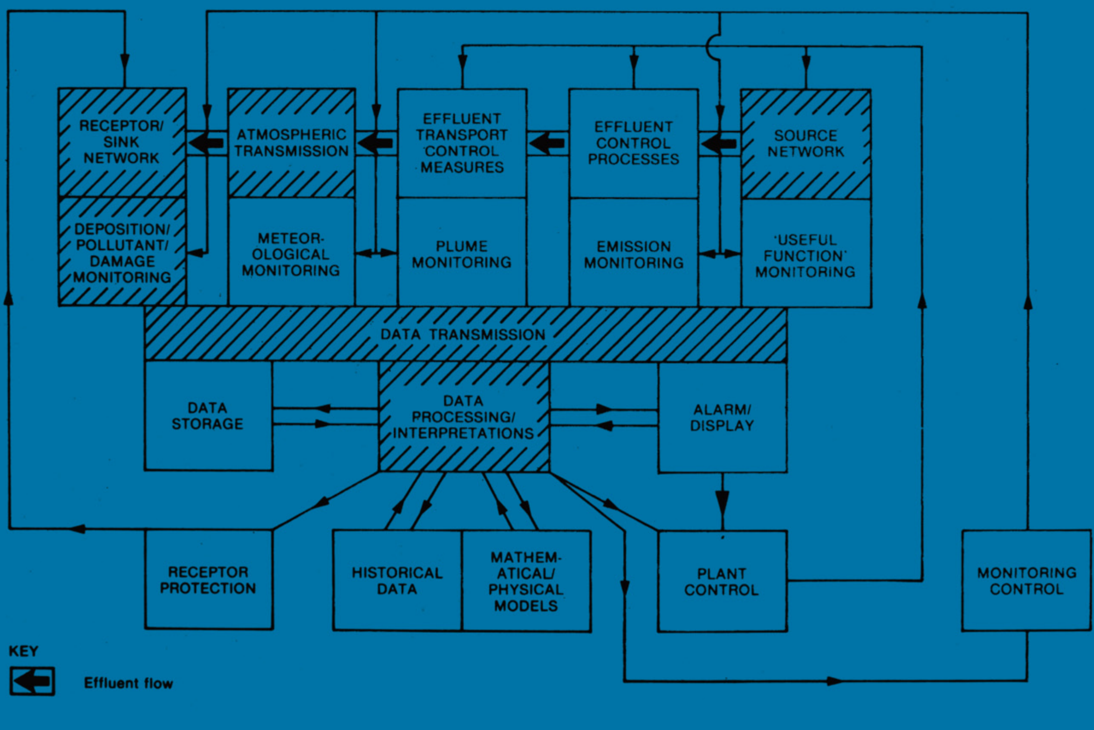
AIR POLLUTION PROBLEMS–2

THE DESIGN OF AIR QUALITY MONITORING NETWORKS

R.E. Munn



THE DESIGN OF AIR QUALITY MONITORING NETWORKS

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AIR POLLUTION PROBLEMS SERIES

THE DESIGN OF AIR QUALITY MONITORING NETWORKS

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University of Toronto, Toronto, Canada

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Foreword to the Series

The number of publications in the environmental area is increasing exponentially (Husar, 1978). Therefore there has to be a special justification for a new series. Since I agreed to accept the responsibility, I have developed my thinking on this topic and I shall now try to explain how I see the role of the series developing. There has been a tendency to view air pollution separately from other environmental problems, water and soil pollution and noise. Environmental problems in their turn have been isolated from the problems of energy, materials and employment. The advent of Environmental Impact Statements has tended to anticipate trade-offs between air pollution and the other environmental factors, but what seems to be required is a Total Impact Statement. The general evolutionary tendency this century has been to move towards using energy to replace muscle, i.e. fewer people producing more goods. This works reasonably well as long as the supply of fuel and materials is unlimited. However, once production is limited by materials, any 'negative' policy of pollution control which uses energy or materials tends to reduce their availablity for other useful purposes. On the other hand options like the development of 'renewable' energy sources, recycling of materials, the introduction of better thermal insulation and redeveloping labour intensive industries, appear to offer a positive approach. Less pollution is produced but *more* energy and/or materials become available for other useful purposes.

Furthermore there is a great deal of discussion about the effects of pollution. How many people die because of it? One thing, however, is certain. There are now a great many people—in national and local government agencies, in research at universities and elsewhere, in companies manufacturing control equipment and even in publishing houses—living from it. There is no doubt that there are acute local problems and the first two monographs in this series will help resolve these. What is less clear is how much of the vast expenditure is really cost-effective in terms of benefits to mankind and life in general in view of other really pressing problems.

The first two monographs in this series deal with modelling and monitoring pollution. Both, I hope, will become basic reading in their fields. Nevertheless they are examples of the 'negative' approach, which has prevailed up until now.

I hope that as the series progresses we shall begin to put pollution in perspective and look at less costly and probably more intelligent ways in which we can deal with it, as an alternative to the 'negative' approach.

Leatherhead, 1981 D.J.M.

Editor's Foreword

Monitoring, like modelling, does nothing to reduce air pollution. On the other hand, in many cases monitoring and modelling cost one or more orders of magnitude less than the control, which actually does set out to reduce pollution.

The design of the network, as Dr Munn points out, depends very closely on its purpose. In general if control is cheap and effective, it will be applied irrespective of monitoring; if it is very expensive, it will not be applied. However, extensive monitoring will probably be undertaken to prove that something is being done (but do not forget, *nothing* is being done about the pollution). One purpose of such a network is to reduce complaints, so the network is densest where complaints are likely to be greatest.

There are of course other purposes for monitoring networks, the principal of these being to validate modelling, which is cheaper than monitoring.

While energy is still plentiful, pollution monitoring networks will doubtless continue to proliferate and Dr Munn's monograph will help ensure that they produce the maximum benefit for their costs.

However, it would be interesting to compare the total cost of air pollution modelling and monitoring with money spent on developing energy systems which make use of solar energy (including wind power and heat pumps); this would certainly reduce pollution and energy usage.

David J. Moore
Series Editor

Preface

This monograph is a review of principles and practical procedures for siting air quality monitoring stations and for designing networks of stations. The scale of interest may range from local to global but a number of similarities prevail.

As pointed out by a referee, it is worth mentioning at the outset that with respect to atmospheric conditions, there is a difference between a *typical* and a *representative* location. In an urban area, for example, a *typical* location with respect to air quality receives a substantial proportion of its dosage from a few adjacent sources, and is situated over a very non-uniform surface (covered by roads, fences, trees, car parks, buildings, etc.). A *representative* location, on the other hand, is one that minimises the influences of nearby sources and of surface irregularities. Similarly, temperatures measured in a Stevenson screen within an enclosed grassy plot are *representative* of thermal conditions that could be expected at neighbouring sites if the buildings, parking lots or shrubbery were replaced by enclosed grassy plots. However, the location is *not typical* of conditions actually found within the urban fabric.

Accepting this distinction and assuming that representative sites are desired, it is important to ask the question 'representative of what?', and to qualify representativeness in terms of monitoring objectives, which is a central theme of this monograph.

I believe that there is need for periodic reviews of the efficacy of existing air quality networks, as more monitoring data become available, and as the source distributions of pollution change. This monograph should help to improve the quality of these reviews and thus should contribute to the overall goals of air quality programmes. In addition, it should aid in the identification of research gaps in the field of network design.

Toronto, 1980 R.E.M.

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1

Historical introduction

The establishment of design criteria for air quality monitoring networks is a topic of considerable importance at the present time. This is due in part to growing recognition that the efficacy of air pollution abatement is dependent on the nature of the associated monitoring activities. Only when the quality of the air is measured and is found to have fallen below some standard will control action usually be initiated. But choosing a 'best' site for a monitoring station often requires a qualitative judgement, and Stern (1976a) has said that 'as air quality monitoring networks have proliferated over the recent past, so have doubts arisen as to where, when and what to monitor'. In this as in many other environmental subject areas, the question of cost effectiveness has become increasingly important.

Air pollution monitoring programmes began in the last century but the first major survey took place in Leicester, England in 1937–39 (Meetham, 1945). Some fifteen monitoring stations were operated in that city, and even in those early days, the importance of selecting representative sites was realised. The Leicester report includes the comment that 'deposit gauges were placed if possible in the centres of large uniform districts, and great care was exercised in choosing sites'. The districts were classified according to whether their surroundings were industrial, commercial, residential, open countryside or forest, a classification still used in many air monitoring programmes.

The authors of the Leicester report showed considerable perception in drawing a distinction between (1) the area that contributes significantly to the concentrations measured at a station (this area changes from day to day in response to changes in wind direction), and (2) the area that the monitoring station can be said to represent (this area changes from day to day). For a uniform distribution of small sources across a large region, area

(2) would be much larger than area (1). When a strong point-source predominates, area (2) could be smaller than area (1). However, no attempt was made in the Leicester report to quantify these ideas.

Beginning in the 1950s, urban air quality networks were established in many large cities of the world. Although the monitoring programmes were modest at first, there have been subsequent increases in station densities and in numbers of pollutants sampled. Some networks are now operated in real time at capital costs of hundreds of thousands of dollars and require trained technicians for maintenance and computer analysis, and professional staff for interpretation. This increase in complexity has led to rising costs and to expanding interest in the subject of network design. Some of the first such studies were in Great Britain (Clifton *et al.*, 1959) and in the USA (Keagy *et al.*, 1961; Stalker and Dickerson, 1961, 1962; Stalker *et al.*, 1962). These investigators tried to answer the question: how many sampling stations are required to estimate average urban values for various pollutants and sampling times? For the next ten years there were no other studies of this type. But since the early 1970s, there has been increasing interest in such questions as network density and the siting criteria required to detect a trend in air quality and to verify the predictions of a diffusion model.

