An ambient air quality monitoring network for Buenos Aires city

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Abstract: This paper proposes an objective methodology for designing a multi-pollutant urban air-quality monitoring network to detect concentrations greater than reference concentration levels (C_L). The network design includes both air quality simulation and an objective analysis based on monitoring tasks. The proposed methodology is applied to the city of Buenos Aires. Pollutants of concern are nitrogen oxides, carbon monoxide and PM_{10}. Considering C_L as 50% of the Air Quality Standards, the design methodology determines six monitoring sites where to measure different pollutants at the same place. 'Spatial representativeness' of detected exceedances is evaluated analysing air quality simulations of cases with $C > C_L$ at any monitoring site and obtaining the areas in the city where concentrations are expected to exceed C_L with 70%, 80% and 90% of probability.

Keywords: urban air quality; air quality management; air quality monitoring network; spatial representativeness; Buenos Aires city; carbon monoxide; nitrogen oxides; particulate matter.

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1 Introduction

Air pollution in cities is a serious environmental problem. Urban air quality is the result of a complex interaction between natural and anthropogenic environmental conditions. In order to develop or implement an affective air quality management plan, it is first necessary to obtain reliable information on ambient pollution levels. Monitoring provides necessary information required by scientists, policy makers and planners to enable them to make informed decisions on managing and improving the environment. However, the limitations of monitoring should also be recognised. In many cases, measurements alone may be insufficient for the purpose of air quality management. Monitoring often needs to be used in conjunction with other objective assessment techniques, including modelling, emission measurement and inventories, interpolation, mapping and interpretation. Some of these techniques have been discussed in Hester and Harrison (1997). Ambient air quality measurements and modelling-based assessments can usefully be regarded as complementary activities.

The placement of air monitoring stations in a network depends upon the nature of monitoring objectives. Different authors have presented methodologies for designing an air-pollution monitoring network using different statistical methods or atmospheric dispersion models (Shindo et al., 1990; Wu and Chan, 1997; Hwang and Chan, 1997; Mazzeo and Venegas, 2000; Tseng and Chang, 2001; Baldauf et al., 2002; Venegas and Mazzeo, 2003; Kanaroglou et al., 2005; Chen et al., 2006). Most of the network design methodologies have been developed for point sources and some of them for urban area sources.

The Metropolitan Area of Buenos Aires is one of the three largest mega-cities in Latin America. The population of the city of Buenos Aires is about three millions inhabitants and the population of the Metropolitan Area is about 14 millions. Buenos Aires city is located on a flat terrain close to the de la Plata River. This river is a shallow large-scale coastal plain estuary that covers an approximate area of 35,000 km^2 and has a width of approximately 42 km in front of the city.

At present, Buenos Aires city has no air-quality monitoring network. However, a few short-time air quality monitoring campaigns have been carried out in the city. Several studies on air pollution in the urban area using those few data have been published elsewhere (Bogo et al., 1999, 2001, 2003; Venegas and Mazzeo, 2000; Mazzeo and Venegas, 2002, 2004; Mazzeo et al., 2005). Other studies on the air quality conditions in Buenos Aires include the development of the first version of an emission inventory for CO and NO_x (expressed as NO_2) (Mazzeo and Venegas, 2003) in the city and the application of an urban atmospheric dispersion model (Venegas and Mazzeo, 2005, 2006) to estimate urban background concentration distributions of these pollutants.

The objectives of this study are:

- to develop an objective procedure to determine the minimum number of monitoring sites (and their locations) needed to detect the occurrence of air pollutant concentrations greater than reference concentration levels (C_L) in an urban area
- to design a multi-pollutant (NO_x, CO and PM_{10}) urban air-quality monitoring network for Buenos Aires city and to evaluate the 'spatial representativeness' of detected exceedances.

