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Design of Urban Air Quality Monitoring Network: Fuzzy Based Multi-Criteria Decision Making Approach

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1. Introduction

The air quality monitoring network (AQMN) is the essential part for air quality management, strategies planning, and performance assessment (Mofarrah and Husain, 2010). Existing methods of establishing ambient air quality monitoring networks typically evaluate the parameters related to air pollutant concentrations, emission source characteristics, atmospheric transport and dispersion, secondary reactions, deposition characteristics, and local topography (Harrison and Deacon, 1998; Bladauf et al., 2002). In most of the cases, AQMN is designed to measure the pollutants of concern such as particulate matter (PM_{10}), carbon monoxide (CO), sulfur dioxide (SO_2), ozone (O_3), nitrogen oxides (NOx), and total hydrocarbons (Chang and Tseng, 1999). Most of the reported AQMN design methods applied to a specific situation wherein one or two specific objectives are considered (Harrison and Deacon, 1998; Mofarrah and Husain, 2010). However, design of AQMN considering the multiple-criteria including multiple pollutants is complicated because air pollution phenomena are complex and dynamic in nature, depends on the meteorological and topographical conditions and involves not only irregularity of atmospheric movement but also uncertainty of human activities. The objective of this study is to develop a systematic approach for designing urban AQMN considering multi-criteria including multiple air pollutants in the system. The optimization is approached based on the utility scores gained from the fuzzy analytical hierarchy process associated with a candidate station, which is estimated over the representative zone (*RZ*) of the potential station.

2. Fuzzy Analytical Hierarchy Process

Fuzzy Analytical Hierarchy Process (AHP) is the extension of analytical hierarchy process (Saaty, 1980) is used for structuring the problem. AHP is an efficient method in which hierarchical structure is developed by a pair-wise comparison between any two criteria. The levels of the pair-wise comparisons range from 1 to 9, where ‘1’ represents that two criteria are equally important, while the other extreme '9' represents that one criterion is absolutely more important than the other (Saaty, 1980). The AHP uses objective mathematics to process the subjective and personal preferences of an individual or a group of decision maker (Saaty, 1980). Generally, decision-making processes are subject to insufficiency of data and lack of knowledge (Tesfamariam and Sadiq, 2006). In fact, even if the data are available, criteria often contain linguistic definitions involving human judgment and subjectivity, which introduce uncertainties in the decision making process. In application to actual system traditional AHP is not so effective in capturing uncertainty and subjective judgments of different experts. The fuzzy AHP developed Zadeh (1965) is modified version of AHP, and can be used to handle the fuzziness of the data. It is easier to understand and can effectively handle both qualitative and quantitative data in the multiple-criteria problems. In this paper triangular fuzzy numbers (TFNs) are used to judge the qualitative information related to AQMN design. The TFN is defined by three real numbers, expressed as (*l, m, n*) with a membership function between 0 and 1 (Fig. 1). The parameters *l*, *m*, and *n*, respectively, indicate the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event (Zadeh, 1965). The mathematical definition of a TFN can be described as (Kaufmann and Gupta, 1988):

$$\mu(x/\tilde{M}) = \begin{cases} 0, & x < l, \\ (x-l)/(m-l), & l \le x \le m, \\ (n-x)/(n-m), & m \le x \le n, \\ 0, & x > n \end{cases} \quad (1)$$

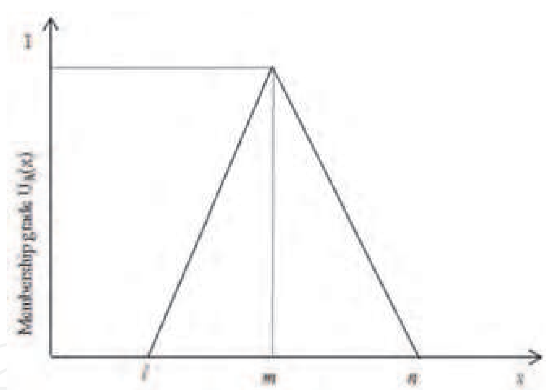

Fig. 1. Construction of triangular membership function

The TFNs for this study are developed in such a way that the most likely value has a membership grade of unity, considering the fact that the lower and upper bonds have a membership value of zero in that fuzzy set. The arithmetic of fuzzy set is little different than regular arithmetic. For example the fuzzy algebraic operations of two TFNs, namely $A\,(l_1, m_1, n_1)$ and $B\,(l_2, m_2, n_2)$ are as follows (Kaufmann and Gupta, 1988):

$$A + B = (l_1 + l_2, m_1 + m_2, n_1 + n_2)$$

$$A - B = (l_1 - n_2, m_1 - m_2, n_1 - l_2)$$

$A.B = \min(l_1 l_2, l_1 n_2, n_1 l_2, n_1 n_2), \mathit{mostlikely}(m_1 m_2), \max(l_1 l_2, l_1 n_2, n_1 l_2, n_1 n_2)$; and if $0 \notin (l_2, n_2)$

$$A / B = A \cdot B^{-1} = \min(l_1 / l_2, l_1 / n_2, n_1 / l_2, n_1 / n_2), \textit{mostlikely}(m_1 / m_2), \textit{and}$$
$$\max(l_1 / l_2, l_1 / n_2, n_1 / l_2, n_1 / n_2)$$

3. Methodology used in this work

A systematic methodology for designing urban AQMN is developed by using multiple criteria, which covered environmental (e.g., air quality), social (i.e., location sensitivity (*LS*), population density (*PD*), population sensitivity (*PS*), and cost parameter (*CP*). The aim of this AQMN design is to study air pollutants' characteristics, human health, social sensitivity, and cost objective. Thus, the proposed design will protect public health, sensitive locations/receptors from exposures to ambient air pollutants, and it will measure the maximum pollutants' concentration for the study area. The framework of this methodology is shown in Fig. 2. This technique will help the decision maker to optimize the AQMN with limited financial and human resources.

