mu_{SO_2}^H \\ \mu_{NO_2}^L & \mu_{NO_2}^M & \mu_{NO_2}^H \\ \mu_{CO}^L & \mu_{CO}^M & \mu_{CO}^H \\ \mu_{O_3}^L & \mu_{O_3}^M & \mu_{O_3}^H \\ \mu_{LS}^L & \mu_{LS}^M & \mu_{LS}^H \\ \mu_{PD}^L & \mu_{PD}^M & \mu_{PD}^H \\ \mu_{PS}^L & \mu_{PS}^M & \mu_{PS}^H \end{bmatrix}$$

To identify the different effects of each alternative on environment, an ordered weighted product (OWP) approach is used in fuzzy aggregation modelling. This determines cumulative risk through multiplication of membership value of alternatives as represented by matrix R and weight coefficient of alternatives as represented in matrix W . The final fuzzy evaluation matrix, u , for fuzzy air quality health index (FAQHI) can be determined as

$$u = [W_{PM_{10}} W_{SO_2} W_{NO_2} W_{CO} W_{O_3} W_{LS} W_{PD} W_{PS}]$$

$$X = \begin{bmatrix} \mu_{PM_{10}}^L & \mu_{PM_{10}}^M & \mu_{PM_{10}}^H \\ \mu_{SO_2}^L & \mu_{SO_2}^M & \mu_{SO_2}^H \\ \mu_{NO_2}^L & \mu_{NO_2}^M & \mu_{NO_2}^H \\ \mu_{CO}^L & \mu_{CO}^M & \mu_{CO}^H \\ \mu_{O_3}^L & \mu_{O_3}^M & \mu_{O_3}^H \\ \mu_{L^S}^L & \mu_{L^S}^M & \mu_{L^S}^H \\ \mu_{PD}^L & \mu_{PD}^M & \mu_{PD}^H \\ \mu_{PS}^L & \mu_{PS}^M & \mu_{PS}^H \end{bmatrix} = [r^L r^M r^H].$$

3.6. Defuzzification

A process known as defuzzification is used to calculate the crisp value of a fuzzy set. Defuzzification is an important step in multi-criteria evaluation. Many defuzzification techniques (maximum operator, centre of area method, first of maximum, last of maximum and mean of maximum) are available and used by various researchers in different field. But these are not directly used in the present study. Instead of these methods, a weighted average approach (scoring method) is used in this study, where a crisp value of a fuzzy set is determined by assigning weights to its membership (Lu et al., 1999; Silvert, 2000; Sadiq and Rodriguez, 2004). In the last step a 3-tuple fuzzy sets expressed by low (r^L), medium (r^M) and high (r^H) values were derived as represented in matrix u. Assigning a set of three weights viz. 1, 2, and 3 respectively for low, medium and high, we can get a non-fuzzy value. This will represent the air quality health index for a particular location/day/sample. Thus the following Eq. (3) was used for determining the *FAQHI*.

$$FAQHI = 1 * r^L + 2 * r^M + 3 * r^H \quad (3)$$

The coefficients (weights) are assigned arbitrarily in this study and guidelines may be established for air quality health index.

4. Results and discussion

Fuzzy Air quality health index (FAQHI) is shown to represent the possible health impact due to poor air quality in a particular area on the basis of sensitivity of people, population density and location sensitivity. Thus, the index will help to estimate the health impact not only on the basis of air quality but also consider the other local conditions.

FAQHI values in F-AHP method are derived from the relative membership degree of the pollutant concentration and exposure parameters data. The membership degree of each of the evaluation alternatives ranged from 0 to 1. Since our objective was to determine the single index value by aggregating the multi-criteria parameters, the developed F-AHP model was used to aggregate the five pollutant parameters (PM_{10} , CO, SO_2 , NO_2 , and O_3) and three exposure parameters (location sensitivity, population sensitivity and population density).