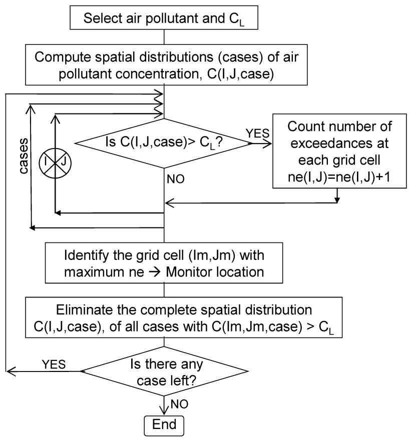
The proposed network design methodology is based on the analysis of the results of atmospheric dispersion models and it is an extension of the network design procedure developed previously for only one pollutant (Venegas and Mazzeo, 2003). We apply the urban atmospheric dispersion model DAUMOD (Mazzeo and Venegas, 1991; Venegas and Mazzeo, 2006) to area source emissions and the ISCST3 (US EPA, 1995) dispersion model to major point source emissions in the city.

2 Description of the proposed site selection procedure to design a multi-pollutant monitoring network

Assuming a limitation on the number of sites, as determined by resource availability, the objective of the proposed network design procedure is to determine the minimum number of monitoring stations and their locations, needed to detect the occurrence of urban background air pollutant concentration (C) greater than a reference concentration level (C_L) in an urban area.

First, a brief description of the monitoring network design methodology for one air pollutant is presented. The first step of this methodology is to choose a reference concentration (C_L) level. The second step is to compute horizontal distributions of hourly air pollutant concentrations in the urban area, for at least one year, using atmospheric dispersion models. The third step is to identify the cases and grid cells with estimated concentrations greater than C_L (the locations of the monitors will be selected among the grid cells identified at this step). In the fourth step, the pre-selected grid cells are ranked according to the number of exceedances ($C > C_L$). The first monitoring site will be located at the grid cell with most exceedances. In the last step, all cases with $C > C_L$ at the selected grid cell are discarded and not included in the further analysis. In order to select the next site location, the grid cells are ranked again according to the number of exceedances in the remaining cases. The second monitoring site will be located at the grid cell with the highest number of exceedances. Once the second monitoring site location is determined, all cases with $C > C_L$ at the chosen grid-cell are discarded. The procedure continues until the last case is eliminated and the site locations needed to 'detect' the occurrence of $C > C_L$ in the area are determined. With these monitors, the efficiency of the network to detect $C > C_L$ would be (ideally) 100%. Figure 1 shows a scheme of this site selection procedure. A detailed description and application of this procedure to determine monitoring site locations to identify the occurrence of hourly and daily NO_x concentrations greater than given concentration values in Copenhagen (Denmark) can be found in Venegas and Mazzeo (2003).

Figure 1 Scheme of the site selection procedure for one air pollutant monitoring network



Then, if there is more than one pollutant of concern, we propose a two-stage procedure to design a multi-pollutant air-quality monitoring network. In this case, the proposed methodology includes the site selection procedure described above followed by an optimisation approach. The first stage (Stage I) undertakes the design of a 'preliminary network'. This 'preliminary network' will include all the monitoring stations ranked according to their 'detection capability' of $C > C_L$ for each air pollutant. These locations come from the application of the site selection procedure described above to each one of the air pollutants with the corresponding averaging time (included in air quality regulations). The second stage (Stage II) includes an 'optimisation analysis' to pick up the most appropriate subset within the initial locations where to install different sensors together in the same place. The costs for sitting a pollutant-specific monitoring network would be higher than that for a common monitoring network with respect to several pollutants simultaneously. Thus, for practical reasons, most monitoring networks install different detection instruments together in a common monitoring network that could be viewed as more economic and feasible applications. Taking into account that the objective of the air quality network to be designed is to detect the occurrence of exceedances ($C > C_L$), we propose to select the monitoring locations according to their detection capability of exceedances of the reference concentration level obtained at Stage I. For example, considering three air pollutants, the 'minimum network' configuration comprises three sites, that are the first monitoring site location obtained from the application of Stage I to each air pollutant. Assuming that all pollutants are measured at every site, the next step is to evaluate the efficiency (%) of this 'minimum network' configuration to detect $C > C_L$ for each air pollutant. This evaluation is done using a compromise-programming model, which combines air quality simulation results and the proposed network configuration. This analysis is repeated for each pollutant separately and gives the percentage of exceedances ($C > C_L$) 'detected' by each considered monitoring site.