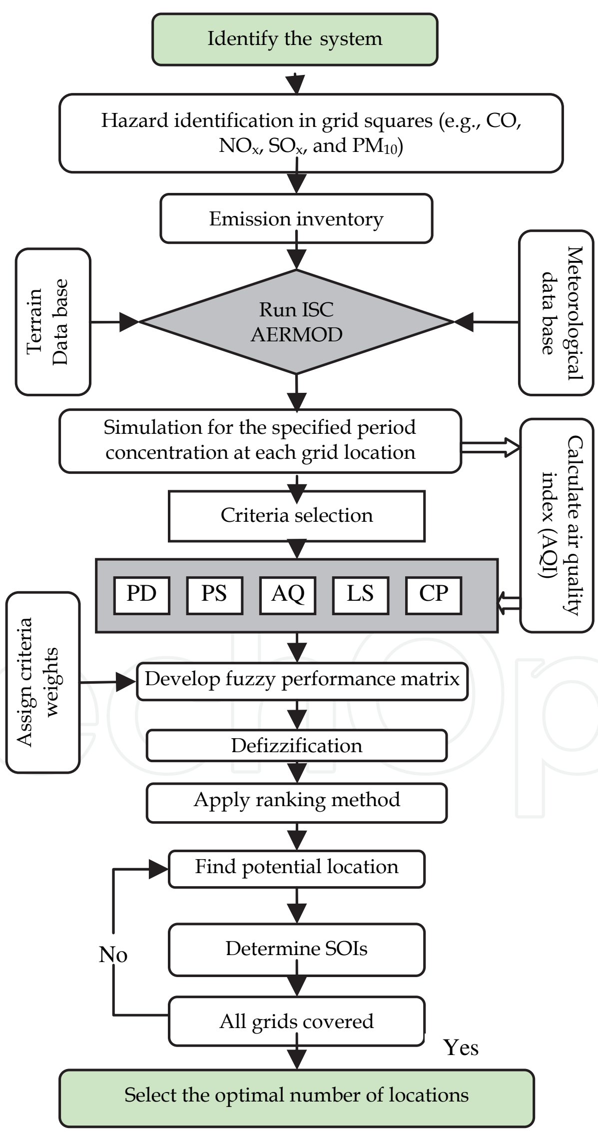

Fig. 2. Framework for designing AQMN

At the beginning, the study area is divided into a continuous grid system in which each grid represents a potential candidate location for monitoring station. Fuzzy synthetic optimization technique is used to identify the potential monitoring sites. The key functions of the methodology are described in the following sections.

3.1 Air quality exceedance index

An air quality index (*AQI*) function is generated comparing the local air quality with the national standards. *AQI* provides overall information about the local air quality. It hints how clean or polluted the local air comparing with the national standards. If the ratio of measured data (C_{ij}) and standard (C_{sj}) grater then one, it means the local air quality is violating the national air quality standards. For this study, concentrations of the major air pollutants such as CO, NO_2, SO_2, and PM_{10} are monitored and subsequently converted into an *AQI* by assigning a probability of occurrence factor to each air pollutants based on their occurrence of exceedance during study periods as eq. 2.

$$AQI_j = \sum_{j=1}^{m} \frac{C_{ij} * p_{ij}}{C_{sj}} \tag{2}$$

C_{ij} = j^{th} pollutant concentration (i.e., CO, NO_2, SO_2, and PM_{10}) in i^{th} grid; C_{sj} = national air quality standard of j^{th} pollutant, p_{ij} is the probability of occurrence of j^{th} pollutant in the i^{th} location over the measurement periods.

Criteria	Assigned scores
Location sensitivity (LS)/ available amenities / grid	LSi
No-basic facility	(1,2,4)
Facilities of low value (e.g., storage facilities)	(1,3,5)
Factories and industry	(2,4,6)
Residential, parks	(3,5,7)
Schools, churches, heritage places	(4,6,8)
Hospitals, sensitive locations	(5,7,9)
Population density (PD)/ number of people / grid	PDi
<50	(1,2,4)
51- 250	(1,3,5)
251-450	(2,4,6)
451-650	(3,5,7)
650-850	(4,6,8)
>850	(5,7,9)
Population sensitivity (PS)/ sensitive population / grid	PSi
<10	(1,2,4)
11-20	(1,3,5)
21-30	(2,4,6)
31-40	(3,5,7)
41-50	(4,6,8)
>50	(5,7,9)
Cost criteria	Ci
Installation cost >$7000	(1,2,4)
$7000-$6000	(1,3,5)
$5900-$5000	(2,4,6)
$4900-$4000	(3,5,7)
$3900-$3000	(4,6,8)
Installation cost <$3000	(5,7,9)

Table 1. Definitions for criteria scores

3.2 Cost objective

An important objective of any AQMN is to minimization of its cost. This objective can also be interpreted as a budgetary constraint. Cost criteria consideration in this evaluation is installation cost. Generally, the installation cost is varied depending on the site location, local labour force and communication facilities. To compare the installation cost within the area of interest a cost index (*CI*) is introduced as:

$$CI_i = Minimize\left[\frac{C_i}{\sqrt{\sum C_i}}\right] \tag{3}$$

where, CI_i = cost index for the grid *i*, C_i = cost score at the i^{th} location over the study area. Considering the local market and communication facility the installation cost score (C_i) of i^{th} grid was assigned as shown in Table 1.

3.3 Definitions of social criteria

In each grid, the social criteria such as *LS*, *PS*, and PS are consequently converted to a score with the help of pre assigned scale shown in Table 1. Finally, the scores are normalized to get social criteria index (*SCI*) at i^{th} location as shown in eq. 4.

$$SCI_i = Maximized\left[\frac{LS_i}{\sqrt{\sum LS_i}} + \frac{PD_i}{\sqrt{\sum PD_i}} + \frac{PS_i}{\sqrt{PS_i}}\right] \tag{4}$$

3.4 Determining of screening scores

The screening score is the composition components of an environmental parameters (eq. 2), cost objective (eq. 3), and social criteria (eq. 4). It is defined by a dimension less function, called screening score (*SC*). The *SC* combines, under a mathematical approach, and is defined by eq. 5.

$$SC_i = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ . \\ A_n \end{bmatrix} \begin{bmatrix} AQI_{iJ} & CI_i & LS_i & PD_i & PS_i \end{bmatrix} \begin{bmatrix} AQI_{A1} & CI_{A1} & LS_{A1} & PD_{A1} & PS_{A1} \\ AQI_{A2} & CI_{A2} & LS_{A2} & PD_{A2} & PS_{A2} \\ AQI_{A3} & CI_{A3} & LS_{A3} & PD_{A3} & PS_{A3} \\ . & . & . & . & . \\ AQIn & CI_{An} & LS_{An} & PD_{An} & PS_{An} \end{bmatrix} \times \begin{bmatrix} w_j & w_c & w_{LS} & w_{PD} & w_{PS} \end{bmatrix} \tag{5}$$

where, $A_1, A_2, \ldots, A_n$ are the possible monitoring station location, and w_j , w_c , w_{LS}, w_{Pd}, and w_{PS} are weighting factors for *AQI*, *CI*, *LS*, *PD*, and *PS* respectively.