The proposed model can be applied for determining the permissible FAQHI for different category areas (Industrial, commercial, residential and sensitive) using the corresponding national ambient air quality standards (NAAQS) values of five air pollutants parameters considered in the model. In India, the air pollution standard is categorized into two areas — Industrial/commercial/residential area and sensitive area. The standard values of the five pollutant parameters as per the National Ambient Air Quality Standard (NAAQS) (2009), India (Central Pollution Control Board, 2009) are $100 \mu\text{g}/\text{m}^3$ for PM_{10} , $60 \mu\text{g}/\text{m}^3$ for SO_2 , $60 \mu\text{g}/\text{m}^3$ for NO_x , $2000 \mu\text{g}/\text{m}^3$ for CO, and $100 \mu\text{g}/\text{m}^3$ for ozone in industrial/commercial/residential area.

Thus, one can calculate the safe or permissible FAQHI for industrial/commercial/residential zone using the corresponding standards (NAAQS) values. Similarly, the permissible FAQHI for sensitive zone can be calculated using the NAAQS values for sensitive zone. These indices can be treated as standard or permissible FAQHI and are compared with the indices observed for the observed concentrations levels of air pollutants. FAQHI for permissible concentrations in residential areas of selected air pollution parameters was calculated as 1.78 whereas the index for sensitive areas is 1.32. Higher index value represents high health risk and vice-versa.

The same model was used for the determination of FAQHI for daily observed concentrations for the three-year period (2009–2011) as shown in the Fig. 3(A)–(E). The corresponding FAQHI are represented graphically in Fig. 4 for each day of three-year period. The FAQHI obtained by executing the model ranged from 1 to 3. A value of one indicates good FAQHI, whereas three indicates poor FAQHI. Since the permissible value of air quality health index (as calculated for NAAQS) for residential areas is 1.78, more than this value indicates potential harmful effects on people, if exposed. Maximum values of fuzzy air quality health indices were found to be 2.154, 2.178 and 2.146 respectively for the year 2009, 2010 and 2011. Whereas the minimum values of fuzzy air quality health index in year 2009, 2010 and 2011 were 1.372, 1.283 and 1.332 respectively. The average values of air quality health index for three consecutive years were 1.686, 1.688 and 1.702. Fig. 4 clearly reveals that the fuzzy air quality health index (FAQHI) values were poor during winter months (November to February). This is due to the fact that the pollutant concentration level was high during winter months as already explained in the first section. It indicates that observed FAQHI values are above 1.78 (permissible limit for residential areas) in most of the day of first three months of each year (January to March) and then there is decreasing trend in the subsequent months. FAQHI values were found to be within the permissible limits in most of the day during April to September in every observed year. Again, there is an increasing trend and FAQHI values exceeded the permissible limit in most of the day during next three months (October to December). Thus, the FAQHI values in Howrah city were found to exceed the permissible limit during winter months and within the recommendation limit during summer and rainy months. Hence, by identifying the source or factors which lead to the increase in the FAQHI value during winter month would enable taking proper controlling measures to reduce risk of human health. Fig. 4 also clearly indicates that the comparative values of daily air quality health index trends for all three observed years are more or less same. Though the concentrations of few pollutants have been increased during the observed years, it does not

influence much in the overall FAQHI. This is because the variations of the pollutant concentration did not follow a uniformed trend.

The major advantage of this model over the existing model (AQI or PSI system of U.S. EPA, ORAQI system of Oak Ridge National Laboratory, Ontario AQI system etc.) is that the present model considers the multi-pollutant parameters (SO₂, NO₂, O₃, CO, and PM₁₀) along with subjective parameters (population sensitivity, population density and location sensitivity) in calculating the index value. Again, most of the existing index system is based on the single parameter index and thus does not consider multi-pollutant and the qualitative parameters in health impact assessment. In fact, the impact of air pollution on human health is fuzziness in nature. Therefore, using a crisp index value for assessing the health impact is not suitable because it does not accurately represent the individual's immunity towards disease resistance. FAQHI will help to link the health risk associated with local air pollution levels, location sensitivity, population sensitivity, and population density. The present study deals with accommodating the uncertainty factors involved in air quality assessment. The decision makers can choose a different α -cut value mentioned in Eq. (1) to accommodate the uncertainty factors. A higher α -cut value, increase the uncertainty level and vice versa.

