Practical use of the ISCST3 model to select monitoring site locations for air pollution control

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Abstract: We present an objective methodology for selection of the minimum number of sampling sites required to register the highest concentration values of air pollutants emitted from a continuous point source. The methodology is based on the analysis of 1 hour concentration values above a threshold value estimated by atmospheric dispersion models. The number and location of the air monitoring stations are determined according to the likelihood that a station can measure high concentration values in accordance with model results. The efficiency of the monitoring network design depends on the accuracy of the considered dispersion model, a low interannual variability of atmospheric conditions and the number of samplers. Following a brief description of the methodology we detail an application to design an air monitoring network. We apply the ISCST3 atmospheric dispersion model to a point source emission, considering one year of hourly meteorological data. In this example, an approximated value of the efficiency of the network design is 0.475 at best.

Keywords: air pollution, air quality control, ISC3 ATD model, monitoring network, network design.

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1 Introduction

Several decades ago, the location of the air monitoring sites was determined in a qualitative way. This mainly arose because of the complex nature of air quality monitoring due to the irregular distribution of sources and the spatial and temporal variability in atmospheric mixing and diffusion. In recent years, the design of air monitoring networks, the optimization of the locations and of the number of stations are based on the prediction of air pollution concentrations using atmospheric dispersion models (Seinfeld, 1972; Noll *et al.*, 1977; Noll and Mitsutomi, 1983). Some authors (Haas, 1992; Wu and Zidek, 1992; Oehlert, 1996; Wu and Chan, 1997) present objective methodologies for designing the optimum size of a network that is already operating. These methods are usually based on statistical considerations and minimization of costs.

During the last few years, new air quality models have been developed in response to regulatory requirements (Carruthers *et al.*, 1994; Weil, 1994; US Code of Federal

Regulations, 1996). These atmospheric dispersion models are used in assessing environmental impact and regulatory issues and are usually run to estimate the highest or 'worst case' concentration for a source. Likewise, the regulatory atmospheric dispersion model results can also be used to select the initial site location of air monitoring stations of a network designed for air pollution control.

In this paper we present an objective method for selecting the number and the location of air monitoring stations to measure 1 hour high concentration values of an air pollutant emitted from a single stack. The procedure uses the Industrial Source Complex Short Time dispersion model (ISCST3) (US EPA, 1995a) and one year of meteorological data over 1 hour intervals. The methodology requires the distribution of the frequency of hourly concentration values higher than a threshold value, with wind direction. The threshold value may be the air quality standard or any other value selected according to the monitoring programme objective. The number and location of the air monitoring stations are then determined according to the likelihood that an air monitoring station can measure the predicted high concentration values.

2 Brief description of the site selection procedure

Assuming there are no monitoring stations in the area, we propose an initial design of an air monitoring network. We present a practical application of one widely-used regulatory dispersion model, the analysis to be undertaken on the model results and the criteria required to rank the monitoring site locations.

The first step of the selection procedure is to estimate the spatial distribution of the air pollution concentration at ground-level under the different meteorological conditions that may occur at the source location. This can be accomplished by applying the ISCST3 model to hourly meteorological data over a one year period. The ISCST3 model is a well-known regulatory atmospheric dispersion model, validated and recommended by the United States Environmental Protection Agency (US EPA). The ISCST3 is a steady-state Gaussian plume model, which is widely used to assess pollutant concentrations from a variety of sources associated with an industrial source complex.

The second step is to obtain the maximum value (C_{max}) for each 1 hour concentration field and its downwind location (X_{max}) from the source. After choosing the threshold concentration value (C_L), the hours where C_{max} is greater than C_L are identified. The proposed procedure is based on an analysis of these situations. From the 1 hour mean surface distribution concentration of each selected case, we determine the extremes of the downwind segment (D_x) in which 1 hour concentration (C) exceeds C_L and where the potential monitoring station will be located. Where there is more than one case with $C_{max} > C_L$ in a given direction, the segment (D_x) can be determined by overlapping the surface concentration distributions and identifying the proportion of distance at which the 1 hour concentration values are always greater than the threshold value for all the cases. In addition to the possible downwind distance range, it is also necessary to determine the crosswind extent. The crosswind segment (D_y) within which 1 hour mean concentrations are higher than the threshold value, can be calculated assuming a Gaussian plume. In this way, the size of an area for the location of a single station, to ensure that it can measure 1 hour concentration values (C) greater than C_L whenever $C_{max} > C_L$, can be obtained.