Another problem concerns the precise siting of a monitoring station. In the mid-1960s, an attempt to produce guidelines was made by the Meteorological Committee of the Air Pollution Control Association. After discussing the question for more than two years, however, the Committee decided that guidelines might be misleading, and abandoned the idea. The only positive result was the publication of a paper on current practices in siting and in the physical design of continuous air monitoring stations (Yamada, 1970), with a related commentary by Charlson (1969).

In the late-1960s, the WMO decided to establish a network of *regional* and *baseline* air chemistry monitoring stations in response to concern about (1) the effects of trace substances, especially CO_2 and particulates, on global climate, and (2) the effects of precipitation on the acidity of lakes and soils at distances of more than 500 km from pollution sources. These stations were to be located in rural areas away from strong local sources of pollution. After a series of meetings of working groups and experts, an operational manual was written (WMO, 1974) and a monitoring programme started (de Koning and Köhler, 1978).

Subsequently, the WMO became concerned about other non-urban pollution problems: (1) the high oxidant and sulphate concentrations that sometimes occur downwind of cities; (2) the increasing accumulation of heavy metals and pesticides at remote locations, presumably transported by the winds; and (3) the emissions of pesticides and herbicides which produce locally high concentrations of these substances in rural and forested areas. In 1976, therefore, the WMO decided to expand its monitoring programme to include *stations with expanded programmes*, for biological and other applications. More details concerning the WMO programme will be given in Chapter 4, section 4.5.

In the early-1970s, the World Health Organisation (WHO) decided to undertake a cooperative project for monitoring air pollution in urban and industrial areas (de Koning and Köhler, 1978). A pilot study took place between 1973 and 1975 with fourteen countries participating (WHO, 1976a). Harmonisation of measurement methods was achieved, which led to the publication of an operations manual for suspended particulate matter (SPM), SO_2, CO, NO_2 and the lead content of SPM (WHO, 1976b). In 1977 a further report was issued (WHO, 1977), which included general guidelines for the siting of stations and for estimating the number of stations required in urban and industrial areas. The report provides useful advice for control agencies, and is recommended reading. The growing interest in this field is evidenced by other recent publications: the books by Noll and Miller (1977) and Perry and Young (1977) and the articles by Bryan (1976) and Gruber and Jutze (1976).

The design of air quality monitoring systems includes such topics as measurement methods, intercalibration procedures, quality control, data storage and data retrieval. However, comprehensive reviews and operational documentation are already available in these cases (e.g. WMO, 1974; WHO,1976b; Stern, 1976b; etc.). This monograph will therefore be directed towards *siting criteria* (Chapter 4) and *network density* (Chapter 5). Even in this limited domain, various scientific disciplines, e.g. epidemiology, chemistry, meteorology, plant physiology and engineering, are involved in the development of design criteria, and the relevant literature is found in many different journals. During the course of preparing this survey, several hundred citations were located; curiously, however, little cross-referencing was to be found. Investigators do not seem to be aware of other studies (or have not felt them worth mentioning!). There is therefore a need to synthesise the literature, and to outline the main research gaps. These are the objectives of this monograph.

2

The objectives of air quality monitoring programmes

2.1 The objectives of air quality monitoring programmes in urban and industrial areas

The most important factor to be considered in designing a monitoring system is the objective(s). Indeed, the International Organisation for Standardisation believes that design criteria 'will only be possible for air quality monitoring systems which deal with equivalent tasks' (IOS, 1975). Unfortunately, air quality data are used for purposes other than those originally intended by the agency that designed the system. This situation is difficult to prevent once the data have entered the public domain.

There are seven principal objectives of urban air quality monitoring programmes.

2.1.1 Objective 1: for regulatory control (surveillance monitoring)

Where air quality standards exist, control agencies and citizens' groups need information on the concentrations of the substances specified in the regulations. This information is obtained from networks of stations whose locations should be widely accepted as being representative of urban conditions; sometimes the network design and station siting criteria may have been specified in an ordinance or by-law.

2.1.2 Objective 2: to determine present conditions and trends (exploratory monitoring)

Monitoring networks may be established to determine present conditions and trends, for the following interrelated reasons: (1) to determine whether there is need for regulatory action; (2) as a diversionary tactic, to postpone a politically difficult decision to control emissions; (3) to promote public relations, by providing comparisons of the quality of the air in different parts of a city, or even in different cities, to reassure the citizens that the air they breathe is not excessively contaminated; (4) to determine trends from consecutive observations, by providing an early-warning system that air quality standards may be exceeded if control measures are not taken.

2.1.3 Objective 3: to make short-term (1–5 day) predictions

Monitoring is required for the development, validation and operational use of models for forecasting air pollution episodes. The data requirements for model development and validation may be different from those required for operational use.

2.1.4 Objective 4: to simulate the effects of various land-use strategies on air quality

Monitoring is required for the development and validation of multiple-source air pollution models that predict climatological frequency distributions of concentrations. The models are used in the preparation of various land-use scenarios for industry, transportation and power generation.

As in the case of Objective 3, the data requirements for model development and validation may be different from those required for operational use.

2.1.5 Objective 5: to study dose–response relations

Dose–response investigations require various kinds of air quality data, to relate to the following effects: (1) health effects (epidemiological studies); (2) vegetation effects; (3) soiling of materials, corrosion of metals, damage to painted surfaces, rubber, nylon, etc.; (4) economic effects (reduction of property values, etc.). In each case, the quality of the air in the immediate vicinity of receptors is important, rather than the general pollution levels in a city. There is need for studies of both episodic extremes and long-term means.

2.1.6 Objective 6: to provide input data on air quality for large inter-disciplinary urban models

Air pollution data are sometimes needed to provide a relatively small input to a 'big' urban model; other components of the model could include transportation, energy through-put, water supply, garbage disposal, and socio-economic factors. In some cases the requirement is for a single numerical value to represent the average air quality of a city, only one value per year being permitted (to match the depth of information for other components of the model).

2.1.7 Objective 7: to study the effects of pollution on urban climate

The introduction of pollution into the air column over a city changes the radiation balance, thus affecting vertical stability, the wind field and the dispersion of both particulate and gaseous pollutants.

2.2 The objectives of air quality monitoring programmes at rural and remote locations

The objectives for monitoring in rural and remote areas are not so different from those for monitoring in cities, but there is less preoccupation about control. The following five objectives can be distinguished.

2.2.1 Objective 1: to study and to model regional and global climate

Suspended particulate matter and various gases (particularly water vapour, CO_2 and the chlorofluoromethanes) affect the atmospheric radiative balance, and thus influence regional and global climate. Long-term trends are therefore important to delineate.

2.2.2 Objective 2: to document and to model the movements of pollutants across national and other jurisdictional boundaries

There are a number of cases in which it has been necessary to estimate the long-range transport of air pollutants across international borders. The most notable example is the West European OECD study (Ottar, 1978).

2.2.3 Objective 3: to study dose–response relations, particularly with respect to acid rains and regional oxidant episodes

The response of poorly buffered fresh-water lakes to acid rains is being studied in several countries: there are also concerns about vegetation damage by oxidants and visibility reductions by sulphates, sometimes hundreds of kilometres downwind of source regions. In these cases there is need for an atmospheric monitoring system that is tuned to the ecological effects programme.

2.2.4 Objective 4: to complement studies of urban air quality with observations of rural air quality

This is necessary (1) in order that background loadings can be subtracted from measured urban concentrations when pollution models are being validated; (2) to separate the effects of long-term changes in emissions from changes in climate; Izrael (1977) stresses the value of 'twinning' an urban reference station with a rural one; and (3) for public-relations purposes, to provide citizens with urban–rural air quality comparisons.

2.2.5 Objective 5: to study and to model the regional and global biogeochemical cycling of trace substances

In recent years there has been increasing interest in the movement of trace substances around the world, including pathways through the biosphere. Biogeochemical cycling has always existed, but human activities are interfering with the cycles, sometimes causing materials to accumulate far from sources. For example, concentrations of pesticides and heavy metals may build up over long periods of time in remote lakes or glaciers. Of particular interest is the cycling of carbon, sulphur and nitrogen. In these three cases, human interference may some day have profound effects on climate (owing to increases in CO_2 emissions), the acidity of rainfall (owing to increases in sulphur emissions), and the incidence of skin cancer (owing to increases in ultraviolet radiation caused by a disruption of the stratospheric ozone layer: in part related to the nitrogen and the chlorofluoromethane cycles).

2.3 Statistical design considerations

The environment is always sampled imperfectly, and there is need to estimate the degree of imperfection to be permitted, given the design specifications of the user. These specifications could be expressed in several ways, and thus the network could be optimised in several different senses also. For a given pollutant whose concentrations vary in time and space across a given area, the following network design criteria could be considered: (1) the mean value for the area is to be estimated with a given accuracy for various averaging times; (2) the possibility of non-detection of a violation of an air quality standard within the area (at fixed grid-square locations, for example) is to be smaller than some given probability; (3) the concentrations at fixed grid-square locations are to be interpolated from measurements made at actual monitoring stations, with sufficient accuracy that the root-mean-square interpolation error will not exceed a designated value; (4) for an existing network, the station locations are to be adjusted so that the design is better than any other of the same size, where the word 'better' is defined in some way, e.g. as in (1), (2) or (3) above; (5) for an existing network, the location of an additional monitoring station is to be chosen in some optimal way; (6) for an existing network, the deletion of one station is to be achieved with minimum disruption to programme goals; (7) the network density is to be sufficient that a change of x% in area-averaged concentrations can be detected with 95% confidence in y years. Other criteria might be considered. In each case the possibility should not be overlooked that optimal network design will be different for different pollutants, and may vary with season.