The major limitation of this study is its validation with actual health data. The model output is compared only with the permissible FAQHI value set for residential areas. The observed indices can be compared with the actual number of daily health complaints in the city for its validation. Though, the proposed air quality index system is more complex than the existing models, but this can be easily programmed to determine the FAQHI value.

5. Conclusions

Published research confirms the association of air pollution with adverse health outcomes, including mortality in large cities of industrialized countries. In the present study, five air pollutants were used as a summary indicator of air quality due to their impact on health particularly in urban population. The F-AHP method was developed for determining FAQHI values to estimate risk assessment. The permissible value of air quality health index for residential areas is 1.78. It was observed that FAQHI values in Howrah City were above 1.78 during most of the days of the first three months of each year (January to March) for the period 2009 to 2011, and then showed a decreasing trend in the subsequent months. FAQHI values were found to be within the permissible limits in most of the day during April to September in every observed year followed by an increasing trend with values exceeding the permissible limit in most of the day during next three months (October to December).

The developed model evaluates the air-quality based on FAQHI by taking into consideration the five air pollutants and three subjective parameters. Further studies are encouraged for validation of FAQHI with the real health data of the city to prove such association.

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Appendix A

Pair-wise comparisons

A pair-wise comparison of the element at a given level was done to estimate the relative importance in relation to the element at the immediate preceding level. A fuzzy judgement matrix () is generated using fuzzy pair-wise comparison index ($\bar{a}_{ij}$). In the fuzzy-AHP model, instead of being discrete numbers (1–9), the fuzzy numbers ($\bar{1}$ – $\bar{9}$) are used to represent triangular fuzzy numbers (Saaty, 1977, 1980) to capture the subjectivity or vagueness of the pair-wise preferences of fuzzy air quality health index attributes. The Satty scale for fuzzy pair-wise comparison is represented in Table A.1. Fig A.1 shows the fuzzy set definition of five triangular fuzzy numbers with the corresponding membership function. Introduction of α is done for construction of fuzzy comparison matrix that improves the scaling scheme of Satty method. This will give lower and upper comparison element for $\bar{a}_{ij}$. Value of α can be assumed on the basis of certainty of situation. For n number of comparison items, the fuzzy judgement matrix () is given by

$$\bar{A} = \begin{bmatrix} \bar{a}_{11} & \bar{a}_{12} & \dots & \bar{a}_{1n} \\ \bar{a}_{21} & \bar{a}_{22} & \dots & \bar{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \bar{a}_{n1} & \bar{a}_{n2} & \dots & \bar{a}_{nn} \end{bmatrix}$$

where, $\bar{a}_{ij} = \bar{1}, \bar{3}, \bar{5}, \bar{7}, \bar{9}$, these number are similar to the pair-wise comparison scales as defined by Saaty (1977) but are fuzzy in nature.

$$\bar{a}_{ij} > 0; \bar{a}_{ji} = 1/\bar{a}_{ij}; \bar{a}_{ii} = 1$$

Fig. A.1. Fuzzy set definition with triangular membership function.

Appendix B

Check for consistency

The pair-wise comparisons of the fuzzy judgement matrix are prone to inconsistency and error in the preference responses of people (Zahedi, 1986), and as a result often become inconsistent. The AHP introduces a consistency measure to avoid this problem and estimate the relative weight in the presence of inconsistency in responses. Saaty (1977, 1980) has shown that in a consistent judgement matrix, $\lambda_{\max} = n$, where n is the dimension of the judgement matrix and $\lambda_{\max}$ is maximum eigen value of matrix. Consistency index (CI) indicates whether a decision maker provides consistent values (comparisons) in a set of evaluation. The CI is defined as in Eq. (B.1).

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (B.1)$$

The final inconsistency in the pair-wise comparisons is solved using consistency ratio $CR = CI/RI$, where RI is the random index, which is obtained by averaging the CI of a randomly generated reciprocal matrix (Saaty, 1980). The threshold of the CR is 10%, and in case of exceeding a three-step procedure is followed (Saaty, 2005). First, identify the most inconsistent judgement in the decision matrix. Secondly, determine a range of values the inconsistent judgement can be changed to so that would reduce the associated inconsistency, and finally to reconsider the judgement to a 'reasonable value'.