This monitoring network design procedure depends on the accuracy of the model results, so the selection of the model to be applied is very important. According to Lee *et al.* (1995) and Irwin (1998), the ISC models tend to over-predict ground-level concentrations for surface releases, under-predict concentrations for rural elevated releases, and perform quite well for urban elevated releases. The network accuracy is related to the model bias in the estimation of the highest concentration values. As the monitoring site locations are determined from the analysis of the model estimates that exceed a given value, the under-predictions of the model may add greater inaccuracy in the network design than the over-predicted cases. In the first case we may not include a monitoring station where it is actually necessary. Once the network is operating, the measurements can be applied to 'calibrate' the model and then the network design can be modified. This 'feedback' procedure is beyond the scope of this paper.

3 Example of the site selection using the proposed methodology

To illustrate the use of the proposed method for designing a monitoring network, we present an application to select the number and site location of sensors to support a control system for an industrial plant. The stack of the plant has a height of 45.0 m, a diameter of 6.0 m, the stack gas exit velocity is 16.0 m/s, the stack gas temperature is 400 K and the emission rate of NO_2 is 60.0 g/s. The standard deviation of the hourly emission data is assumed to be negligible, so the hourly emission rate values are approximately the same. The meteorological data used as input to the atmospheric dispersion model ISCST3, was taken over a one year period in 1994. The meteorological data includes: ambient temperature, wind-speed and wind direction, cloud cover and cloud ceiling height from Buenos Aires Airport Meteorological Station (National Weather Service of Argentina). The hourly atmospheric stability has been calculated by the Pasquill and Turner stability class (US EPA, 1995b) and mixing heights have been estimated according to Zilitinkevich (1975). In this example a polar grid receptor array is considered, centered at the source. The rings are placed 50 m apart, at distances ranging from 100 m to 6000 m from the source, and at directions of 10° to 360° in 10° increments. The following design criteria have been employed:

- Averaging time: 1 hour
- Total time period: 1 year
- Threshold concentration (C_L): 80 μg/m³.

Figure 1 shows the cumulative frequency distribution of the calculated 1 hour maximum concentration values (C_{max}) of NO_2 at ground-level. The C_{max} values range from 10 μg/m³ to 106 μg/m³. A high proportion (68.8 %) of the 1 hour C_{max} values are within the interval 10–40 μg/m³, and there is 2.83 % of hourly C_{max} values that exceeds the threshold value of 80 μg/m³. The distribution of the number of estimated hours where $C_{max} > 80$ μg/m³ with plume direction is given in Figure 2. The largest number of hours when the threshold value is exceeded occur most often when the plume is at a direction of 20°, and the fewest number of hours are observed when the plume is at 250° or 290°. The model results for 1994, indicate that the highest values of C_{max} (>80 μg/m³) can be found in 17 directions. The monitoring stations may be distributed at those locations. Table 1 shows the directions ranked according to the number of hours in 1994 where $C_{max} > 80$ µg/m^3. The third column of Table 1 includes the cumulative relative frequency of cases.

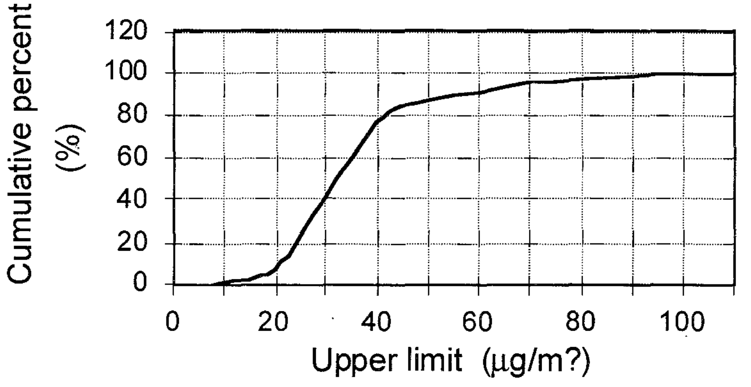

Figure 1 Cumulative frequency distribution of 1 hour maximum concentrations (µg/m^3).