This initial network configuration can be expanded including remaining sites with high number of exceedances identified at Stage I. The monitoring site location to be included should be chosen to improve the efficiency of detection of $C > C_L$ for the pollutant with the lowest percentage of exceedances 'detected' by the previous network configuration. Then, as done before, the efficiency of the new network configuration is evaluated for each air pollutant. It is worth mentioning that, as we assume that all pollutants are supposed to be measured at every site of the proposed network, the analysis of the network efficiency also shows if, for any of the air pollutants, there is a site location where no cases of $C > C_L$ are detected.

The credibility of this monitoring network design procedure depends first on the accuracy of the emission inventory and secondly on the performance of the atmospheric dispersion models used.

Once the network is operating, the measurements will be applied to 'calibrate' the network design. Statistical methods can assist in assessing site redundancy of the monitoring network in reporting the number of exceedances. A relocation strategy is then needed to improve the network efficiency. This 'calibration' is beyond the scope of this study (at present the network is not in operation) but several methods that can be applied in this process are described in Hwang and Chan (1997), Tseng and Chang (2001), Kanaroglou et al. (2005) and Chen et al. (2006).

3 Design of a multi-pollutant monitoring network for Buenos Aires city and evaluation of 'spatial representativeness' of detected exceedances

3.1 Atmospheric dispersion models and input data

The emission inventories for Buenos Aires city (Mazzeo and Venegas, 2003; Venegas and Martin, 2004) considered in this analysis, include area and point sources of CO, NO_x and PM_{10}. The inventories have a spatial resolution of 1×1 km and a typical diurnal variation. The database of the emission inventories have been developed considering the following activities as area sources: residential, commercial and small industries, road traffic and aircraft operations at the domestic airport located in the city. In general, traffic emissions are determined as line sources, particularly emissions of traffic on major roads. However, in addition to the traffic on the main road network (avenues), in the city there is a substantial volume of traffic on streets. The emission inventories for Buenos Aires treat mobile sources as area sources reporting total traffic emission (on avenues and streets) for each grid square in the city. We apply the urban atmospheric dispersion model DAUMOD (Mazzeo and Venegas, 1991, 2004; Venegas and Mazzeo, 2002, 2005, 2006) to area source emissions. There are also three power plants located in the city near the coast. The stacks of these power plants are the only point sources to be considered because there is no other large industry in the city. The thermal power plants burn natural gas during most part of the year except for a few days (the coldest) during winter when they are compelled to burn gas-oil. For this reason, their contribution to CO and PM_{10} concentrations in the city is negligible. On the other hand, they are responsible for half the annual emission of NO_x in the city. However, due to the very tall stacks and the emission conditions, the impact of their emissions on the air quality in the city occurs at the grid cells near their locations (Venegas and Mazzeo, 2005). Their contribution to NO_x concentrations in the city is much smaller than the contribution of area source emissions (mainly mobile source emissions). Fulfilling Argentine regulations, the Industrial Source Complex ISCST3 (US EPA, 1995) dispersion model has been applied to estimate air pollution concentrations due to point source emissions. Hourly meteorological data registered at a weather station of the Argentine Meteorological Service located at the domestic airport have been used in calculations.