The *SC* from eq. 5 is also fuzzy value. For decision purpose the comparisons of fuzzy data is not straightforward. To obtained crisp value of *SC*, centroidal method (Yager, 1980) is used. The centroid index of the fuzzy number represents the crisp score of an alternative A_i. If the fuzzy *SC* for a grid A_i is SC_{Ai} (α_1, β_1, γ_1), then the crisp score of that location can be computed as follows:

$$SC_x(A_i) = \frac{(\beta_1 - \alpha_1)(\alpha_1 + 2/3(\beta_1 - \alpha_1)) + (\lambda_1 - \beta_1)(\beta_1 + 1/3(\lambda_1 - \beta_1))}{(\beta_1 - \alpha_1) + (\lambda_1 - \beta_1)} \quad (6)$$

where, $SC_x(A_i)$ is the crisp score of grid A_i and α_1, β_1, and γ_1 are the lowest, most likely and maximum values of SC_{Ai}. Depending on the SC_x (A_i) values the grids location are screened, and potential locations were ranked for second step analysis.

3.5 Determination of representative zone (RZ)

After the identification and quantification of the objectives of the monitoring network, the second step is to determine the degree of representativeness (*Dr*) and the representative zone (*RZ*) associated with each candidate monitoring location. The *RZ* for a monitoring station is established on the basis of the concept of a sphere of influence area surrounding the potential station, for which the pollutants measurements can either be regarded as representative or can be extrapolated with known confidence. Sphere of influence (SOI) is defined as the zone over which the metrological (MET) data for a given monitoring location can be considered representative (Mofarrah and Husain, 2010). A grid cell (*i*) will belong to the *RZ* of a monitoring station at grid cell (k), if the D_r of cell (*i*) is greater than zero (eq. 7).
The D_r is dictated by a predetermine cutoff value (*Rc*) in the spatial correlation coefficient (*R*) between the pollutant's concentration at the monitoring locations identified and the neighboring locations surrounding it. The spatial correlation coefficient (*R*) gives an indication of the relationship among locations to be selected in the monitoring network (Elkamel et al., 2008). The *R* lies between -1 and +1 (Liu et al., 1986). The computation of *R* is carried out in all radial directions surrounding each potential location until the *R* falls below the predetermined cut-off value (R_c). In this study *RZ* is considered the area surrounding it in which the *R* of this location with the nearby locations is higher than the cut-off value (R_c). This means the pollutants concentration measured at this location are representatively correlated with a certain degree of confidence to any location in the network within the area. Fig. 3 illustrates the general concept of *RZ*. By this concept it is assumed that, when a station is installed in a grid square (i.e A5), the nearby grid squares, as are marked on Fig. 3, are not allowed to be installed with the same class of station if their D_r is higher than zero. When searching for the next station location, the marked grid squares will be skipped for enhancing the solution efficiency.

$$D_r = \begin{cases} \sum_{j=1}^{4} R^2, & if\,(R - R_c) \geq 0 \\ 0, & Otherwise \end{cases} \quad (7)$$

where, *R is* spatial correlation coefficient of the concentrations between two adjacent monitoring locations $x_1 = (x_{11}, x_{12}, \ldots x_{1p})$ and $x_2 = (x_{21}, x_{22}, \ldots x_{2p})$ with a sample size p can be expressed (Elkamel et al., 2008) as:

$$R = \frac{\sum_{i=1}^{p}(x_{1i} - \bar{x}_1)(x_{2i} - \bar{x}_2)}{\sqrt{\sum_{i=1}^{p}(x_{1i} - \bar{x}_1)^2 \sum_{i=1}^{p}(x_{2i} - \bar{x}_2)^2}} \quad (8)$$

where, $\bar{x}_1 = \frac{1}{p}\sum_{i=1}^{p} x_{1i}$ and $\bar{x}_2 = \frac{1}{p}\sum_{i=1}^{p} x_{2i}$ are the average concentrations at location 1 and 2, respectively. Once D_r of the each pathetical location is calculated, the ranking of the potential location can be quantified in terms of grid utility scores. A grid score $U_{(g)}$ for gth candidate location is defined as the sum of SC_x of all grids correlated with gth location as:

$$U_{(g)} = SC_{(xg)} + \sum_{i=1}^{n} D_r \times SC_{xi} \quad (9)$$

where, n is the number of grids correlated with gth location. Highest $U_{(g)}$ means better location for air quality monitoring station. The RZ of the sphere can be defined as the number of square grids place inside it.

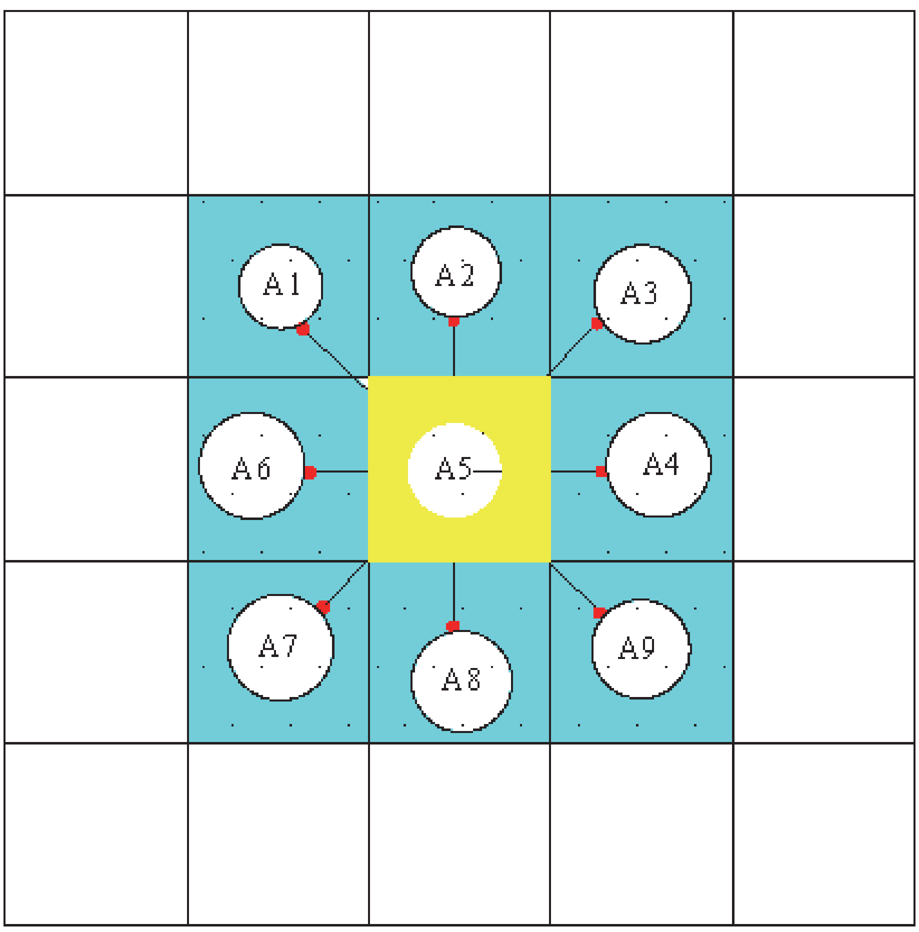

Fig. 3. Representative location zone

4. Application of the methodology

Riyadh, the capital city of Saudi Arabia was considered to demonstrate the proposed methodology. Riyadh is one of the major industrial cities in the Kingdom of Saudi Arabia; it has multiple types of heavy and light industries such as oil refinery, power plant, cement industry etc. The population of the city is above four million with very high growth rates.