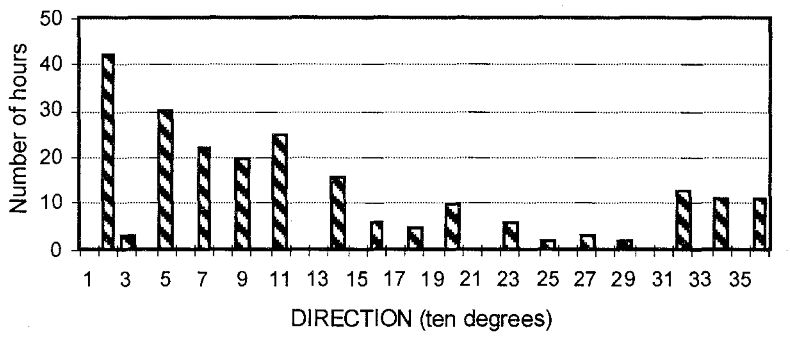

Figure 2 Distribution of the number of hours with $C_{max} > 80$ µg/m^3 with plume direction. Model results considering 1994 hourly meteorological data.

The variation of the 1 hour C_{max} range (when $C_{max} > 80$ µg/m^3) with the downwind direction from the source can be seen in Figure 3. The largest range (80–106 µg/m^3) occurs at a direction of 20° and the smallest range (84.0–85.8 µg/m^3) occurs at a direction of 250°. The ranges of downwind distance (X_{max}) associated with $C_{max} > 80$ µg/m^3 are shown in Figure 4. All of the maximum concentration values are located at distances of between 3300 m and 4200 m from the source. The widest range is at a direction of 20° (X_{max} from 3350 m to 4200 m) but also at a direction of 50°, 110°, 270° and 290° (from 3300 m to 4150 m), and the shortest variation of X_{max} is observed at 250° (from 3300 m to 3400 m). Although the ranges included in Figure 4 specify approximate potential monitoring zones, the location of sensors within those ranges does not guarantee the detection of concentration values greater than 80 µg/m^3 just because the actual 1 hour

C_{max} value exceeds 80 μg/m^3. To illustrate the selection of the proper potential monitoring zone, we show the two typical situations that we found in the analysis of the downwind distance distributions calculated by the model for the example we are considering (Figure 5). In both graphs, if the air monitoring station is located within zone 1 or zone 3, only one of the two C_{max} > 80 μg/m^3 included in each scheme can be registered by the sensor. However, if the sensor is sited at zone 2, it can register 1 hour concentration values greater than the threshold values whenever the actual C_{max} > 80 μg/m^3. In this way, we determine the main axis (D_x) in the downwind direction. Assuming a crosswind Gaussian distribution we calculate the transverse axis (D_y) of the elliptic zone where the hourly concentration values exceed 80 μg/m^3. The area of this ellipse and its position in each of the 17 directions of interest can easily be computed. The dimensions of D_x, D_y and the area of the ellipse are included in Table 1. The smallest zone (16 020 m^2) is located at a direction of 20°, with D_x = 500 m, D_y = 41 m and the largest zone (325 465 m^2) is located at 340°, with D_x = 2350 m and D_y = 176 m.

Table 1 Monitoring site locations ranked according to the decreasing number of hours with C_{max} > 80 μg/m^3 at each plume direction, estimated by the ISCST3 model for 1994 meteorological data. Cumulative percent (%) of hours with C_{max} > 80 μg/m^3. X_1 and X_2 are the nearest and farthest extremes respectively of the downwind segment. D_x and D_y are the axis of the elliptic area where the calculated 1 hour mean concentration values exceed 80 μg/m^3.

Site number	Plume direction (°)	Cumulative percent (%)	X_1 (m)	X_2 (m)	D_x (m)	D_y (m)	Area (m^2)
1	20	18.5	3200	3700	500	41	16 020
2	50	31.7	3200	3850	650	56	28 577
3	110	42.7	2800	4150	1350	110	116 725
4	70	52.4	3050	3850	800	61	38 044
5	90	61.2	2800	4050	1250	105	103 445
6	140	68.3	2700	4300	1600	127	159 743
7	320	74.0	2950	4000	1050	79	65 462
8	360	78.9	2900	4050	1150	89	80 378
9	340	83.7	2500	4850	2350	176	325 465
10	200	88.1	2950	4150	1200	99	93 603
11	160	90.8	2600	4400	1800	139	197 149
12	230	93.4	2650	4750	2100	162	267 314
13	180	95.6	2600	4650	2050	149	240 515
14	30	96.9	2600	4650	2050	154	247 865
15	270	98.2	2400	4650	2250	173	305 643
16	250	99.1	2550	4500	1950	146	224 276
17	290	100.0	2500	4550	2050	157	252 363