In summary, a first step in the design of an air quality monitoring network is to establish the objectives of the programme and to decide upon the nature and magnitude of the estimation errors that can be tolerated. Where there are multiple objectives, the system as a whole may sometimes be optimised only if sub-optimal network design is used for some of the components.

3

Time and space variability in air quality

3.1 Introduction

Air quality varies in both time and space. This is to be expected, but the complication for network design is that the variations are neither random nor well behaved. There are, in fact, several inter-related factors which affect the time and space fields of the concentrations of trace substances. Some of these factors are: (1) non-uniform emission rates (irregular distribution of sources and of source heights; daily, weekly and annual cycles of emissions; long-term changes in source locations and strengths); (2) large-scale meteorological factors (daily and annual weather cycles; synoptic weather patterns; long-term climatic oscillations and trends); (3) modulations in the large-scale meteorological factors owing to local topography and urban effects; (4) variations in the rates of chemical transformations and deposition (diurnal cycles, precipitation scavenging, uptake by vegetation, etc.); (5) random fluctuations (owing to atmospheric turbulence, etc.).

These factors are inter-related to a certain extent, e.g. space heating requirements and thus emission rates depend on temperature and wind. In fact, high correlations between urban air quality and meteorological conditions are usually obtained only in cases where emissions are approximately constant (van Dop and Kruizinga, 1976).

When appropriate time and space averages are used, the effects on air quality of each group of factors mentioned above can usually be isolated. However, the presence of 'noisy' data complicates the sampling problem considerably.

3.2 Time variability

Concentrations of a pollutant such as SO_2 measured continuously at an urban monitoring station show considerable variability. Variations are large near emissions (particularly near tall chimneys) but decrease downwind; pollutants eventually become well mixed throughout the lower atmosphere. The variations can be classified according to the following time scales.

3.2.1 Minute-to-minute variations

These are due mainly to wind direction fluctuations, which cause pollutants from point-sources to reach a monitoring station intermittently.

3.2.2 The daily cycle

When many observations of pollution concentrations are averaged by hour of the day, a strong diurnal cycle is found. This behaviour is due to cycles in both emission rates and meteorological conditions. Vehicular traffic is greatest near 8 a.m. and 5 p.m., for example, not always in phase with the daily patterns in space heating, electric consumption and industrial activity.

The atmosphere, too, has a well-defined diurnal cycle, night-time stability alternating with day-time convection during fine weather. The morning break-up of a radiation inversion brings pollution from tall chimneys down to ground level, so causing a peak in concentrations (the fumigation process): this is often amplified by the morning peak in emissions. Photochemical reaction rates are highest in the early afternoon, on the other hand, so that oxidant concentrations are highest then.

3.2.3 Large-scale weather fluctuations

In the temperate zones, high-pressure and low-pressure systems often alternate in crossing a region at about 3–5-day intervals. Occasionally, however, a relatively long period of strong winds or of stagnation conditions may interrupt the pattern and hence shift the periodicities to such an extent that the cycles cannot be found when standard averaging techniques are used. The movements of these large-scale weather systems have a major influence on air quality.

3.2.4 Weekly emission cycles

Emissions are less, and the diurnal cycle is different, on Saturdays and Sundays compared to other days. In the case of automobile traffic, for example, the morning peak is delayed an hour or so, and is not so great on Sundays as on weekdays. As a result, the concentrations of pollutants on average are generally lower at weekends than on weekdays, and the diurnal cycles are different. A reported exception is in Los Angeles; high oxidant concentrations during the weekends are presumably due to a reduction in the emissions of substances such as the oxides of nitrogen which destroy oxidants.

3.2.5 Annual emission and weather cycles

Annual cycles in air quality are to be found in almost every urban area, owing to annual cycles in emission rates and in the relevant meteorological factors.

3.2.6 Long-term emission and climatic trends

Many air pollution monitoring programmes have been in existence for ten years, so that there is a possibility of studying air quality trends. One of the first published investigations was that by Schmidt and Velds (1969) of Rotterdam SO_2 concentrations. The downward trend in the winters from 1962/63 to 1967/68 could be explained from meteorological considerations alone. However, a further analysis by van Dop and Kruizina (1976) of the longer period from 1961 to 1974 provided evidence for a slow reduction in emissions, as well as for the climatological trend found earlier. Other trend analyses include those by Auliciems and Burton (1973) of smoke concentrations at Kew Gardens, England from 1922 to 1971, and by Chock *et al.* (1975) of air quality in Riverside, California from 1964 to 1972.

3.3 Space variability

Spatial patterns of air pollution are often classified according to size:

- microscale (0–100 m)
- neighbourhood scale (100–2000 m)
- urban scale (5–50 km)
- regional scale (100–1000 km)
- continental, hemispheric and global scales

The urban scale corresponds to the atmospheric mesoscale, in which a diurnal cycle in the behaviour of the meteorological elements is often important.

Air pollution isopleths can be drawn on any of these scales, provided that: (1) the network density is sufficient; (2) the monitoring stations are sited in comparable ways *vis-à-vis* all scales smaller than the one of interest; (3) the instruments are intercalibrated; (4) the sampling times are concurrent; and (5) values averaged over intervals of at least an hour or so are used. For instantaneous observations, the isopleths are irregular, but as averaging time increases the curves become smoother. The patterns can be explained in terms of locations and strengths of emissions, and of spatial variations in the relevant meteorological factors.

When studying space–time relationships, the need for comparable siting of stations cannot be overemphasised. This is why the discussion on siting criteria for a single station (Chapter 4) precedes the sections on network design.

3.4 Correlation analysis

The following kinds of correlation exist amongst air quality data: (1) time correlations (autocorrelations) in series of measurements of a single pollutant at one station; (2) cross-correlations in measurements of several pollutants at one station; (3) space correlations in concurrent measurements of a single pollutant at two stations; (4) space correlations in measurements of a single pollutant at two stations, the times of observation differing by a fixed amount. (lagged correlations).

Some remarks on each type of correlation follow.

3.4.1 Autocorrelations

Time correlations for a single pollutant measured at one station for various lag times may be calculated readily. The correlation is one for zero lag, decreasing to zero for large lag unless the data contain trend, in which case the correlation coefficient converges to a non-zero value (*Figure 3.1*). A third possibility (illustrated in *Figure 3.1*) is that of a time series containing periodicities; negatives values of the autocorrelations are then possible, although a decaying amplitude is almost universally observed.

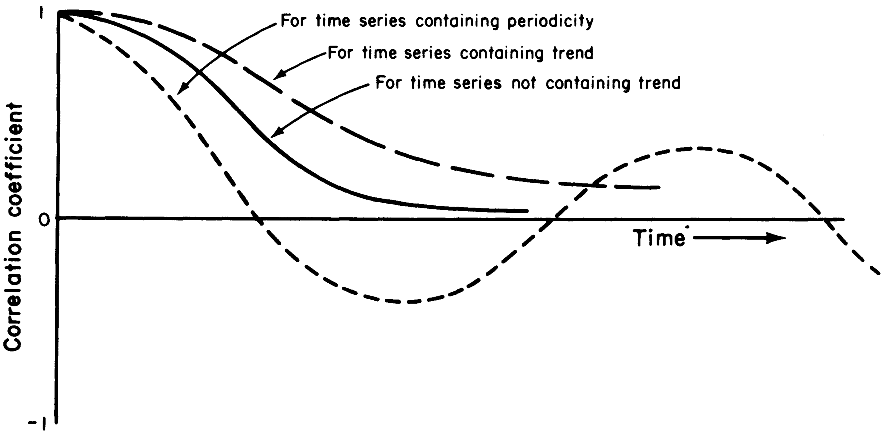


Figure 3.1 Schematic representation of autocorrelations

3.4.2 *Cross-correlations*

Concentrations of several pollutants measured at a single sampling station are usually correlated with each other. These cross-correlations tend to occur because (1) the pollutants respond in similar ways to given meteorological conditions, (2) emissions tend to have similar diurnal cycles, and sometimes similar annual cycles and (3) many sources tend to emit several pollutants at the same time, and at the same relative rates, e.g. SO_2, NO_x and particulates from power stations.

3.4.3 *Space correlations with no time lag*

Space correlations often exist in environmental data. In the case of air quality networks this is due to (1) daily, weekly and seasonal cycles in emission rates, (2) daily and seasonal cycles in the relevant meteorological factors (mixing heights, winds, etc.), and (3) relevant meteorological systems of larger dimensions than the distance between the two monitoring stations whose observations are being correlated. Space correlations resulting from (1) and (2) are increased because of (3), e.g. space heating emissions are higher during cold weather; mixing heights are low during warm anticyclonic conditions. In addition, (3) sometimes produces correlations (positive or negative) owing to the orientation of point or regional pollution sources with respect to wind direction. Space correlations and time correlations are therefore inextricably linked.

By prestratifying data sets according to wind direction sectors, Munn (1975) found interesting patterns in the Detroit/Windsor, Sarnia/Port Huron area. For example, if two sampling stations were on opposite sides of a strong point-source, there were negative correlations for winds blowing along the line of stations but positive correlations for cross-winds. An example is given in *Figure 3.2,* which shows the space correlation coefficient field when a rural station (Marine City) was used as reference (Munn, 1975). The data set consists of 24-h suspended particulate concentrations measured every third day over fourteen months, only those cases being chosen in which the regional surface wind was in the sector W–NW–N.