Therefore, to maintain the air quality standard the city authorities have planned to re-assess the current air quality monitoring network. There are six existing air quality monitoring stations in Riyadh city owned and operated by different organizations. Most of these existing air AQMNs are not working properly or not serving at satisfactory levels. The main objective of this study is to design the air quality monitoring network for Riyadh city and to identify the optimal station locations to satisfy the future air quality monitoring demands. To design the AQMN three major emission sources such as point sources, area sources and line sources were considered. The detailed emission inventory can be found elsewhere (Mofarrah and Husain, 2010). The major point sources in Riyadh city are power plants, refinery and cement industries. The old and new industrial cities under development are considered as the area source. The automobile sources for the selected major roads based on traffic counts, composition of traffic, and model years were considered as the line sources in this study. The database for emission inventory was developed based on production rate, fuel consumption and the emission factors as suggested by USEPA.

At the beginning, the study area (40km x 60km) was conceptually divided into 441 square grids as subsystems. Each grid component includes environmental parameters (i.e., sulfur dioxide (SO_2), nitrogen dioxides (NO_2), carbon monoxide (CO) and fine particulate matters (PM_{10})), social objectives (i.e., *LS, PD, PS*) and cost criteria (*CI*). The concentration level of each air pollutant was simulated on; hourly, 8-hourly, and 24-hourly basis using Industrial Source Complex (ISC3) air quality software programs. The concentration distribution of selected air pollutants over the study area is shown in Fig. 4. If we compare the pollutants distribution (Fig. 4) with the Saudi Arabian national air quality standard (Table 2), it is clear that some regions within the study are experiencing high level of air pollution threats. For this study, the social and cost objective data of each grid were also modeled as fuzzy variables according to the fuzzy scale mentioned in Table 1.

Pollutant	Measurement period	Limit
SO_2	30 day period, one hour average	730 μg/m³
	12 month period, 24 hour average	365 μg/m³
	12month period, annual average	80(μg/m³)
Inhalable Particulates (fpm)	12-month period, the 24-hour maximum	340(μg/m³)
	12-month period, the annual average	80(μg/m³)
Nitrogen Oxides Defined as Nitrogen Dioxide (NO_2)	30 day period, the one-hour average	660(μg/m³)
	12-month period, the annual average	100(μg/m³)
Carbon Monoxide (CO)	30-day period, the one-hour average	40 (mg/m³)
	30-day period, the 8-hour average	10(mg/m³)

Table 2. Ambient air quality standards for Saudi Arabia (Source Presidency of Meteorology and Environment, Saudi Arabia)

4.1 Criteria weight computation

Based on the importance of each criterion on AQMN design, a fuzzy pair-wise comparisons matrix (PCM) $\tilde{A}_F$ is formed considering C_1, C_2, C_3, C_4 and C_5 are respectively, location sensitive *(LS)*, population sensitive (*PS*), cost, air quality (*AQ*) and population density (*PD*). The preference scale as shown in Table 3 was used in this case.