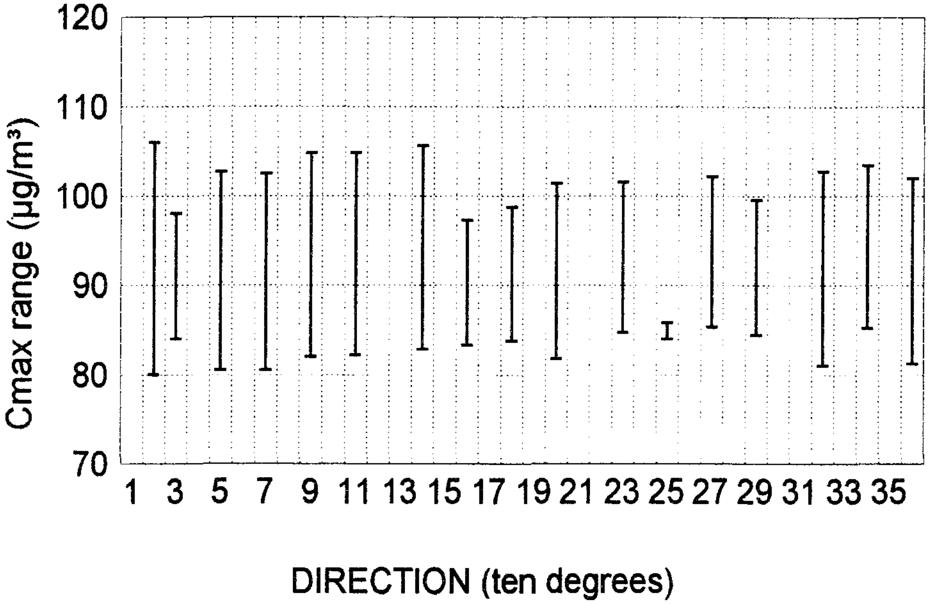

Figure 3 Variation of 1 hour C_{max} range ($C_{max} > 80\,\mu g/m^3$) with plume direction.

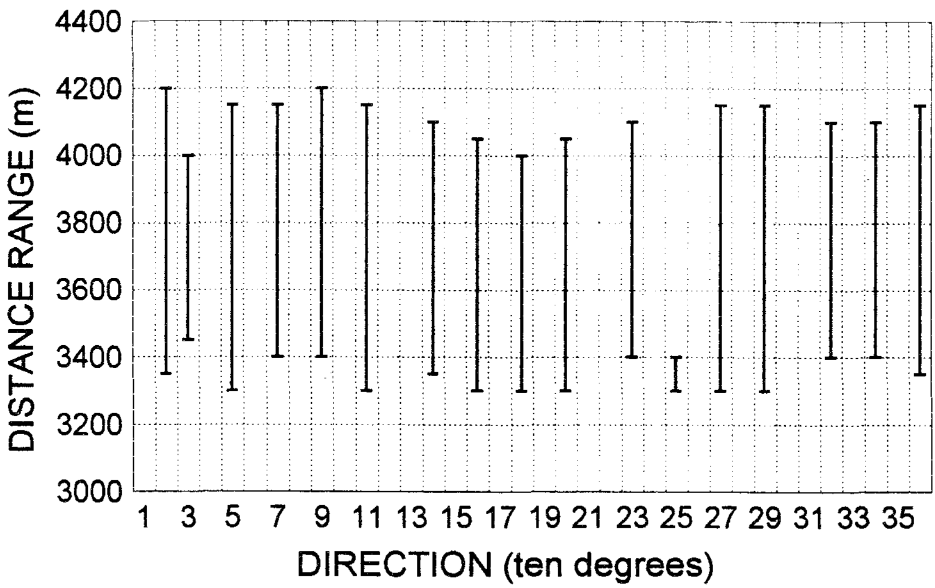

Figure 4 Variation of downwind distance range (associated with $C_{max} > 80\ \mu g/m^3$) with plume direction.