3.4.4 *Space correlations with lag times included*

The highest space correlations sometimes occur when observations at one station are time-lagged with respect to those at another. This is taken as evidence for transport of pollution across a region, and provides information on the direction and speed of travel. The lag time giving the highest space correlation is presumably equal to the travel time.

In an application to Los Angeles oxidant and carbon monoxide data, Chock and Levitt (1976) have computed space correlations for various pairs

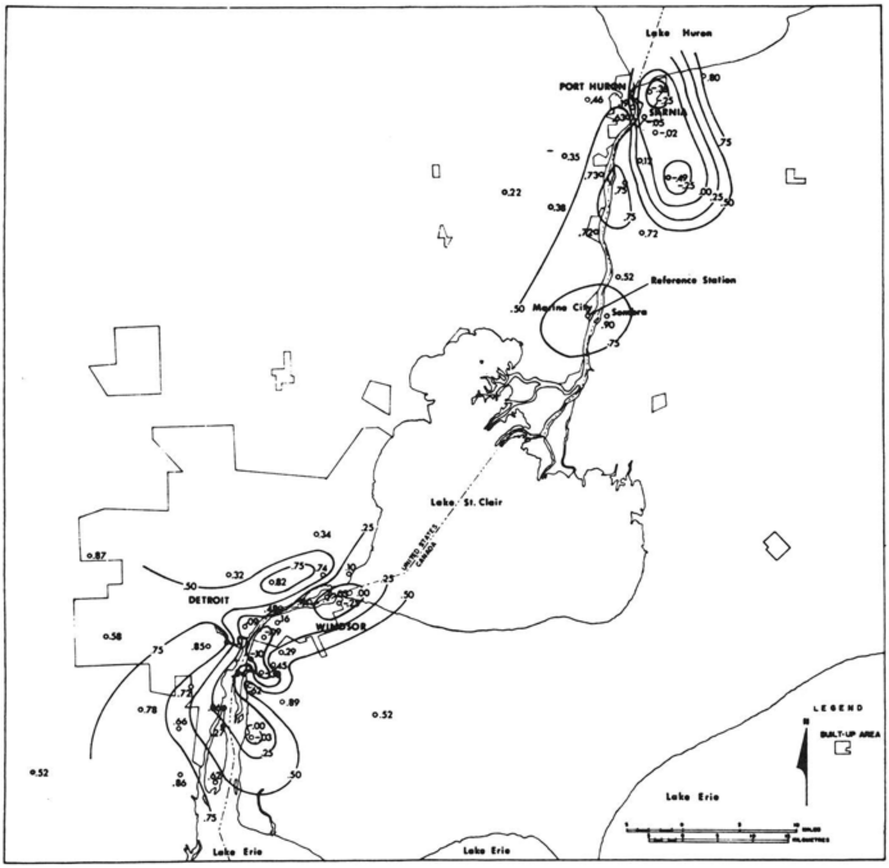


Figure 3.2 Isopleths of spatial correlation coefficients with Marine City, Michigan as reference station for a subset of days when regional surface winds remained in the sector W–NW–N (Munn, 1975)

of monitoring stations, using lag times ranging from −5 h to +5 h. The results suggest that oxidants are being transported by the wind, so producing high space correlations over relatively long distances (up to 55 km). For carbon monoxide, however, local sources predominate, and correlations are small for pairs of stations separated by only a few kilometres.

Elsom (1978) has determined the space correlation fields for 24-h concentrations of smoke and SO_2 for the winter of 1971/72 (Tuesday, Wednesday, Thursday and Friday observations only) in the Greater Manchester area. Elsom notes that because pollution concentrations are log-normally distributed, the logarithms of the concentrations should be used to compute space correlations. The results given in *Figure 3.3* show that the data are correlated across the area, more so for smoke than for SO_2

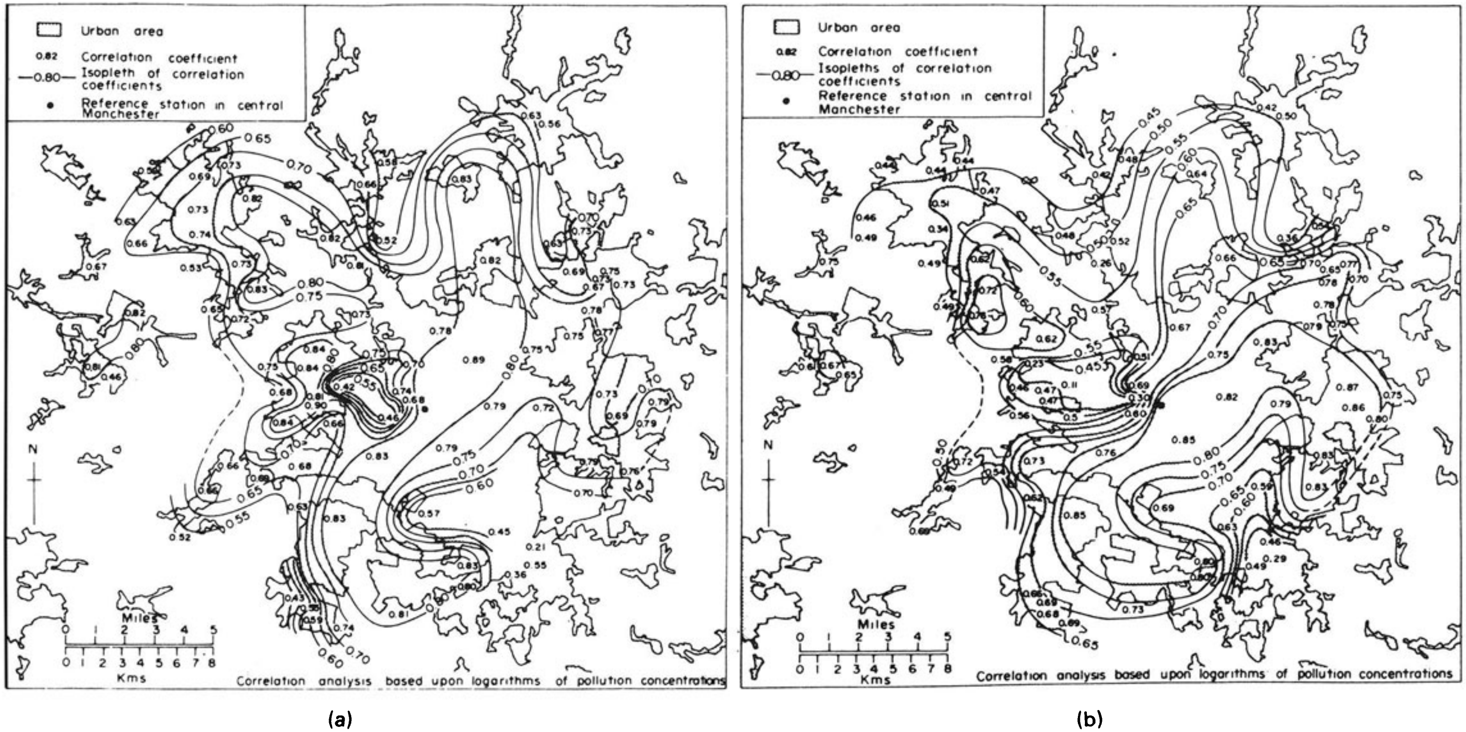


Figure 3.3 Spatial correlation analysis in winter 1971/72 for Greater Manchester with a central Manchester station as reference: (a) for daily smoke concentrations; (b) for daily SO_2 concentrations (Elsom, 1978)

(probably because smoke comes predominantly from low-level sources). The existence of such correlations implies that a monitoring station provides partial information about air quality in the surrounding area, a fact that can be exploited in the design of monitoring networks (see Chapter 5, section 5.2).

To sum up, air quality measurements are correlated in both space and time. This complicates the problem of network optimisation because the classical statistical techniques that assume random sampling procedures cannot be used.

3.5 Frequency distributions, means and standard deviations

Air quality data sets are conventionally analyzed in terms of frequency distributions, means and standard deviations. Whereas the techniques described in section 3.3 require that the data be ordered consecutively in time and that there be no missing observations, frequency distributions can be obtained even if measurements are made only one day a week or one month a season. Care must be taken, of course, to ensure that data sets provide unbiased estimates of the statistical properties of the parent populations.

For a Gaussian distribution, the important statistics are the mean, $\bar{X}$, and standard deviation, s. However, it has been found empirically that most air quality data sets are distributed log-normally. The statistics most widely computed therefore are the geometric mean $\bar{X}_G$ and the geometric standard deviation s_G. These parameters are used in some statistical approaches to network design; *see* Chapter 5, section 5.2.2, for example.

It should be appreciated that individual values in the frequency distributions are not randomly distributed. A series of high values may occur, as well as a run of blanks. Significance tests should therefore be applied with caution.

It should also be mentioned that the relevance of the log-normal approximation for estimating the frequencies of rare events has been questioned.

4

Siting criteria for a single station

4.1 Introduction

Meteorologists are able to draw weather maps from networks of stations located 200 km or more apart. This is partly because of the care that has been taken in the selection of observing sites (open exposures, grassy plots, similar mounting of instruments, etc.). Because of the difficulty in meeting such stringent siting criteria in built-up areas, most weather-observing stations are located at airports or in the countryside.

The siting of an air quality monitoring station is even more difficult because the distribution of pollution sources (including mobile and fugitive emissions) must be considered as well as the local microclimate. Siting criteria are available for rural areas (*see* section 4.2) but there are only general guidelines for cities. Charlson (1969) remarked almost ten years ago:

> The Meteorology Committee of the Air Pollution Control Association has often been asked to provide a set of rules for the location of air samplers. Much thought on this matter has resulted in the belief that no such set of rules can be generated from meteorological fact and set down in cook-book fashion. On the other hand, there exists overwhelming evidence that the present lack of meteorological consideration in monitoring station design as well as location often precludes the use of data for comparative purposes.