Table A.1

Fuzzy numbers used for making pair-wise comparisons.

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

α is a fuzzification factor.

^aThe intensity of importance definition is in accordance with the description proposed by Saaty (1977, 1980).

^bMinimum, most likely, and maximum values.

Appendix C

Determination of fuzzy weights

Various techniques are used to compute the final fuzzy weights, such as, computation of the eigenvector, arithmetic mean, geometric mean, etc. But there are no significant differences observed in all the techniques. Consequently, for this work, the eigen vector computation was adopted to estimate the weights. Weights of attributes or parameters can be obtained through determination eigen values of comparison matrix (Saaty and Vargas, 2000). Maximum eigen value ($\lambda_{\max}$) of any crisp matrix, A, can be calculated using characteristic equation $|A - \lambda I| = 0$. Now substitution of $\lambda_{\max}$ in equation, $AX = \lambda_{\max}X$ will give corresponding eigen value of A. Where A is $n \times n$ order matrix and X is $n \times 1$ order matrix. Normalization of matrix X will give the importance of elements of particular parameter.

Appendix D

Determination of fuzzy weights

The local priorities at each level are aggregated to obtain final preferences of the alternative. This computation is carried out from the evaluation alternatives (bottom level) to the top level (goal or objective). As depicted in Fig. 2, each of the alternatives (level 3), A_i , $i = 1, 2, 3$ is aggregated through level 3 (evaluation alternatives), level 2 (criterion factors) and finally to level 1 (goal). Aggregation of priorities of each parameters will give AHP score for the parameter at the upper level, this determine preference of alternatives. This hierarchical structure is constituted by three levels scheme. The highest level (goal) is Fuzzy Air Quality Health Index, which will give quantified description of health impacts due to poor air quality of a particular location.

After determining the relative importance at each hierarchical level, the overall weight of parameter is to be determined. Let weighting at each level is denoted by w_k and the fuzzy global preference weight is denoted by G_k , where k denotes number layer (1, 2, ..., n). Therefore, following Fig. 2 at each level of k , the fuzzy global preference weights (G_k) are computed as Eq. (D.1):

$$G_k = w_k \times G_{k-1} \quad (D.1)$$

where, k is number of layers.

From above given relations, the following equations can be formed:

$$G_1 = w_1; G_2 = w_2 \times G_1 = w_1 \times w_2; G_3 = w_3 \times G_2 = w_1 \times w_2 \times w_3$$

This operation can be used for determination of final fuzzy AHP score and global weight. Global weight is overall ranking weight that can be obtained by multiplication operation of the weights of lower layer with upper one, which was overall ranked in the hierarchy.