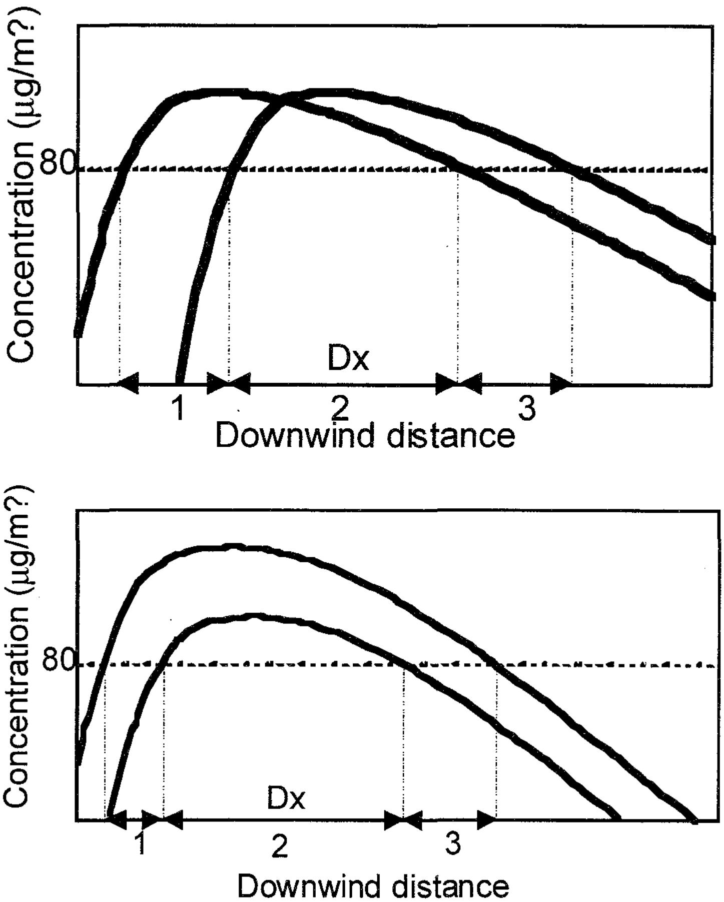

Figure 5 Typical ground-level concentration (µg/m^3) versus downwind distance calculated by the model for the example used in this study.

Figure 6 shows the distribution of the frequency of 1 hour C_{max} > 80 µg/m^3 with the hours of the day estimated by the model. It can be seen that, in this example, with a stack height of 45 m, the model estimates that 1 hour C_{max} > 80 µg/m^3 may occur mainly during nocturnal hours.

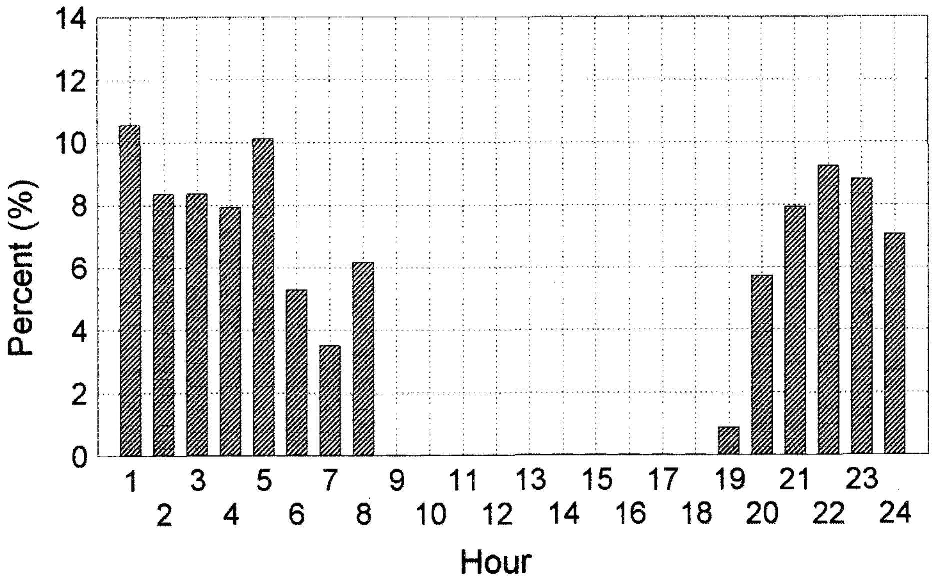

Figure 6 Frequency of occurrence of $C_{max} > 80\ \mu g/m^3$ with the hours of the day.