4.2 Practical considerations

There are practical considerations that exclude otherwise eligible sites from selection as monitoring stations: (1) availability of electric power; (2) protection from vandalism; (3) willingness of property owners to permit the use of the land; (4) site accessibility, particularly at weekends; (5) cost of land rental, of shelter construction, of duct work, etc. (generally, public rather than private property is selected). These constraints exist but they should never become the major considerations in siting an air monitoring station.

4.3 Sampling variability owing to instrumentation

4.3.1 Difference in analytic methods

The concentrations of a trace substance can usually be determined in several ways. But even in controlled laboratory conditions, a comparison of readings obtained from different types of monitors may show discrepancies owing to: interference effects caused by other trace substances in the sample; humidity and temperature effects; anisokinetic problems; differences in time constants, etc. As an example, Kretzschmar (1975) compared the aerosol concentrations as determined by three methods in the centre of Antwerp. The results were significantly correlated but the correlation coefficients (0.91–0.80) were not particularly high. Bryan (1976) has stated that 'insufficient data are available at the present time upon which to make an exclusive selection of one method for each major air contaminant at the expense of rejecting all others'.

Availability and choice of instrumentation may have a large impact on network design and data interpretation. Air pollution equipment is continually being improved and it is essential that a record be kept of the instrumentation actually in use. Before a sensor is replaced by one with a radically different design, there should be an overlapping period of observations. Special mention should be made of response times. If the requirement is for a daily or monthly average value of pollution concentrations, a slow response time for the sensors is preferred; to detect short-duration peaks, on the other hand, fast response times are required.

Comparisons of concentrations measured with different instruments should not be made unless an intercalibration has been performed.

4.3.2 Incorrect operating procedures

Even for a single instrument that is known to perform satisfactorily within the expected range of environmental conditions, there may be errors owing to incorrect calibrations, calibration drift, defective parts, use of faulty intake tubing, etc. For example, Mamane and Donagi (1976) found a large decrease in SO_2 concentrations at a station in Tel-Aviv when the sampling lines were changed from polyethylene to polypropylene.

In the case of large monitoring programmes involving several agencies, an effective way of quantifying some of the above-mentioned types of variability and bias is to exchange samples amongst laboratories. For example, an international comparison of instruments for measuring sulphur dioxide and nitrogen dioxide has been carried out amongst four laboratories, two in The Netherlands and two in West Germany (Lahmann *et al.*, 1976). Within the concentration ranges of the test gases (250–500 $\mu g\,m^{-3}$ of SO_2 and 100–300 $\mu g\,m^{-3}$ of NO_2), the relative standard deviation of the results was less than 5%.

Two additional kinds of sampling variability will be discussed in sections 4.4–4.6; *viz.* the microscale variability in atmospheric concentrations at a sampler intake point, and the inappropriate siting of an intake tube or even of a monitoring station in terms of the stated objectives for monitoring.

Although the existence of these factors is generally recognised, there are few guidelines on how to determine their composite effect, and current practice is *ad hoc.* Courtecuisse and Benarie (1975) have estimated a 10% standard deviation for replicate measurements of urban suspended particulate matter, but Benarie (1974) has cautioned that this value should not be applied to other pollutants or to non-urban environments.

4.4 The micrometeorological environment near a sampling station

4.4.1 Air-flow distortions caused by the sampler and the sampling shelter

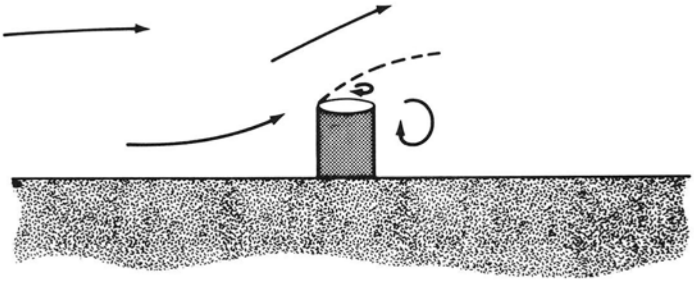
A sampling device may disturb the air flow and the concentration fields. Instruments that are particularly susceptible to this kind of effect include the rain-gauge, the dustfall can, the evaporation pan and the flat-plate pollen sampler (*see Figure 4.1a*, for example). In each case, the collection efficiency is a function of wind speed and turbulence intensity.

On a somewhat larger scale, a sampling shelter is an obstacle to the air flow and may deform the concentration pattern within 5–25 m of the sampler (*see Figure 4.1b*, for example).

4.4.2 The micrometeorological environment over open countryside and far from sources

Over open countryside far from sources, wind speeds and concentrations of trace gases (e.g. SO_2, ozone) usually increase from the ground up to a height of about 10 m; at greater elevations, vertical gradients are insignificant most of the time. The magnitude of the concentration gradients near the ground depends on (1) the rate of uptake of the gas by the surface (this rate is a function of the physical/biological state of the surface), and (2) the atmospheric vertical exchange rate (this is a function of meteorological factors). If the surface of the earth were a perfect reflector, there would be no vertical gradients except close to sources. In fact, however, concentrations near the ground are sometimes low, simply because the surface is absorbing the gases

(a)



(b)

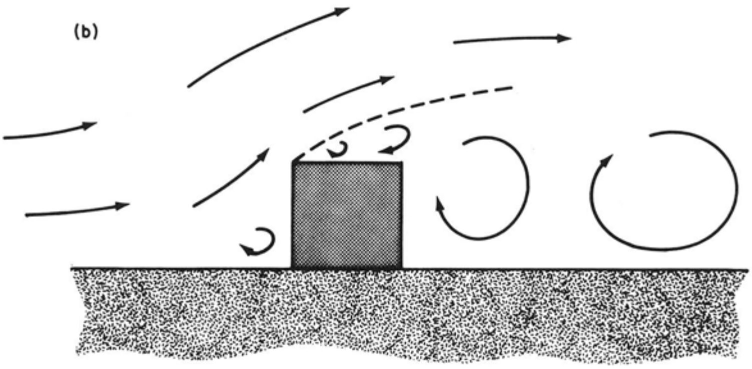


Figure 4.1 Schematic representation of (a) air flow around a rain-gauge or a dustfall can, and (b) air flow around a sampling shelter

more quickly than can be replenished from above. Wet surfaces with moderate to high pH values are particularly effective absorbers of SO_2 and oxidants.

An example of a vertical profile of SO_2 is given in *Figure 4.2* (Garland *et al.*, 1974). Included in the diagram are measurements of wind speed and of potential temperature, all at heights of 0.2, 0.5, 1.0 and 2.0 m at Cardington, England. The site was surrounded by a few hundred metres of mown grass. From the profiles, Garland *et al.* were able to infer a transfer rate from the atmosphere to the grass of 0.17 $\mu g\ m^{-2}\ s^{-1}$. At night, the transfer rates were considerably reduced because (1) the stomata (the main entry point of trace gases into vegetation) closed and (2) the atmospheric exchange rates decreased owing to the formation of temperature inversions.

In the case of suspended particulates, the surface of the earth is sometimes a source rather than a sink. Particularly during dry weather, surface dust is lifted into the atmosphere by moderate to strong winds, and by moving vehicles. As a result, the concentrations of particulate matter decrease with height, and the particles become smaller.

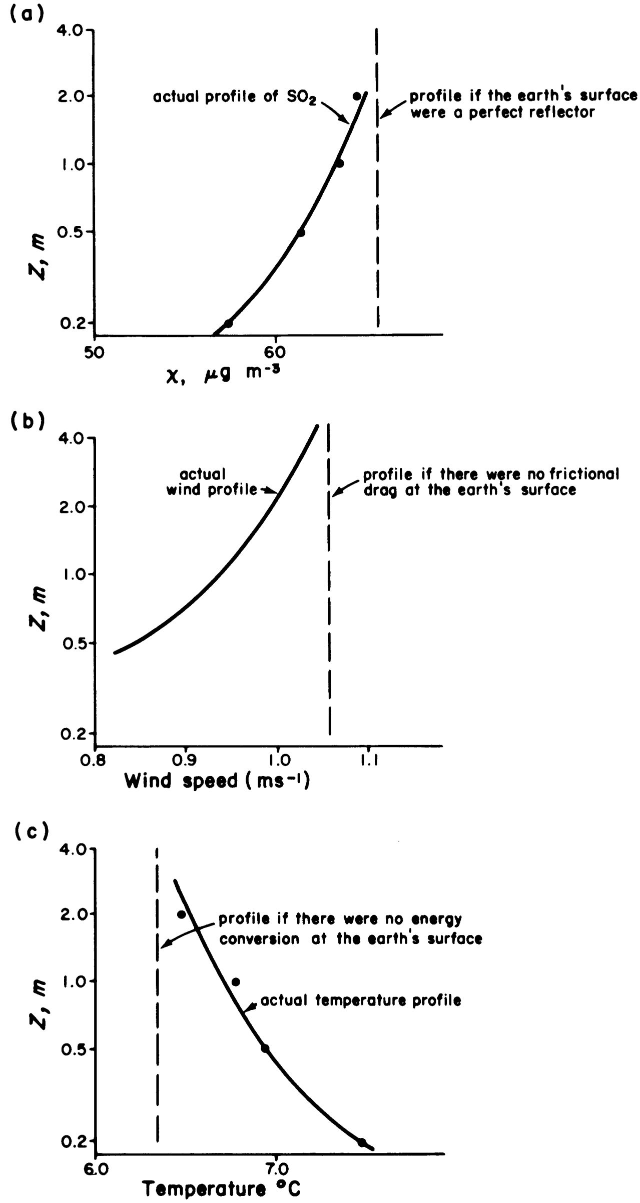


Figure 4.2 Vertical profiles of (a) SO_2, (b) wind speed, and (c) temperature, measured on 17 March 1972, 1210 to 1317 hours GMT over short grass in rural England (Garland *et al.*, 1974). Z is height and χ is concentration of SO_2

4.4.3 The micrometeorological environment in cities

The concentration gradients described above are distorted and often completely masked in cities for three reasons: (1) buildings and trees disturb the air flow and generate additional turbulence; (2) moving vehicles stir the air; (3) multiple pollution sources emit substances into the atmosphere at various elevations; (4) multiple heat sources cause convective eddies to form at various elevations, stirring the air.