3.2 Monitoring site selection

We apply the site selection methodology described in Section 2 to determine the minimum number of sensors and their locations to identify the occurrence of 1 h and 8 h average CO concentrations, 1 h average NO_x concentrations and 24 h average PM_{10} concentrations greater than reference concentration levels. Reference concentration levels considered in calculations are chosen as 50% the value of the Air Quality Standard for each pollutant. Though the choice of C_L is arbitrary, uncertainties in air quality model predictions have been taken into account in the definition of C_L. Evaluations of the performance of atmospheric dispersion models (Hanna et al., 2001; Hall et al., 2002; Venegas and Mazzeo, 2002) show that, on average, relative bias of model predictions may be between +50% to –50%. In this way, for NO_x (averaging time: 1 h) $C_L = 0.20$ mg m^{-3}, for CO (averaging time: 1 h) $C_L = 20.0$ mg m^{-3}, for CO (averaging time: 8 h) $C_L = 5.0$ mg m^{-3} and for PM_{10} (averaging time: 24 h) $C_L = 0.075$ mg m^{-3}.

We compute the horizontal distribution of hourly values of NO_x and CO concentrations, 8 h average CO concentrations and daily PM_{10} concentrations (C) for Buenos Aires city. Considering one air pollutant at a time and following Stage I of the network design methodology, the minimum number of sensors needed to register the occurrence of $C > C_L$ in the city is determined. Results of Stage I determine a 'preliminary' air-quality monitoring network with 17 sites (Figure 2) that includes 16 sensors of NO_x, four sensors of CO and four sensors of PM_{10}. It can be seen that only one site location is common to the three pollutants of concern. Therefore, for practical reasons and limited resources, we go over the optimisation analysis (Stage II). Due to operational and economical reasons, in this case study, the upper bound of the number of monitoring site locations is six. The 'minimum network' configuration that includes the locations with the highest percentage of exceedances ($C > C_L$) for each pollutant is shown in Figure 3(a)). The analysis of the efficiency of this network reveals that NO_x and PM_{10} should be measured at the three locations but CO at only two. The percentages of cases with $C > C_L$ at monitoring sites, associated to this configuration are: NO_x (1 h): 87.2%; CO (1 h): 73.7%; CO (8 h): 95.4%; PM_{10} (24 h): 98.5%.

Figure 2 Monitoring site locations of the 'preliminary network', determined at Stage I. ΔNO_x, oCO, ∇PM_{10} (grid size: 1 × 1km)

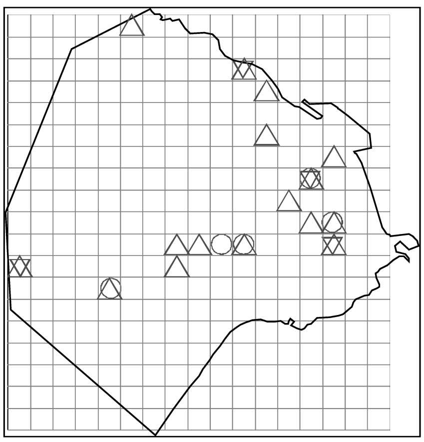
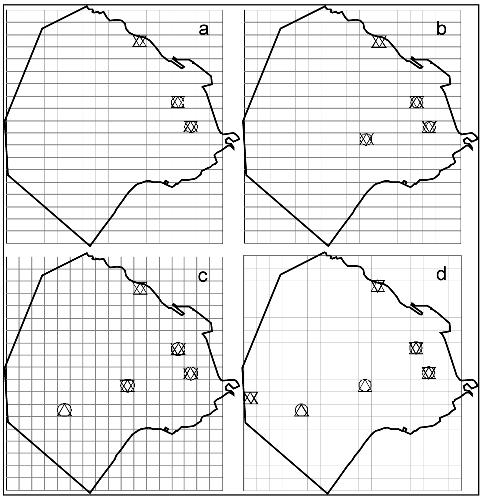