4 Influence of the interannual variability of atmospheric conditions on the efficiency of the network design

According to the model results for the given stack, in the previous section we found that the 1 hour NO_2 concentration values greater than 80 $\mu g/m^3$ could be fully controlled by installing 17 monitoring stations. We located the possible sites and estimated their length (D_x) and width (D_y). We also determined by the application of the ISCST3 model, a theoretical probability (the third column in Table 1) of detecting concentration values greater than 80 $\mu g/m^3$ associated with the number of sampling sites. For example, if the network consists of the first four sampling sites in Table 1, 52.4% of the cases predicted by the model with $C_{max} > 80\ \mu g/m^3$ could be detected. It is necessary to determine if the network design procedure, according to the model results considering hourly meteorological data from a single year, is able to give acceptable results when repeating the model with another year of meteorological data. (From herein the network obtained considering only the model results for 1994 is referred to as '1994 monitoring network'.) The aim of this study was to determine whether the model estimations of 1 hour $C_{max} > 80\ \mu g/m^3$ for another year of hourly meteorological data can be 'detected' by the '1994 monitoring networks'. Five different monitoring networks are proposed, based on five location criteria (Figure 7): the sensor is located near one of the extremes of the segment D_x (Net#1 and Net#5); the sensor is located in the middle of D_x (Net#3); or it is located midway of the previous positions (Net#2 and Net#4). These site locations are selected according to the model estimates for the 1994 data. We then apply the ISCST3 model using the hourly meteorological data of Buenos Aires Airport Station registered during another period of one year (1995).

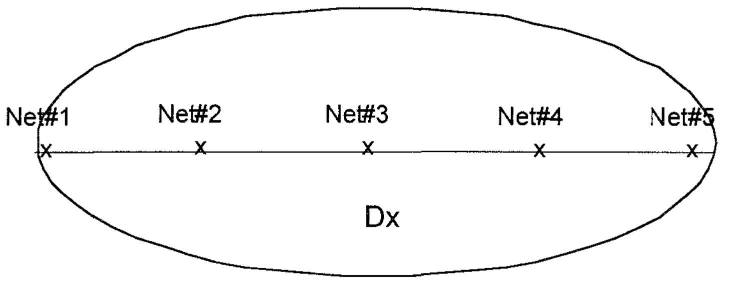

Figure 7 Five possible '1994 monitoring networks' (Net#1, Net#2, Net#3, Net#4 and Net#5) showing the position of an air monitoring station inside the ellipse that bounds the area where $C_{max} > 80\ \mu g/m^3$ is expected to be found according to model results.

Table 2 presents the downwind distance (X) from the source at which the monitoring station is located in each direction, for each '1994 monitoring network'. The adjacent column indicates the percentage (%) of all the cases with $C_{max} > 80\ \mu g/m^3$ modelled by the ISCST3 for 1995 'detected' at each site. As can be seen all of the Net#3 sites will be able to detect every situation with $C_{max} > 80\ \mu g/m^3$ modelled with 1995 data. However, Table 3 shows that the percentage of cases with $C_{max} > 80\ \mu g/m^3$ for 1995, that each '1994 monitoring network' (as a whole) can detect is below 100%. This is because the $C_{max} > 80\ \mu g/m^3$ values, estimated by the model for 1995 in three directions (40°, 80° and 300°) are not included in the proposed '1994 monitoring networks', because no $C_{max} > 80\ \mu g/m^3$ appeared at these directions in the model estimations for 1994 data (Figure 8).

Figure 9 includes the cumulative relative frequency of the hourly concentration values greater than $80\ \mu g/m^3$ at each site of the five '1994 monitoring networks' according to the model results for 1995 hourly meteorological data. The ideal curve in Figure 9 (values in the third column of Table 1) is obtained from the model results for 1994 hourly meteorological data. The maximum difference between the cumulative frequencies shown in Figure 9 is 4.6% when considering 14 monitoring sites.

Table 2 Plume direction and distance (*X*) of the monitoring sites of each proposed '1994 monitoring network'. The efficiency of each site is indicated by the percentage (%) of hours with $C_{max} > 80$ μg/m^3 (that each site is able to 'detect') calculated by the model for 1995 meteorological data.