For the so-called 'city canyon', Georgii *et al.* (1967) have observed the CO concentration patterns shown in *Figure 4.3.* Stagnation zones may occur near the ground, which results in the accumulation of pollutants. Every so often, however, a gust of wind sweeps away the stagnating air. These microscale effects are greatly affected by wind direction. Even for a simple obstruction to the wind (as shown in *Figure 4.1b*), a change of only 20–40° in the angle of flow would have a major effect on the wind field. If a fumehood was located on the upwind side of the obstacle, or a short chimney was on the roof, puffs of pollution could reach ground level from time to time with very little dilution.

With respect to suspended particulate matter in cities, Mainwaring and Harsha (1975) have measured the 24-h concentrations at three heights on a

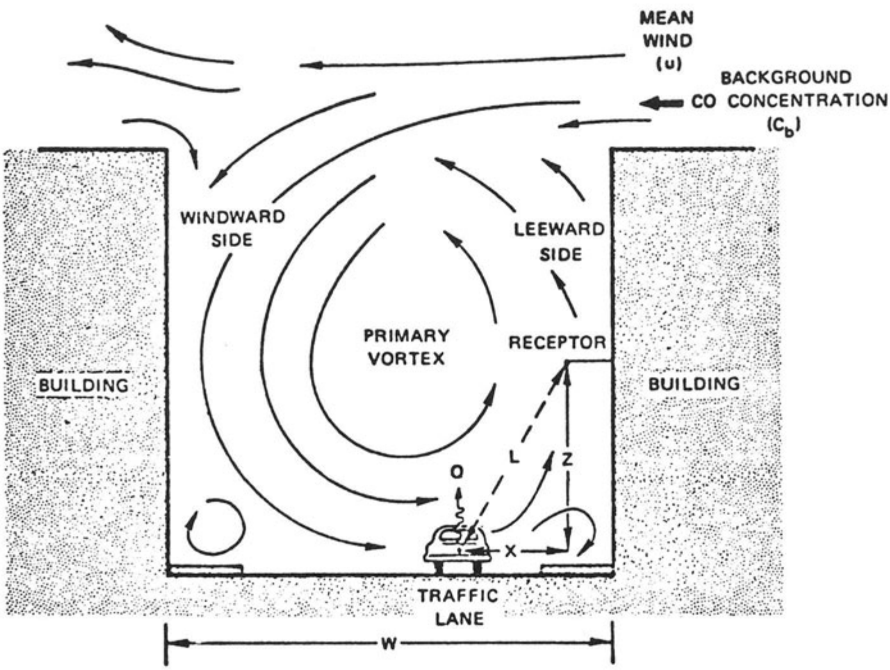


Figure 4.3 Schematic representation of the air circulation in an urban canyon when there is a cross-wind (Georgii *et al.*, 1967)

twenty-storey building in downtown Melbourne, Australia. The samplers were located on balconies at the 11-m, 40-m and 65-m levels. As might be expected, concentrations decreased with height, the 65-m value being 33% of that at 11 m when the wind speed averaged 8.5 m s^{-1} but only 12% when the speed was 0.9 m s^{-1}.

As another example, Pace *et al.* (1977) studied the suspended particulate concentrations at thirty-one sites in seven cities of the United States. They concluded that, on average, concentrations varied inversely with height up to about the 10-m level; above that, the drop-off was small. In this connection, the reason for the apparent discrepancy between the Australian and the United States results is that sampling stations for particulate matter are usually sited in North America away from tall buildings and busy traffic arteries.

4.5 Criteria for siting air quality monitoring stations in open countryside

The World Meteorological Organisation (WMO) has established three kinds of air quality monitoring stations: *baseline* (in very remote locations, e.g. Antarctica, mountain tops, etc.); *regional* (in rural or forested countryside); and *monitoring stations with extended programmes* (for ecological and other applications). All three types should conform to the long-standing criteria for siting meteorological stations (open exposure, surrounded by a grassy plot, etc.). No land-use changes should be expected. The following additional siting criteria have been established (WMO,1974, 1978).

Baseline station siting criteria

A baseline station should be located away from population centres, highways and air routes, preferably on isolated islands, on mountains above the tree line, or in or adjacent to a relatively inactive surface such as an ice sheet or ocean.

It should experience only infrequent effects from local natural phenomena such as volcanic activity, forest fires, dust and sandstorms.

It should be located in an area where no changes in land-use practices which may significantly affect the functioning of the station are anticipated for at least several decades, within about 100 km of the station in the directions of prevailing winds. The essential criterion is that 'clean air' conditions should prevail for a substantial proportion of the time.

The system of baseline stations should provide a global coverage and (together with regional stations with extended programmes) include all major biomes.

As each station will have its own local climate and topography as well as its own local and regional surrounding distribution of man-made and natural sources, valid measurements of background levels will not be possible at any station 100% of the time. Because the conditions which define the 'background mode' of operation as opposed to the 'non-background mode' are unique for each station, no general criteria can be established. Only a careful analysis of the data, including the statistical distribution of the values, combined with an analysis of appropriate meteorological variables (e.g. trajectories) and other observations will enable a definition to be made of those periods of time when the data do represent valid background conditions. Each individual station must establish objective criteria for the selection of periods with a 'background mode' of operation and carefully record their occurrence. As an example for CO_2 monitoring, it should be required approximately during 50% of the time, and should be reasonably distributed throughout the year.

At continental sites, particularly in tropical areas where the day-time mixing extends to several-kilometre altitudes, it may not be possible to avoid completely local influences for any appreciable length of time. This would specifically apply to compounds with a pronounced exchange with vegetation with its daily cycle of assimilation and respiration (e.g. CO_2). Such sites may still be acceptable for baseline stations provided that the daily cycle is well defined to enable a reasonable determination of the background value to be made.

While sites along sea coasts where the wind is from the sea for a substantial amount of time or isolated mountain peaks above the vegetation line may be the first choices (provided that the influence from local circulations such as land/sea breezes and mountain/valley winds do not unduly influence the measurements), it may also be possible to find locations within areas of uniform vegetation that can provide measurements representative of very large areas. It will be necessary to document the suitability of a given site, however, and it is not possible to substantiate this without preliminary measurements. Such preliminary investigations will also help determine the most suitable location among several competing choices.

These preliminary measurements must include records of the daily cycles under different meteorological conditions and for each season. Attention must be given to establishing the temporal variability of the quantities to be measured as well as their mean value. All measurement must have meteorological data from the same site as the pollutant measurements. Wind speed and direction are particularly important: they help establish the likelihood of meeting the siting criteria as well as determine which wind directions will satisfy the criteria.

It must be determined that the site will give data representative of a large area. Particularly for continental locations, this will require measurements at several spots in the general area. Aircraft surveys coupled with simultaneous measurements at the candidate sites during each season are strongly recommended.

Existing data at or near the sites will be useful but great care must be exercised in extrapolating climate data. This is particularly true in mountainous regions where isolated peaks may set up their own wind regimes. Nothing will substitute for actual measurements at the site. Should the proposed site be shown to satisfy the criteria set forth here and if, furthermore, its geographic location fills a need in the current network, the station may be considered part of the baseline network. A continuing programme to evaluate the validity of the records at each site must be maintained.

A baseline station should attempt to mount a 'full' climatology programme in addition to the pollutant measurements. An absolute minimum is continuous records of wind speed and direction, precipitation, temperature, humidity and pressure. If possible, cloud type, amounts and heights should be estimated as well as visibility.

The adequacy of the meteorological observations and their complete documentation is fundamental to the success of the programme. No matter how sophisticated the equipment used to measure the non-meteorological variables or how skilled the analyst, it will not be possible to interpret the data without high quality meteorological data of sufficient frequency.

It must be emphasised that careful and competent interpretation of the data to extract the global and large area signals from local effects is as important as good chemical and meteorological measurements. *The judgement of the importance and utility of the WMO network will ultimately be based on these interpretations.*

Regional station siting criteria

The siting of regional air-pollution stations is less critical than that of baseline air-pollution stations. The fundamental requirement is *a rural environment.* Suburban environments should be avoided, as the results will most likely be influenced by long-term changes in an urban environment than in a regional one.

A regional station should be located sufficiently far away from built-up areas so as not to be dominated by fluctuations in pollution from local sources. The minimum distance of a site from the nearest pollution sources depends on the intensity of the pollution sources. For large sources like fossil-fuelled power stations, this distance might need to be as much as 40 km; for smaller sources the distance can be less. There may be areas where even such minimum distances cannot be found. In this case one may tolerate a closer source provided adequate records of winds are collected to make it possible to screen the pollution data obtained. A station may function excellently under certain wind conditions but not during others.