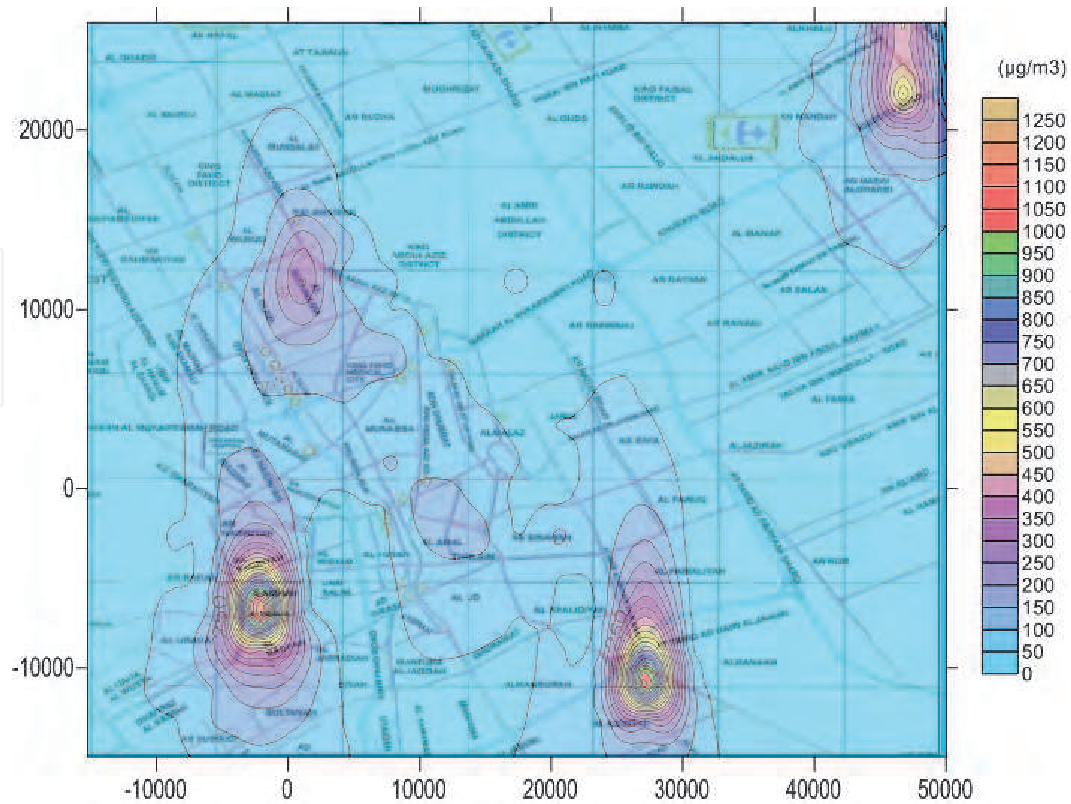

Fig. 4. (a) Distribution of SO_2 for 12month period, annual average

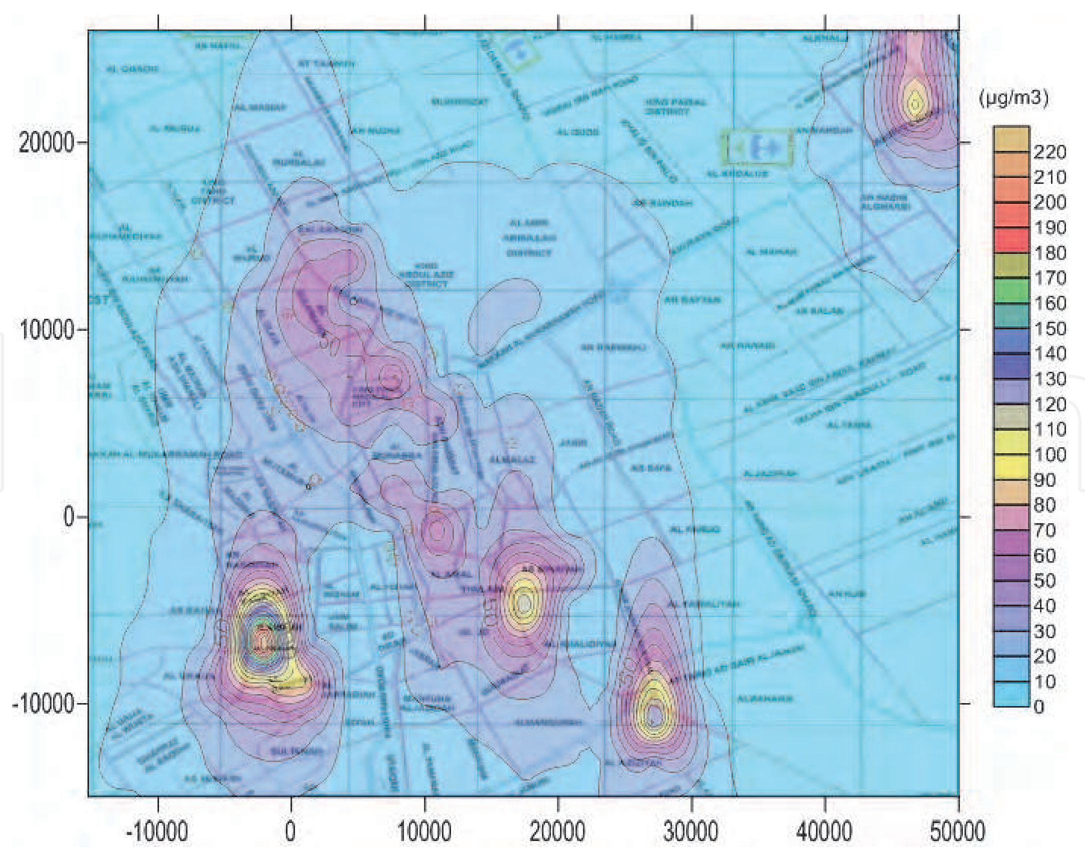

Fig. 4. (b) Distribution of NO_2 for 12month period, annual average

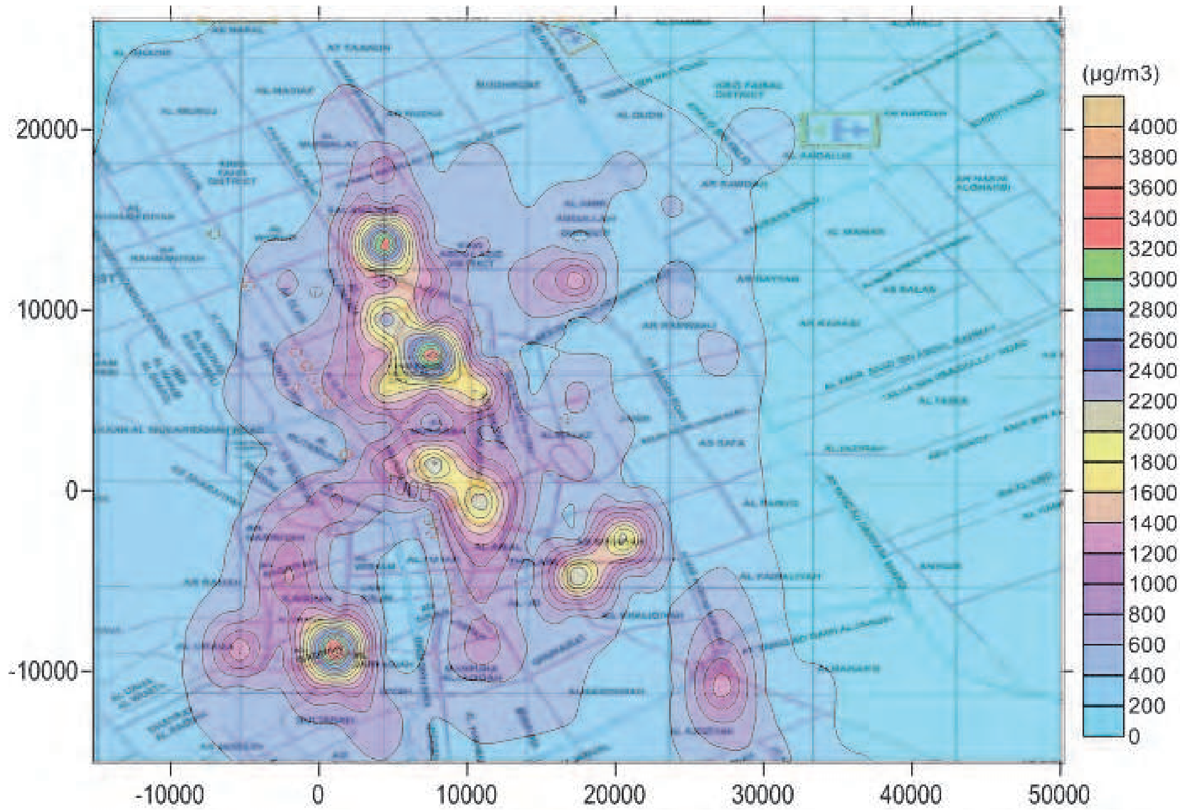

Fig. 4. (c) Distribution of CO for 30-day period, the 8-hour average

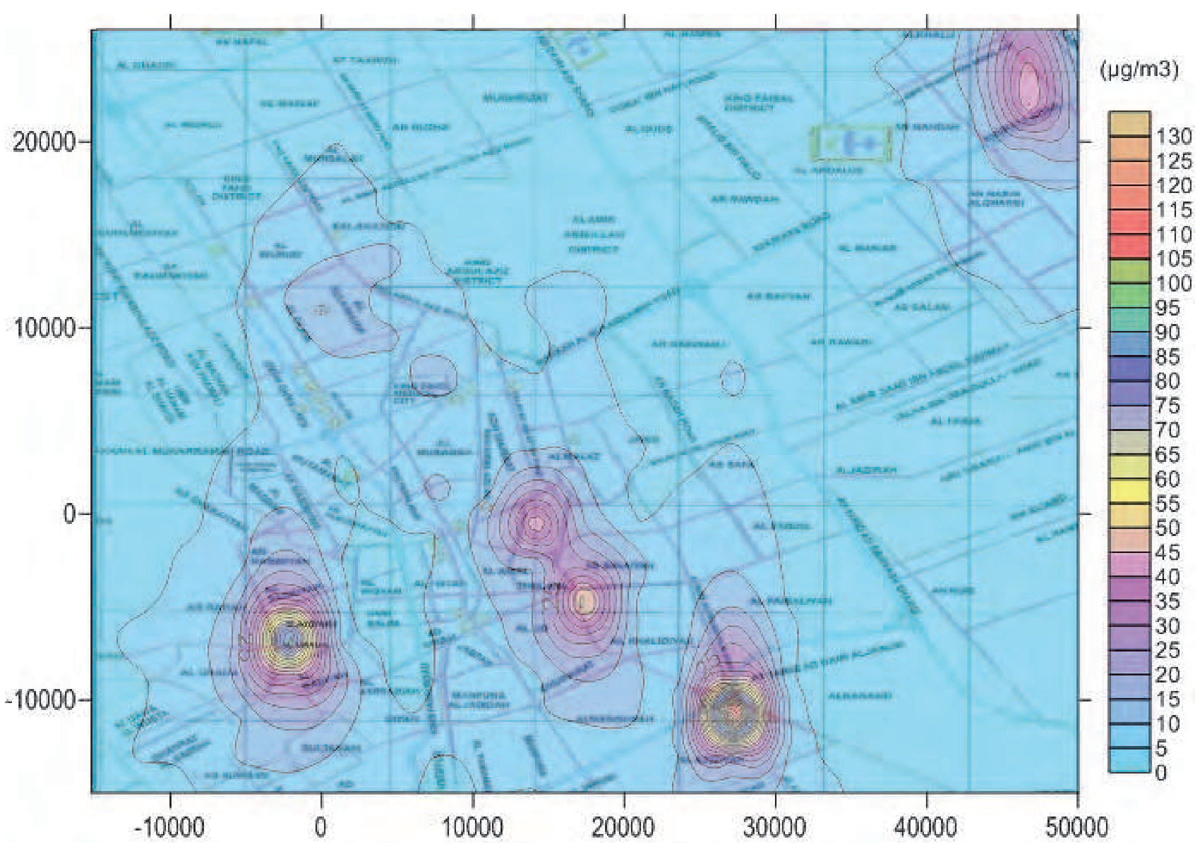

Fig. 4. (d) Distribution of PM_{10} for 12month period, the 24-hour maximum

How important is A relative to B?	Preference index (Saaty 1988)	Fuzzy value (l, m, u; Jie et al. 2006)
Equally important	1	(1, 1, 1)
Moderately more important	3	(1,3,5)
Strongly more important	5	(3,5,7)
Very strongly more important	7	(5,7,9)
Overwhelmingly more important	9	(7,9,11)
	2	(1,2,4)
Intermediate values	4	(2,4,6)
(Need to judge two)	6	(4,6,8)
	8	(6,8,10)

Table 3. Criteria preference scale

$\tilde{A}_F =$

	C_1	C_2	C_3	C_4	$C5$
C_1	1, 1, 1	0.33,0.5,1.0	0.25,0.33,1	0.33,0.5,1	2,3,4
C_2	1, 2,3	1, 1, 1	0.33,0.5,1	0.17,0.2,0.25	0.5,1,1
C_3	1,3,4	1,2,3	1, 1, 1	0.2,0.25,0.33	0.33,0.5,1
C_4	1,2,3	4,5,6	3,4,5	1, 1, 1	0.17,0.2,0.25
$C5$	0.25,0.33,0.50	1,1,2	1,2,3	4,5,6	1, 1, 1

After constructing $\tilde{A}_F$, relative weights of each criterion is calculated by using fuzzy extent analysis (Lee et al., 2006) as follows:

Row	Left	Middle	right
The first row sum	3.92	5.34	8.00
The 2nd row sum	3.00	4.70	6.25
The 3rd row sum	3.53	6.75	9.33
The 4th row sum	9.17	12.20	15.25
The 5th row sum	7.25	9.33	12.50
Total	**26.87**	**38.32**	**51.34**

Criteria	Left	Middle	right
LS (C_1)	3.92/51.34= 0.0763	5.34/38.32 = 0.1393	8.0/26.87 = 0.2978