Site number	Plume direction	Net#1		Net#2		Net#3		Net#4		Net#5	
	(°)	*X* (m)	(%)	*X*(m)	(%)	*X*(m)	(%)	*X*(m)	(%)	*X*(m)	(%)
1	20	3250	100	3350	100	3450	100	3550	100	3650	100
2	50	3250	100	3400	100	3550	100	3700	100	3800	100
3	110	2850	89	3200	100	3500	100	3800	100	4100	93
4	70	3000	90	3200	100	3450	100	3600	100	3800	90
5	90	2850	94	3150	97	3450	100	3700	100	4000	97
6	140	2800	89	3150	95	3500	100	3850	95	4200	89
7	320	3000	100	3250	100	3500	100	3700	100	3950	100
8	360	2950	93	3250	100	3500	100	3750	93	4000	86
9	340	2600	100	3150	100	3700	100	4200	100	4750	83
10	200	2900	100	3200	100	3550	100	3850	100	4100	100
11	160	2700	100	3100	100	3500	100	2900	100	4300	75
12	230	2750	100	3250	100	3700	100	4150	100	4650	100
13	180	2700	100	3100	100	3650	100	4100	100	4550	100
14	30	2700	100	3150	100	3600	100	4100	100	4550	100
15	270	2500	50	3100	100	3550	100	4050	100	4550	75
16	250	2650	75	3100	100	3500	100	3950	100	4400	75
17	290	2600	67	3100	100	3550	100	4000	100	4450	100

Table 3 Network efficiency to detect the hours with $C_{max} > 80\ \mu g/m^3$ predicted by the model considering 1995 hourly meteorological data. (The networks have been designed from the model results considering 1994 hourly meteorological data.)

	Net#1	Net#2	Net#3	Net#4	Net#5
Efficiency	92.0%	97.6%	98.4%	97.6%	92.8%

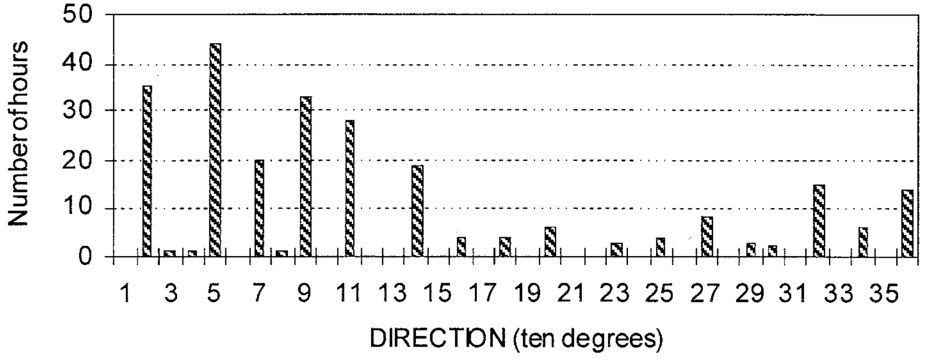

Figure 8 Distribution of the number of hours with $C_{max} > 80\ \mu g/m^3$ with plume direction. Model results considering 1995 hourly meteorological data.

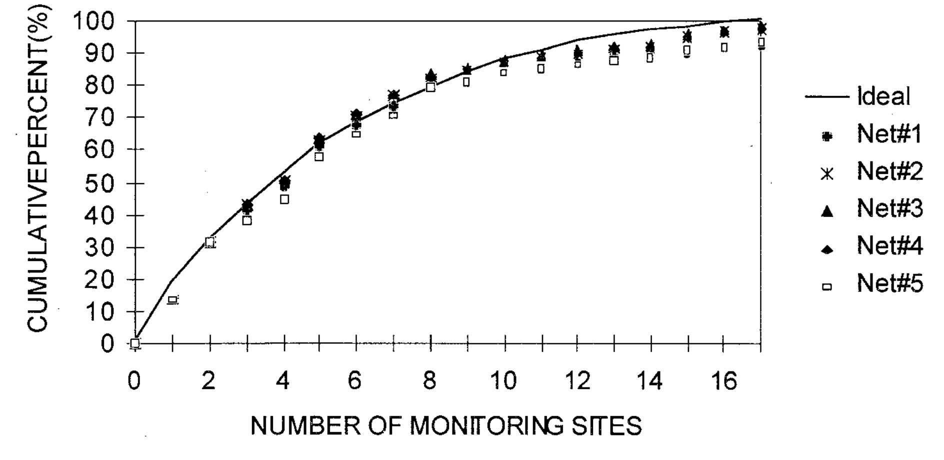

Figure 9 Cumulative percent frequency of 1 hour $C_{max} > 80\ \mu g/m^3$ values estimated by the atmospheric dispersion model for 1995 meteorological data, that each '1994 monitoring network' can detect versus the number of monitoring sites. The ideal curve is the design probability of any of the '1994 monitoring network' considering the model concentration estimations for 1994 meteorological data.