It should be pointed out in this connection that precipitation samples will probably be least affected by pollution sources since they are representative of conditions over a considerable depth of the atmosphere. The same is probably true for turbidity whereas dry deposition and air samples at ground level will be much more influenced by nearby sources. Of course, the data obtained will be the best guide to determine the representativeness of the station. Strong fluctuations in the data will indicate undue influence from nearby sources.

Even if regional criteria for a station are met, topography and other factors necessitate local criteria to be set. As for topography, valleys should be avoided since, at least in temperate and cold climates, they will collect cold and stable air at night and in the winter which is not representative of the region. The summits or higher slopes of elevated areas are much more desirable in this respect. Mountain peaks, however, are again less suitable since they do not represent *average regional conditions.*

As for other local factors to be considered, that of local dust is most important, which emphasises the need to tarmac roads and keep a good grass cover on earth surfaces. This excludes the presence of intensely cultivated soils in the vicinity unless the climate is such that they are permanently moist.

Smoke from local burning should also be avoided but in this case, a distance of, say, a few thousand metres is sufficient to avoid such influence. Furthermore, the sampling site should not be too much exposed to high winds.

A principal climatological station should be established at a regional air pollution station.

The WMO background air pollution monitoring network was organised originally to assist in studies of climate, and because of concerns about acid rains. More recently, a need to support other kinds of studies (ecological, biogeochemical cycling, etc.) has been recognised, and this has led to the establishment of monitoring stations *with extended programmes.* For such sites, the following criteria (in addition to the criteria already specified) were established in 1976 (WMO, 1976): (1) there should be no influence from local (within 10 km) pollution; (2) sampler intakes should be above the surface boundary layer and clear of trees, etc. (a forest clearing would not be

Table 4.1 The framework for the WMO background air pollution monitoring network (WMO, 1978)

Objectives	*Space scale of phenomenon* (km) *Horizontal*	*Vertical*	*Approximate time scale of phenomenon (years)*	*Variables to be measured*	*Site selection criteria*	*WMO classification of station type*	*Suggested number of stations*
I. Determine global inventories and their trends (mainly for climatic studies)	10^4	10	1	CO^a (including isotopic composition), chemical composition of precipitates[a], solar radiation (including turbidity), N_2O, CO, (CH_4), total and surface O_3, condensation nuclei	1. Local and regional influence of population centres, land-use practices, power generation, etc., must be absent, or avoidable by the use of suitable objective data-selection criteria	Baseline	10–15
II. Determine lati tudinal transport for global biogeo-physical modelling	10^4–10^3	10	0.1–1		2. Local and regional surface exchanges sufficiently weak so that surface measurements represent composition through the depth of the atmosphere 3. Land-use changes not likely to influence collection of background data (at least after application of selection criteria) for several decades	Baseline	2–5

III. Determine air–surface exchange within, and atmospheric transport between, large-scale areas characterised by different land and different sea surface conditions	10^3	1–3	0.01–0.1	Same as above, plus gaseous sulphur and nitrogen compounds[a], suspended particulate matter[a], chemical composition of particulates[a]	Same as above, but minor continuous local influences may be acceptable provided their effect may be removed by some kind of averaging	Baseline or regional with extended programme	plus 10 to 20
IV. Determine air–surface exchange and atmospheric transport within regions characterised by significant man-made influences and possible long-term changes in atmospheric composition	10^2–10^3	1–3	hours–days	Gaseous sulphur and nitrogen compounds, suspended particulate matter[a], chemical composition of precipitation and of particulates[a], turbidity[a], surface O_3	Local influence of man-made pollution or natural surface exchanges absent or avoidable by use of suitable objective data selection criteria	Regional	>100

[a] Priority measurements.

suitable); (3) the site should be representative of the area; and (4) a fetch of about 400 m over homogeneous vegetation is desirable.

4.5.1 Some general comments

The framework for the WMO programme has been further clarified as a result of a meeting of a Siting Criteria Review Committee, when *Table 4.1* was developed (WMO, 1978). The information in this table will no doubt be modified in the years to come but the general outline is the culmination of a major conceptual development that has taken place over the last ten years. About ten baseline and one-hundred regional stations are operating around the world at present (Kronebach and Munn, 1977; de Koning and Köhler, 1978).

The siting criteria for all three types of stations are reasonable. However, one of the reviewers of this monograph has made the important additional point that areas should be avoided where 'sink' losses are more than usually effective. A site with low vertical mixing characteristics coupled with a reactive surface for the pollutant considered could be misleading. A typical example is the measurement of SO_2 from ships over the North Sea, which often shows zero surface concentrations in warm, stable south-west winds when there is little doubt that much SO_2 is still present aloft on its way to Scandinavia. Valley sites without local sources are also best avoided, as they tend to give consistently lower concentrations of reactive pollutants than hill sites in the same area.

4.6 Criteria for siting urban air quality monitoring stations

The WMO siting criteria for regional and baseline stations cannot be met in urban areas. Yet there is need for air quality monitoring in cities, sometimes in the vicinity of strong concentration gradients, e.g. near busy thoroughfares, even though the representativeness of measurements made at a single point is difficult to assess. This is called *impact monitoring.*

To aid in the selection of a monitoring site, three general ways of estimating the concentration fields and variabilities will be mentioned, although none is satisfactory.

4.6.1 Mathematical models

In a few idealised cases, mathematical modelling can be used, e.g. in forecasting the concentrations of pollution downwind of an expressway which has a generally open exposure. For example, Butler *et al.* (1976) predicted the NO concentrations given in *Table 4.2*; the values are in reasonable agreement with observations made at distances of 0 and 25 m from the downwind edge of a motorway in Birmingham, England. For more

Table 4.2 Comparison of calculated and measured concentrations of NO (ppm) downwind of a motorway carrying 4500 vehicles h^{-1} (Butler *et al.*, 1976)

	Distance from edge of hard shoulder (m) 0	25
Calculated concentration of NO($C(x)$)	0.216	0.124
$C(x)+0.08$[a]	0.296	0.204
Mean measured concentration of NO	0.304	0.205

[a]0.08 ppm background level of NO at site.

complex terrain and source distribution, the possibility exists of applying a multiple-source urban air pollution model. In all probability, however, numerical models are not yet sufficiently accurate at the neighbourhood scale to be of much assistance.

4.6.2 Wind-tunnel models

A second approach is to test a scale model in a wind tunnel. This may reveal the major micrometeorological effects but the technique is time-consuming and costly, requiring *inter alia* simulations of various wind directions: the amount of test data quickly becomes too great to be of much value in the operational task of selecting monitoring stations.

4.6.3 Qualitative appraisal

A third alternative is to ask a small group of people (including an engineer, chemist, micrometeorologist, plant physiologist and epidemiologist) to assist in the selection of sites, relying on their judgement to make the best possible choice on the basis of (1) an appraisal of the effects of local geometry on air quality, (2) an appraisal of the effects of local sources of pollution on air quality, and (3) the stated objectives of the monitoring programme.

Three further points need to be emphasised. In the first place, monitoring stations cannot be chosen by sticking pins on a map; personal visits to proposed sites are always required. Secondly, test data should be obtained and analyzed before a site is given permanent status; preferably, a portable sampling shelter should be used during the first year of operation. Thirdly, a separate appraisal is needed for each pollutant. Some substances are emitted mainly from tall chimneys, others from ground-level sources; still others are the products of chemical reactions in the atmosphere. For convenience and economy, several substances are often measured at the sampling station, without careful thought being given to the sources and sinks of the pollutants, and to the objectives of the monitoring programme.

Table 4.3 Detailed site description for air monitoring stations (EPS, 1976)

1.Station number		2. Station address			3. Operator			
4. Land use in immediate area		5. Topography and vegetation description		6. Site elevation		7. Angle of elevation of nearby building(s)		
8. Major industrial air pollution sources influencing station				9. Roadway influences on station				
Industry name	Industry type	Direction from station	Distance from station	Roadway name	Type	Lanes	Direction from station	Distance from station
10. Other significant air pollution sources			11. Height of station enclosure		12. Type of station enclosure		13. Are site photographs available?	
14. Is sample inlet sketch available?		15. Is mani-fold detail sketch available?		16. Form completed by				

17. Other pertinent information:

In summary, this section has provided a few guide lines but no firm criteria for siting urban air quality monitoring stations. However, a recapitulation will be given in Chapter 7 separately for each monitoring objective, following the discussion on methods for network design.

4.7 Predicted land-use patterns

A factor to be considered in siting a monitoring station is the likelihood that current land uses will remain unchanged over the next few years or decades. This is a difficult prediction to make, of course, and sometimes a monitoring station may become quite unsuitable after only a year or so of operation because of unexpected changes in zoning by-laws.

On the other hand, the reason for monitoring may be to assess change, e.g. to determine the impact of a proposed development such as a factory, highway or power station. Even more so in that case, however, a criterion for a good monitoring site is that it should have a micro-environment (within 50 m or so) that is likely to remain stable. This simplifies the task of assessing the impact of the major development.

Some of the micro-environments that are not likely to change over the years and that could be considered for siting monitoring stations include (1) a park, (2) a cemetery, (3) an historic property, (4) a conservation area or biological reserve. In all cases, station documentation should be prepared and reviewed at regular intervals. A Canadian proposal for a site documentation form is given in *Table 4.3* (EPS, 1976).

5

Methods available for network design

5.1 Introduction

When only three or four monitoring stations are planned for a city, a widely used rule-of-thumb is to select one site in each of an industrial, a commercial and a residential neighbourhood; *see*, for example, WHO (1976a, b). If the landscape is rugged, an additional station or two may be established, e.g. at the bottom of a valley or at the top of a hill.