PS (C_2)	3.00/51.34= 0.0584	7.40/38.32 = 0.1227	6.25/26.87 = 0.2326
Cost (C_3)	3.53/51.34= 0.0688	6.75/38.32 = 0.1762	9.33/26.87 = 0.3474
AQ (C_4)	9.17/51.34= 0.1786	12.20/38.32 = 0.3184	15.25/26.87 = 0.5676
PD (C_5)	7.25/51.34= 0.1412	9.33/38.32 = 0.2436	12.5/26.87 = 0.4653

The weights of *AQ* were re-distributed to the *CO*, SO_2, PM_{10} and NO_2 on the basis of their impotence (i.e., considering the local environment and human health point of view). The complete set of criteria weights are shown in Table 4.

Criteria	*Weights*	***Sub-criteria***			
		CO	SO_2	PM_{10}	NO_2
LS (C_1)	w_1=(0.0763,0.1393,0.2978)	-	-	-	-
PS (C_2)	w_2=(0.0584,0.1227,0.2326)	-	-	-	-
Cost (C_3)	w_3=(0.0688,0.1762,0.3474)	-	-	-	-
AQ (C_4)	w_4=(0.1786,0.3184, .5676)	C_{41} = 20% of C_4	C_{42} = 25% of C_4	C_{43} = 35% of C_4	C_{44} = 20% of C_4
PD (C_5)	w_5=(0.1412,0.2436,0.4653)	-	-	-	

Table 4. Weights of each criteria and sub-criteria

5. Results and discussions

The concentration level of each pollutant was compared with the Saudi National Air quality standards (Table 2) to calculate the air quality index (*AQI*). Social and cost objectives data of each grid were also predicted and converted into fuzzy scores according to Table 1. The step by step calculations of potential location identification is described in the following section by considering few grids. Table 5 shows the *AQIs* and assigned scores of different parameters. The criteria scores (Table 5) are multiplied with the weighting factors (Table 4) to form fuzzy screening scores matrix as shown in the Table 6.