5 An approximated efficiency of the air pollution network design

The efficiency of the network to accomplish the task is derived from the efficiency of the network design procedure (including the bias in the model predictions, the interannual variability of atmospheric conditions and the number of monitoring stations) and from the bias of the air pollution sampling instruments. One method of obtaining an approximated value of the efficiency (ε) of the network design to detect $C_{max} > C_L$ can be expressed by:

$$\varepsilon = [(1 - E_a)(1 - E_m)(P_n)] \tag{1}$$

where E_a is the error due to the interannual variability atmospheric conditions, E_m is the error in the model predictions of $C_{max} > C_L$, and P_n is the probability associated with the number of monitoring sites. For the example presented in the previous section we calculated that E_a is less than 5% for the five proposed networks (see Figure 9). If model estimates are within a factor of two of the observed values (Olesen, 1994; Weil, 1994; Lee *et al.*, 1995; Irwin, 1998) then the error of the network design is highly dependent on the accuracy of the dispersion model used. According to the network design described in section 2, we may consider that only some of the model under predicted values may lead to a loss of some cases of $C_{max} > C_L$. If we assume that the ISCST3 model predicts only 50% of the actual cases of $C_{max} > 80\ \mu g/m^3$ then $E_m = 0.5$. In the example, the probability associated with the number of sampling sites is $P_n = 1$ if the network has 17 monitoring stations (the number of stations needed according to Table 1). For a different number of sampling sites, the value of P_n is given by the cumulative percent (%) included in the third column of Table 1. In the example, for 17 monitoring stations, the accuracy of the network design is $\varepsilon = (1 - 0.05)(1 - 0.5)(1) = 0.475$. Figure 10 includes the variation of ε versus the number of samplers. The efficiency of the network design increases with the number of samplers, ranging from 0.09 to 0.475.

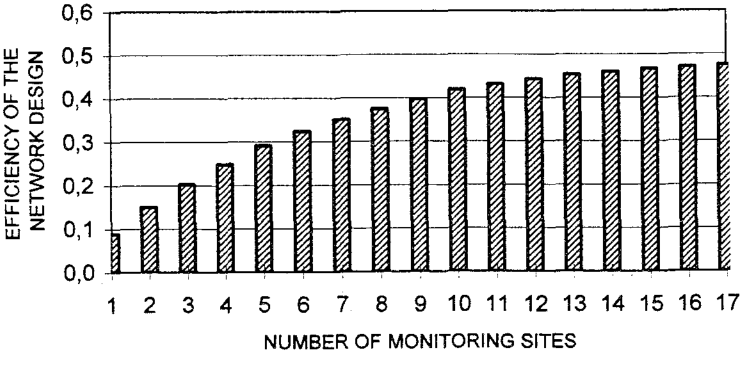

Figure 10 Approximate efficiency of the network design procedure (ε) versus the number of monitoring sites.

6 Summary

This paper presents an objective methodology for designing an air quality monitoring network to control the highest concentration values generated from an elevated point source, by using the ISCST3 atmospheric dispersion model. The application of this procedure can be summarized as follows:

- The application of the atmospheric dispersion model to a stationary source emission using 1 year of hourly meteorological data.
- The selection of a threshold concentration value (e.g. the air quality standard or a value within 10% or 20% of the predicted maximum concentration).
- The identification of the maximum 1 hour concentration values that exceed the threshold value, determination of the number of occurrences of these cases in each direction, and the downwind distance at which the maximum is located.
- Each elliptic area (main and minor axes) of a potential monitoring zone is determined based upon the certainty that every situation with 1 hour C_{max} greater than the threshold value is included in the selected area.

For the example presented in this paper we obtain an approximated value of the efficiency of the network design that was 0.475 at best.

Finally, the selection of the number and operation schedule of the monitoring sites will be the responsibility of the environmental control administration, considering that the efficiency of the network increases with a greater number of monitoring stations. Once the network is operating, its measurements and the atmospheric dispersion model results can both be used to improve the efficiency of the network.

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