References

- Boender CGE, de Graan JG, Lootsma FA. Multi-criteria decision analysis with fuzzy pairwise comparisons. *Fuzzy Sets Syst.* 1989; 29(2):133–143.
- Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: a major environmental and public health challenge. *Bull. World Health Organ.* 2000; 78(9):1078–1092. [PubMed: 11019457]
- Buckley JJ. Fuzzy hierarchical analysis. *Fuzzy Sets Syst.* 1985; 7(3):233–247.
- Chang D-Y. Application of the extent analysis method on fuzzy AHP. *Eur. J. Oper. Res.* 1996; 95(3): 649–655.
- Cheng C-H. Evaluating weapon systems using ranking fuzzy numbers. *Fuzzy Sets Syst.* 1999; 107(1): 25–35.
- Deng H. Multi-criteria analysis with fuzzy pairwise comparison. *Int. J. Approx. Reason.* 1999; 21(3): 215–231.
- Gent JF, Triche EW, Holford TR, Belanger K, Bracken MB, Beckett WS, Leaderer BP. Association of low-level ozone and fine particulates with respiratory symptoms in children with asthma. *J. Am. Med. Assoc.* 2003; 290(14):1859–1867.
- Gorai AK, Tuluri F, Tchounwou PB. A GIS based approach for assessing the association between air pollution and asthma in New York State, USA. *Int. J. Environ. Res. Public Health.* 2014; 11(5): 4845–4869. <http://dx.doi.org/10.3390/ijerph110504845>. [PubMed: 24806193]
- Koenig, JQ., Mar, JF. Sulphur dioxide: evaluation of current California air quality standards with respect to protection of children. 2000. Available: / www.oehha.ca.gov/air/pdf/oehhaso2.pdf
- Lee, AR. UMI dissertation services. A Bell & Howell Company; 1999. Application of modified fuzzy AHP method to analyse bolting sequence of structural joints.
- Lee M, Pham H, Zhang X. A methodology for priority setting with application to software development process. *Eur. J. Oper. Res.* 1999; 118(2):375–389.
- Leung LC, Cao D. On consistency and ranking of alternatives in fuzzy AHP. *Eur. J. Oper. Res.* 2000; 124(1):102–113.
- Lu R-S, Lo S-L, Hu J-Y. Analysis of reservoir water quality using fuzzy synthetic evaluation. *Stoch. Env. Res. Risk A.* 1999; 13:327–336.
- Malaysia. A Guide to Air Pollutant Index in Malaysia. Kuala Lumpur, Malaysia: Department of Environment, Ministry of Science, Technology, and the Environment; 1997.
- National Ambient Air Quality Standards. Central Pollution Control Board Notification, New Delhi, 18th November 2009. 2009 [Last accessed on 12th September 2014] Available online at, http://www.cpcb.nic.in/upload/Latest/Latest_48_FINAL_AIR_STANDARD.pdf.
- Ontario. A Guideline to the Ontario Air Quality Index System. Toronto, Ont. Canada: Ontario Ministry of the Environment, Air Resource Branch; 1991. 0-7729-8230-9
- Oak Ridge Air Quality Index (ORAQI) Report. Oak Ridge, TN: Oak Ridge National Laboratory; (ORNL-NSF-EP-8)
- Saaty TL. A scaling method for priorities in hierarchical structure. *J. Math. Psychol.* 1977; 15(3):234–281.
- Saaty, TL. The Analytic Hierarchy Process. New York: McGraw Hill International Publication; 1980.
- Saaty, TL. Theory and applications of the analytical network process: decision-making with benefits, opportunities, costs, and risk. Pittsburgh: RWS Publications, University of Pittsburgh; 2005.
- Saaty, TL., Vargas, LG. Models, Methods, Concepts and Applications of the Analytic Hierarchy Process. Boston: Kluwer Academic Publishers; 2000.
- Sadiq R, Rodriguez MJ. Fuzzy synthetic evaluation of disinfection by-products—a risk-based indexing system. *J. Environ. Manag.* 2004; 73(1):1–13.
- Schwartz J. Air pollution and hospital admissions for the elderly in Birmingham, Alabama. *Am. J. Epidemiol.* 1994; 139(6):589–598. [PubMed: 8172170]
- Silvert W. Fuzzy indices of environmental conditions. *Ecol. Model.* 2000; 130(1–3):111–119.
- Smith KR, Samet JM, Romieu I, Bruce N. Indoor air pollution in developing countries and acute lower respiratory infections in children. *Thorax.* 2000; 55(6):518–532. [PubMed: 10817802]

- U.S. EPA. Guideline for Reporting of Daily Air Quality — Pollutant Standards Index (PSI). Research Triangle Park, North Carolina: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards; 1976.
- U.S. EPA. Guideline for Reporting of Daily Air Quality — Pollutant Standards Index (PSI). Research Triangle Park, North Carolina: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards; 1998.
- van Laarhoven PJM, Pedrycz W. A fuzzy extension of Saaty's priority theory. *Fuzzy Sets Syst.* 1983; 11(1–3):199–227.
- WHO. WHO Regional Publication, European Series No. 85. Copenhagen: World Health Organization Regional Office for Europe; 1999. Monitoring ambient air quality for health impact assessment. (Available online at http://www.euro.who.int/__data/assets/pdf_file/0010/119674/E67902.pdf) [Last accessed on 12th September, 2014]
- WHO. Copenhagen: World Health Organization, Regional Office for Europe; 2000. Evaluation and use of epidemiological evidence for environmental health risk assessment. (E68940). Available online at <http://www.euro.who.int/document/e68940.pdf> [Last accessed on 12th September, 2014]
- WHO. Geneva: World Health Organization; 2009. Global Health Risks: Mortality and Burden of Diseases Attributable to Selected Major Risks. (Available online at http://www.who.int/healthinfo/global_burden_disease/GlobalHealthRisks_report_full.pdf) [Last accessed on 12th September 2014]
- Zadeh LA. Fuzzy sets. *Inf. Control.* 1965; 8(3):338–353.
- Zahedi F. Group consensus function estimation when preferences uncertain. *Oper. Res.* 1986; 34(6): 883–894.
- Zhu K-J, Jing Y, Chang D-Y. A discussion on extent analysis method and applications of fuzzy AHP. *Eur. J. Oper. Res.* 1999; 116(2):450–456.