Grid no	*AQI (SO2)*	*AQI (NO2)*	*AQI (CO)*	*AQI (PM10)*	*Assigned scores (LS)*	*Assigned scores (PS)*	*Assigned scores (CI)*	*Assigned scores (PD)*
A1	22.7798	38.8779	58.3944	27.4490	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)
A2	22.4193	38.9320	65.7578	24.7020	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)
A3	31.5411	51.0081	81.7773	32.3196	(1,3,5)	(1,3,5)	(3,5,7)	(4.6.8)
A4	45.5648	69.3000	97.5538	45.8194	(2,4,6)	(2,4,6)	(3,5,7)	(5,7,9)
A5	66.8583	96.5431	107.2574	58.2306	(2,4,6)	(1,2,4)	(3,5,7)	(4,6,8)
A6	46.5463	78.2129	109.7475	45.0471	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)
.	.		.	.	.	.	.	.
.	.		.	.	.	.	.	.
A436	2.486	14.478	19.775	24.351	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)
A437	3.204	17.229	21.650	21.579	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)
A438	5.808	21.943	25.775	17.283	(1,3,5)	(1,3,5)	(3,5,7)	(4.6.8)
A439	13.402	69.518	73.369	17.328	(2,4,6)	(2,4,6)	(3,5,7)	(5,7,9)
A440	31.328	346.130	343.296	21.558	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)
A441	5.118	21.599	23.418	16.571	(1,2,4)	(1,2,4)	(3,5,7)	(5,7,9)

Table 5. *AQIs* and assigned scores for different criteria

Grid no	*AQI (SO2)*	*AQI (NO2)*	*AQI (CO)*	*AQI (PM10)*	*(LS)*	*(PS)*	*(CI)*	*(PD)*
A1	1.017,1.813,3.232	1.389,2.476,4.413	2.086,3.719,6.629	1.716,3.059,5.453	0.076,0.279,1.191	0.058,0.245,0.93	0.206,0.881,2.432	0.706,1.705,4.188
A2	1.001,1.785,3.181	1.391,2.479,4.42	2.349,4.187,7.465	1.544,2.753,4.907	0.076,0.279,1.191	0.058,0.245,0.93	0.206,0.881,2.432	0.706,1.705,4.188
A3	1.408,2.511,4.476	1.822,3.248,5.79	2.921,5.208,9.283	2.02,3.602,6.421	0.076,0.418,1.489	0.058,0.368,1.163	0.206,0.881,2.432	0.565,1.462,3.722
A4	2.034,3.627,6.466	2.475,4.413,7.867	3.485,6.212,11.074	2.864,5.106,9.102	0.153,0.557,1.787	0.117,0.491,1.396	0.206,0.881,2.432	0.706,1.705,4.188
A5	2.985,5.322,9.487	3.449,6.148,10.96	3.831,6.83,12.176	3.64,6.489,11.568	0.153,0.557,1.787	0.117,0.491,1.396	0.206,0.881,2.432	0.565,1.462,3.722
A6	2.078,3.705,6.605	2.794,4.981,8.879	3.92,6.989,12.459	2.816,5.02,8.949	0.076,0.279,1.191	0.058,0.245,0.93	0.206,0.881,2.432	0.706,1.705,4.188
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
A436	0.646,1.152,2.054	0.706,1.259,2.245	0.87,1.551,2.764	1.056,1.883,3.357	0.076,0.279,1.191	0.058,0.245,0.93	0.206,0.881,2.432	0.706,1.705,4.188
A437	0.769,1.371,2.445	0.773,1.379,2.458	0.771,1.374,2.45	1.362,2.427,4.327	0.076,0.418,1.489	0.058,0.368,1.163	0.206,0.881,2.432	0.565,1.462,3.722
A438	0.98,1.747,3.114	0.921,1.641,2.926	0.617,1.101,1.962	2.468,4.4,7.843	0.153,0.557,1.787	0.117,0.491,1.396	0.206,0.881,2.432	0.706,1.705,4.188
A439	3.104,5.534,9.865	2.621,4.672,8.329	0.619,1.103,1.967	5.695,10.153,18.098	0.153,0.557,1.787	0.117,0.491,1.396	0.206,0.881,2.432	0.565,1.462,3.722
A440	15.455,27.552,49.116	12.263,21.861,38.971	0.77,1.373,2.447	13.312,23.732,42.307	0.076,0.279,1.191	0.058,0.245,0.93	0.206,0.881,2.432	0.706,1.705,4.188
A441	0.964,1.719,3.065	0.836,1.491,2.658	0.592,1.055,1.881	2.175,3.877,6.912	0.382,0.975,2.68	0.117,0.491,1.396	0.138,0.705,2.084	0.706,1.705,4.188

Table 6. Weighted screening scores matrix

The crisp values of weighted fuzzy screening scores (*SC*) of each grid were estimated by applying eq. 6 and reported in Table 7. Based on the top SC_x scores, 50 potential locations were indentified for second step analysis.

Grid no	Grid screening scores (SC)	Crisp values of (SC_x)
A1	0.065,0.133,0.278	0.1586
A2	0.067,0.137,0.285	0.1628
A3	0.076,0.16,0.326	0.1871
A4	0.099,0.198,0.392	0.2298
A5	0.112,0.223,0.436	0.2569
A6	0.099,0.194,0.388	0.2273
.	.	.
.	.	.
A436	0.045,0.098,0.217	0.1202
A437	0.043,0.103,0.223	0.1231
A438	0.055,0.12,0.253	0.1428
A439	0.083,0.171,0.344	0.1990
A440	0.231,0.429,0.806	0.4887
A441	0.06,0.125,0.261	0.1483

Table 7. Grid screening scores

To determine the degree of representativeness (Dr) and the representative zone (RZ) associated with each candidate monitoring location, three different cutoff values (R_c), 0.45, 0.60 and 0.75 were used separately and compared with the coefficient in the spatial correlation (*R*) between the pollutant concentration of the potential monitoring station and the neighboring locations surrounding it. Ten optimal locations and corresponding number of grids coverage were indentified for different cutoff value as shown in Fig. 5. The results show that cutoff value has significant effect on the representative zone (RZ) assessment. However, considering the geometry of the study area and analysis of the different cutoff values it was found that the 0.6 cutoff value is the best suited for the Riyadh city. Hence, the grid scores $U_{(g)}$ and top ten optimal locations distribution with cutoff value 0.6 is evaluated as shown in Fig. 6. Due to heavy industries and high populations' exposure, 1-2 optimal locations were found near a major point source such as power plant at grids A397 to A441 (Fig. 6). However, this part is outside of the present study area, but respecting the study results, we suggested putting at least one air monitoring station at grid A419 or A398.