Figure 3(b)–(d) shows the configurations obtained incorporating site locations under the criterion of 'detection capability' of $C > C_L$ and therefore improving the number of exceedances 'detected'. Each time a monitoring site location is added to a configuration, the analysis of the efficiency of the new network assists in determining the places where to install the different detection instruments. Finally, the proposed air quality network (Figure 3(d)) requires six monitors of NO_x (efficiency: 94.2%), four monitors of CO (efficiency: 97.4% for 1 h average and 100% for 8 h average) and four monitors of PM_{10} (efficiency: 100%). The three pollutants would be measured at two sites, NO_x and CO at another two sites and NO_x and PM_{10} at the remaining two locations. Notice that when the number of site locations increments from 5 to 6 (Figures 3(c) and (d)) the analysis of the efficiency of the last network reveals that measuring PM_{10} at the new site makes no necessary to measure PM_{10} at the location incorporated in Figure 3(b). This result is related to the 'spatial representativeness' of detected exceedances at this monitoring site, as can be seen in next session.

Figure 3 Air-quality monitoring network configurations proposed during the optimisation analysis (ΔNO_x, oCO, ∇PM_{10}). Efficiency of each configuration: (a) NO_x (1 h): 87.2%; CO (1 h): 73.7%; CO (8 h): 95.4%; PM_{10} (24 h): 98.5%; (b) NO_x (1 h): 92.1%; CO (1 h): 89.5%; CO (8 h): 100%; PM_{10} (24 h): 99.5%; (c) NO_x (1 h): 93.1%; CO (1 h): 97.4%; CO (8 h): 100%; PM_{10} (24 h): 99.5% and (d) NO_x (1 h): 94.2%; CO (1 h): 97.4%; CO (8 h): 100%; PM_{10} (24 h): 100%



3.3 *'Spatial representativeness' of detected exceedances*

Once the proposed network (Figure 3(d)) is in operation, every time $C > C_L$ at a monitoring site, we are interested to know where else in the city the concentration could exceed C_L, within a known probability. This analysis is done for both one air pollutant and one monitor at a time. Considering the N_T estimated horizontal distributions of pollutant concentrations that show $C > C_L$ at the monitoring site, we compute the number $n(i,j)$ of cases with $C > C_L$ for each grid cell (i, j) in the city. The horizontal distribution of the relative frequency (%) estimated as $f(i, j)= (n(i, j)/N_T)* 100$ is calculated. From the contour map of $f(i, j)$, we obtain the areas where concentration is expected to be greater than C_L with a probability $f(i, j) \geq 70\%$, $f(i, j) \geq 80\%$ and $f(i, j) \geq 90\%$ every time a monitor registers $C > C_L$. Figures 4 and 5 show the results for NO_x and PM_{10}, respectively. Results for CO reveal that $f(i, j)$ at every grid cell is less than 70%, except for the four sites where the monitors are located. This means that 'spatial representativeness' of detected exceedances of C_L for CO concentrations, is local. For NO_x and PM_{10}, the 'spatial representativeness' of a detection of $C > C_L$, associated to a probability of 70%, 80% and 90% of occurrence of $C > C_L$ at other sites, are summarised in Table 1.

Figure 4 Areas where NO_x (expressed as NO_2) concentration is expected to be greater than C_L with a probability greater than 70% (light grey), 80% (medium grey) and 90% (dark grey) every time the monitoring site indicated in each plot registers that $C > C_L$

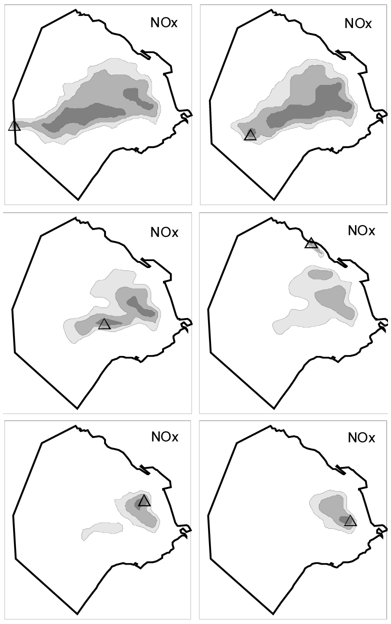


Figure 5 Areas where PM_{10} concentration is expected to be greater than C_L with a probability greater than 70% (light grey), 80% (medium grey) and 90% (dark grey) every time the monitoring site indicated in each plot registers that $C > C_L$