HIGHLIGHTS

- Designed a fuzzy-AHP model for determination of fuzzy air quality health index
- Demonstrated the application of the model for air quality health impact assessment
- Examined the diurnal variations of FAQHI for health impact assessment.
- Compared the observed FAQHI with the permissible level of FAQHI.
- Demonstrated the calculation of permissible FAQHI on the basis of NAAQS

Fig. 1.
Steps involved in the development of model.

Fig. 2.
Hierarchical structure of the model.

Fig. 3.
Diurnal variation of pollution concentration during three year period (2009 – 2011) (A) SO₂ (B) NO₂ (C) PM₁₀ (D) CO (E) Ozone.

Fig. 4.
Diurnal variations of fuzzy air quality health index (FAQHI) during three year period (2009–11).

Table 1

Consistency ratio and consistency index of crisp matrices.

Matrices	Maximum eigen value	CI	RI	CR
PI'	5.38	0.09	1.12	0.08
EI'	3.12	0.06	0.58	0.1
FAQHI'	2.06	0.06	NA	NA

Table 2

Individual and cumulative weight of each parameters.

Goal or objective	Criterion parameters	Evaluation alternatives		Cumulative weight of the evaluation alternatives (W)
		Parameter	Weight	
Fuzzy air quality health index (FAQHI) (Weight= 1)	Pollutants parameters (PI) (Weight = 0.74)	SO ₂	0.11	0.081
		CO	0.15	0.111
		PM ₁₀	0.19	0.141
		NO ₂	0.25	0.185
		O ₃	0.30	0.222
	Exposure index parameter (EI) (Weight = 0.26)	LS	0.11	0.029
		PD	0.26	0.068
		PS	0.63	0.163

Table 3

Descriptive statistics of air pollutant concentration in Howrah city.

	Pollutants concentration				
	SO ₂ (µg/m ³)	NO ₂ (µg/m ³)	PM ₁₀ (µg/m ³)	CO (mg/m ³)	O ₃ (ppm)
Year 2009					
Minimum	1.49	6	27.8	0.42	0.003
Maximum	132.56	202	692	3.83	0.103
Mean	17.68	63.87	185.57	1.60	0.033
Standard dev	20.92	39.73	121.16	0.72	0.020
Year 2010					
Minimum	4.91	13	30.4	0.29	0.0025
Maximum	224.02	349.96	224.02	5.04	0.35
Mean	28.954	75.84	175.66	1.344	0.0213
Standard dev	29.74	49.25	138.52	0.961	0.0445
Year 2011					
Minimum	4.71	5.08	31.71	0.12	0.0051
Maximum	215.64	426.03	1281.57	3.96	0.426
Mean	43.048	78.0	160.012	0.939	0.078
Standard dev	31.471	61.51	117.32	0.632	0.061

Table 4

Membership function of air pollutant parameter.