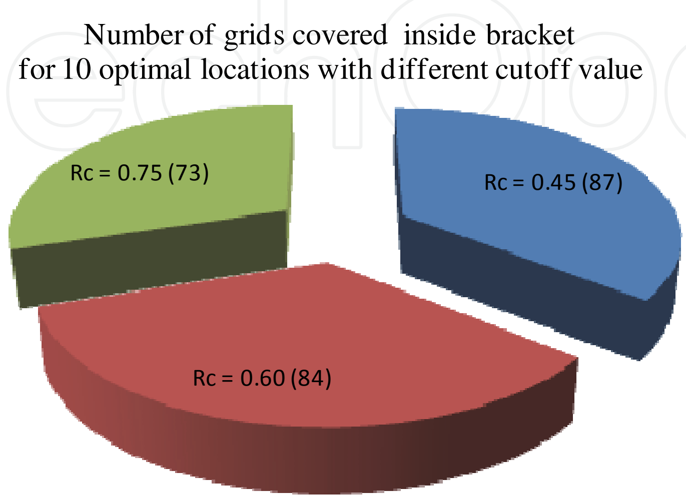

Fig. 5. Ten Optimal stations with number of grids covered for different cutoff values

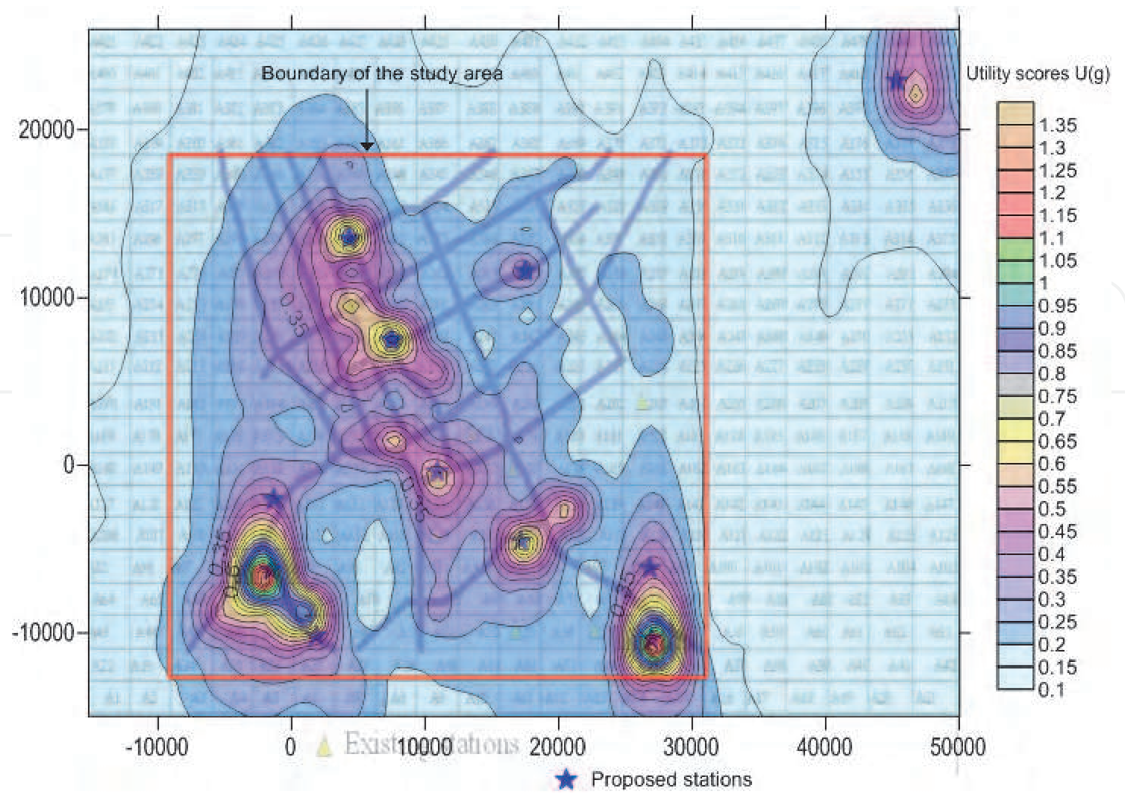

Fig. 6. Location of the ten Optimal stations (for cutoff value 0.6)

For a specific situation the agency can choose either a high or a low value of R_c. A high R_c based network may not necessarily cover more area, but the covered region is well represented. On the other hand a low R_c based network, would offer more coverage of the region, but the covered region may not be satisfactorily represented (Mofarrah and Husain, 2010; Elkamel et al., 2008). The final decision in such a case is of course dependent on the respective agency. It should be noted that the design of an air quality network with higher cutoff values (R_c) is the addition of some more monitoring stations in the network, as compared to that of a network designed with a lower R_c values . The selection of the R_c varies case by case, based on budget, type of air monitoring station, meteorological condition, and the purpose of the monitoring network.

6. Conclusions

The AQMN represents an essential tool to monitor and control atmospheric pollution. The use of some specific criteria in conjunction with the mathematical models provides a general approach to determine the optimal number of monitoring stations. In this study, fuzzy multiple-criteria approach in conjunction with the degree of representativeness technique was used to develop optimal AQMN design. The triangular fuzzy numbers (TFNs) were used to capture the uncertainty associated from human judgement (e.g., assigning weights, scoring). The coverage area of the monitoring station is an essential part of an AQMN which was determined on the basis of representative zone. The effect of the correlation coefficient as well as the cutoff values on coverage of the network was also studied by changing the cutoff values. This methodology provides a systematic approach, which allows multiple-criteria and multiple pollutants in AQMN design. However, the design of an AQMN depends on many site-specific issues and good upfront planning is therefore crucial in properly assessing the problem and designing an optimal AQMN.

7. Acknowledgement

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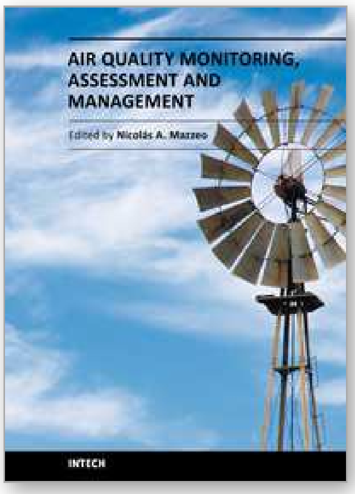

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Human beings need to breathe oxygen diluted in certain quantity of inert gas for living. In the atmosphere, there is a gas mixture of, mainly, oxygen and nitrogen, in appropriate proportions. However, the air also contains other gases, vapours and aerosols that humans incorporate when breathing and whose composition and concentration vary spatially. Some of these are physiologically inert. Air pollution has become a problem of major concern in the last few decades as it has caused negative effects on human health, nature and properties. This book presents the results of research studies carried out by international researchers in seventeen chapters which can be grouped into two main sections: a) air quality monitoring and b) air quality assessment and management, and serves as a source of material for all those involved in the field, whether as a student, scientific researcher, industrialist, consultant, or government agency with responsibility in this area.