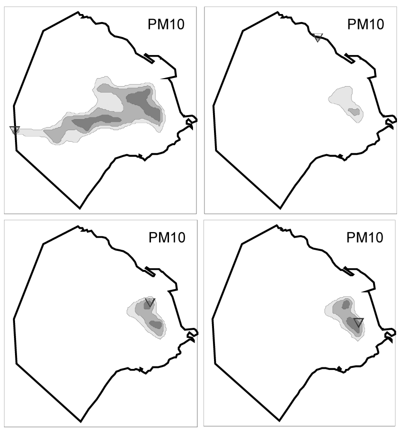


Table 1 Areas where NO_x and PM_{10} concentrations (C) are greater than C_L with a probability greater than 70%, 80% and 90% when $C > C_L$ at a monitoring site of the network

	Probability					
	70%		*80%*		*90%*	
Pollutants	*Min.* (km^2)	*Max.* (km^2)	*Min.* (km^2)	*Max.* (km^2)	*Min.* (km^2)	*Max.* (km^2)
NO_x (expressed as NO_2)	13.0	64.0	5.7	44.0	1.0	14.8
PM_{10}	5.7	39.7	1.0	23.3	1.0	7.0

4 Conclusions

This paper presents an objective methodology for designing a multi-pollutant air-quality monitoring network to identify the occurrence of urban background concentrations greater than reference concentration levels in an urban area using atmospheric dispersion models. The proposed procedure has two stages. In summary, Stage I includes the following steps:

- the selection of a reference concentration level (C_L)
- the use of atmospheric dispersion models to calculate air pollutant concentration (C) spatial distributions in the study area
- the identification of the cases and the grid cells with $C > C_L$
- the selection of monitoring sites to 'detect' the occurrence of $C > C_L$ in the urban area.

Stage I is applied to each pollutant (and short-time reference periods) of concern separately. The combination of the results obtained for each pollutant gives a 'preliminary network' configuration based on the 'detection capability' of $C > C_L$. Stage II includes an 'optimisation analysis' of the 'preliminary network', to select the sites where to install different detection instruments together in a common monitoring network.

The proposed methodology is applied to design a multi-pollutant (NO_x, CO and PM_{10}) monitoring network for Buenos Aires city to identify the occurrence of exceedances of reference concentrations (C_L) assumed to be 50% of the Air Quality Standards. We run the DAUMOD and ISCST3 dispersion models to area and point source emissions, respectively, to obtain the spatial distributions of air pollutant concentrations (C) in the city. After the analysis of the cases with $C > C_L$, we determine the minimum number of monitors needed to detect the occurrence of these exceedances. The optimisation analysis reveals that six monitoring sites located in the city would be able to detect these exceedances with efficiencies greater than 94%, depending on the air pollutant considered.

The 'spatial representativeness' of a detection of $C > C_L$, is a measure of the area in the city where the concentration (C) is expected to be greater than C_L with a known probability, when the network detects an exceedance. For NO_x concentrations, the extension of the 'spatial representativeness' associated to a probability of 70%, ranges between 13.0–64.0 km^2, for 80% it varies between 5.7–44.0 km^2 and for 90%, between 1.0–14.8 km^2. For PM_{10} concentration, the 'spatial representativeness' associated to a probability of 70% varies between 5.7–39.7 km^2, for 80% it varies between 1.0–23.3 km^2 and for 90%, between 1.0–7.0 km^2. The results for CO concentration indicate that, for all monitoring sites, 'spatial representativeness' of a detection of $C > C_L$ is local.

If the resources available are limited, this method can help in the selection of a minimum number of monitoring stations and their locations. It can be a useful tool either to start with a new air quality network or to prioritise site relocation of existing monitoring stations.

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