Pollutants	Range of applicability	Membership to low (μ_L)	Membership to medium (μ_M)	Membership to high (μ_H)
SO ₂ in $\mu\text{g}/\text{m}^3$	<20	1	0	0
	20 $\times$ < 80	$(80 - x)/(80 - 20)$	$(x - 20)/(80 - 20)$	0
	80 $\times$ 125	0	$(125 - x)/(125 - 80)$	$(x - 80)/(125 - 80)$
	>125	0	0	1
NO ₂ in $\mu\text{g}/\text{m}^3$	<20	1	0	0
	20 $\times$ <80	$(80 - x)/(80 - 20)$	$(x - 20)/(80 - 20)$	0
	81 $\times$ 125	0	$(125 - x)/(125 - 80)$	$(x - 80)/(125 - 80)$
	>125	0	0	1
PM ₁₀ in $\mu\text{g}/\text{m}^3$	<50	1	0	0
	50 $\times$ < 100	$(100 - x)/(100 - 50)$	$(x - 50)/(100 - 50)$	0
	100 $\times$ 150	0	$(150 - x)/(150 - 100)$	$(x - 100)/(150 - 100)$
	>150	0	0	1
CO in mg/m^3	<2	1	0	0
	2 $\times$ < 10	$(10 - x)/(10 - 2)$	$(x - 2)/(10 - 2)$	0
	10 $\times$ 12	0	$(12 - x)/(12 - 10)$	$(x - 10)/(12 - 10)$
	>12	0	0	1
O ₃ in $\mu\text{g}/\text{m}^3$	<100	1	0	0
	100 $\times$ < 160	$(160 - x)/(160 - 100)$	$(x - 100)/(160 - 100)$	0
	160 $\times$ 240	0	$(240 - x)/(240 - 160)$	$(x - 160)/(240 - 160)$
	>240	0	0	1

Table 5

National Ambient Air Quality Standards (NAAQS), CPCB (2009).

Pollutant	Time weighted average	Concentration in ambient air	
		Industrial, residential, rural and other areas	Ecologically sensitive area (notified by central government)
Sulphur dioxide (SO ₂)	Annual average *	50 µg/m ³	20 µg/m ³
	24 h **	80 µg/m ³	80 µg/m ³
Nitrogen oxides (NO ₂)	Annual average	40 µg/m ³	30 µg/m ³
	24 h **	80 µg/m ³	80 µg/m ³
PM ₁₀	Annual average	60 µg/m ³	60 µg/m ³
	24 h **	100 µg/m ³	100 µg/m ³
Carbon monoxide (CO)	8 h	2.0 mg/m ³	2.0 mg/m ³
	1 h	4.0 mg/m ³	4.0 mg/m ³
Ozone	8 h	100 µg/m ³	100 µg/m ³
	1 h	180 µg/m ³	180 µg/m ³

* Annual Arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals.

** 24 hourly or 8 hourly or 1 hourly monitored values, as applicable, shall be complied with 98% of the time in a year. 2% of the time, they may exceed the limits but not on two consecutive days of monitoring.

NOTE: Whenever and wherever monitoring results on two consecutive days of monitoring exceed the limits specified above for the respective category, it shall be considered adequate reason to institute regular or continuous monitoring and further investigations.

Table 6

Ratings of subjective parameters for determining the exposure index.

Parameters/attributes	Ratings
Location sensitivity (LS)	
Industrial	1
Commercial/residential	2
Sensitive	3
Population density (PD)	
0–10,000	Survey results directly used for membership determination.
10,000–20,000	
20,000–30,000	
Population sensitivity (PS)	
0–25%	1
26–50%	2
>50%	3

Table 7

Membership function of subjective parameter.

Exposure parameter	Range of applicability	Membership to low (μ_L)	Membership to medium (μ_M)	Membership to high (μ_H)
Location sensitivity (LS)	x 1	1	0	0
	1 x 2	$(2 - x)/(2 - 1)$	$(x - 1)/(2 - 1)$	0
	2 x 3	0	$(3 - x)/(3 - 2)$	$(x - 2)/(3 - 2)$
	3 x	0	0	1
Population density (PD)	x 5000	1	0	0
	5000 x 10,000	$(10,000 - x)/(10,000 - 1000)$	$(x - 1000)/(10,000 - 1000)$	0
	10,000 x 20,000	0	$(20,000 - x)/(20,000 - 10,000)$	$(x - 10,000)/(20,000 - 10,000)$
	20,000 x	0	0	1
Population sensitivity (PS)	x 1	1	0	0
	1 x 2	$(2 - x)/(2 - 1)$	$(x - 1)/(2 - 1)$	0
	2 x 3	0	$(3 - x)/(3 - 2)$	$(x - 2)/(3 - 2)$
	3 x	0	0	1