When the planned number of monitoring stations exceeds about six, a more objective method for network design is required. Two general approaches are discussed in this chapter: (1) the statistical method, and (2) the modelling method.

The basis for the *statistical method* is that urban air pollution measurements are correlated in space and time, which means that data obtained from a monitoring network contain a certain degree of redundant information (*see* Chapter 3, section 3.4). From a knowledge of the correlation fields, it is possible in principle to design a network which is optimal for specific goals.

The basis for the *modelling method* is that dispersion of pollution can be predicted, to a certain extent, from knowledge of emission characteristics and the meteorological fields. It is therefore possible to predict the broad features of the concentration field, and to optimise a network to meet any given monitoring objective, e.g. to select sites where the concentrations are most likely to be the highest in the city.

The primary drawbacks of the two methods are: (1) the first method presupposes the existence of a monitoring network from which the time and space correlation fields can be estimated; (2) the second method requires information on source strengths and on the meteorological fields throughout the city. The best strategy is to use a combination of the two approaches.

5.2 Statistical methods

5.2.1 A quasi-subjective approach

Rhoades (1973) developed criteria for reducing the size of a dustfall and sulphation monitoring network in St. Louis, Missouri. Because new air pollution control programmes were to be introduced without an increase in staff, the number of monitoring stations had to be decreased from 54 to about 35. Rhoades used the techniques listed below for removing stations. Each approach gave a slightly different result, so that the final decision on network design was subjective.

5.2.1.1 A distance criterion. For each station, its two closest neighbours were noted. The number of times that a station was listed as neighbour was then counted, yielding the following totals:

Number of times a station was listed as a neighbour	*Frequency of occurrence*
0	3
1	15
2	23
3	9
4	4

Using proximity to another station as a simple criterion, the sites appearing four and three times would be eliminated. (In the final reckoning, eleven of these thirteen stations were removed.)

5.2.1.2 Departure of a station mean from the areal mean. The stations were ranked from 1 to 54, separately for sulphation and for dustfall, in terms of the departure of the station mean from the areal mean; the station with the least departure was ranked 1, etc. The rankings for the two pollutants were then averaged, after an arbitrary 1.5 weighting for dustfall had been introduced: sulphation was believed to be less important than dustfall at that time in the St. Louis control programme. In this connection, it is interesting to note that in the set of twenty-four stations with the lowest weighted ordering, there were nine common members of the subsets of twenty-four stations with lowest dustfalls and sulphations.

The rankings could be applied to network design in two different ways: (1) if an objective of the network was to estimate areal mean values for use in determining long-term trends, stations with high rankings would be removed; (2) if an objective of the network was to estimate peaks, stations with low rankings would be removed.

5.2.1.3 Isopleth distortion. Using networks of 54, 40 and 30 stations for both dustfall and sulphation, isopleths were drawn independently by three draughtsmen. The values at predesignated grid points were then estimated by eye.

Assuming that the values obtained from the 54-station network were true values, the following comparisons were made:

	Deviation from values estimated from a 54-station network (%)
Dustfall	
40 stations	17.4
30 stations	22.0
Sulphation	
40 stations	7.4
30 stations	8.3

The techniques of Rhoades are easy to apply, but are simplistic, overlooking complexities which are discussed in the following subsections. If such approaches are to be used, however, several modifications might be considered: (1) retain pairs of stations having the largest gradients; (2) retain pairs of stations having the smallest gradients; (3) retain stations with the largest absolute or relative variability; (4) retain stations with the smallest absolute or relative variability. The most appropriate strategy depends upon the objective of the monitoring programme.

5.2.2 Use of the coefficient of geographic variation

For a Gaussian distribution, a coefficient of variation C_V may be defined as

$$C_V = 100\ s/\overline{X} \tag{5.1}$$

where $\overline{X}$ and s are the mean and standard deviation of the population of x. However, air pollution concentrations tend to be distributed log-normally. The appropriate statistic is therefore the coefficient of geographic variation C_{GV} which can be obtained from the relation

$$C_{GV} = 100 \text{ antilog } s_g - 100 \tag{5.2}$$

Stalker *et al.* (1962) have employed C_{GV} to determine the minimum number of pollution sampling stations required to estimate the true areal mean within specified confidence limits:

$$n = (C_{GV})^2 t^2/p^2 \tag{5.3}$$

where n is the minimum number of stations, t is Student's t for specified confidence, and p is the allowable percentage departure from the true mean. This relationship is shown in *Figure 5.1* for five values of p.

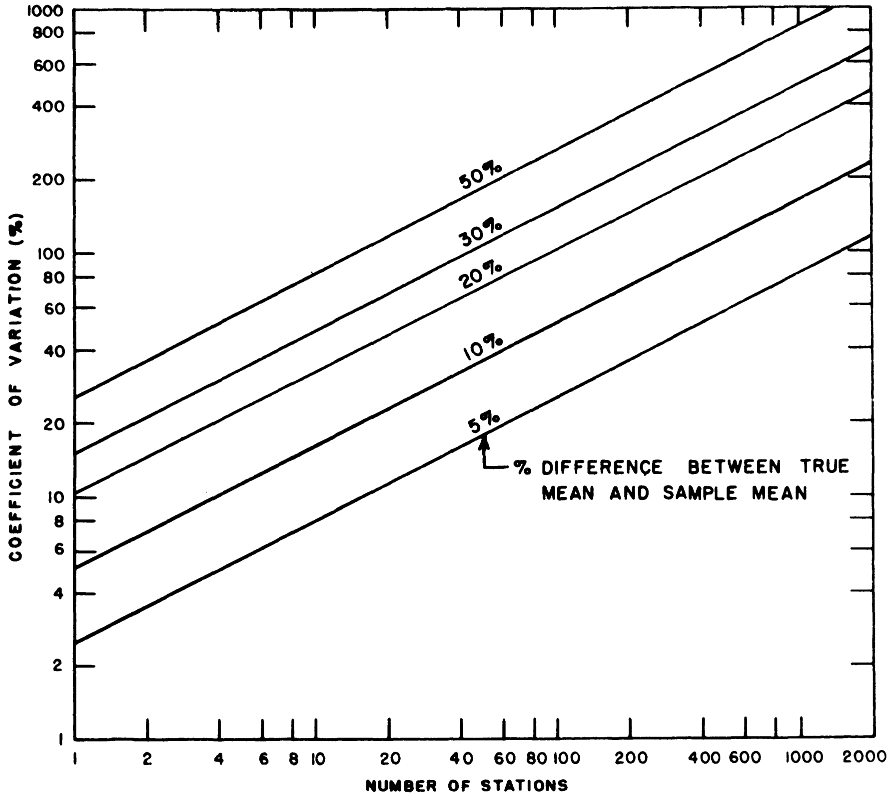


Figure 5.1 Nomogram for estimating the number of sampling stations required to obtain a true monthly mean within specified limits (Stalker *et al.*, 1962)

Using data from a large network (119 stations) in Nashville, Tennessee, Stalker *et al.* (1962) determined the number of stations required for measuring two-hourly, daily, monthly, seasonal and annual mean concentrations within ±20% of the mean obtained from the complete network of stations. The results are shown in *Table 5.1*. As might be expected, network density decreases with increasing averaging time. A seasonal variation in network density is also apparent, with fewer stations being required in the summer than in the winter. This is because summer concentrations of pollution are uniformly low, particularly at residential sites; thus a single station is a good predictor of air quality over a relatively large neighbourhood.

In a somewhat similar type of analysis, Clifton *et al.* (1959) used measurements of daily concentrations of smoke and SO_2 made at twenty-eight stations in Sheffield, England. The investigators used arithmetic rather than geometric means and standard deviations, i.e. equation (5.1) instead of

Table 5.1 Number of sampling stations required for measuring 2-h, daily, monthly, seasonal, and annual mean concentrations of certain atmospheric pollutants in Nashville, Tennessee with ±20% accuracy at 95% confidence level[a].

	Sampling stations required per 25.6 km^2				
Time period	*Sulphation*	*Dustfall*	*Suspended particulate matter*	*Soiling index*	*Sulphur dioxide*
2-Hourly				60	38
Daily			9	60	38
Monthly					
Sept.	14	27	5	2	1
Oct.	17	25	3	4	10
Nov.	12	80	4	7	9
Dec.	6	41	2	14	8
Jan.	11	100	2	9	10
Feb.	8	16	2	9	12
Mar.	20	22	3	—	11
Apr.	7	18	3	8	5
May	14	20	2	10	1
June	7	11	2	6	1
July	9	20	2	7	1
Aug.	6	57	7	5	1
Season					
Autumn	12	20	3	3	4
Winter	7	21	2	6	9
Spring	11	8	3	9	3
Summer	6	9	3	4	1
Annual	6	7	2	4	—

[a] Stalker *et al.* (1962).

equation (5.2). Some results are given in *Table 5.2.* When eight of the twenty-eight sites were selected at random, and mean monthly values were calculated, the coefficient of variation was in all cases less than ±20%.

Clifton *et al.* also examined the effect of separation distance on the coefficient of variation, using monthly mean values for a twelve-month period at the twenty-eight stations. The results given in *Table 5.3* suggest that in order to keep the coefficient of variation to within ±20%, monitoring sites must be not more than 0.8 km apart.

The laboratory was in the centre of a 'neighbourhood' within the central business district of Sheffield. Some experiments were therefore undertaken in which some of the instruments were at radial distances of from 200 m to 1200 m from the central monitoring station. The results in *Table 5.4* indicate that 500 m is the maximum permissible separation distance, if the coefficient of variation for daily means is not to exceed ±20%.

Table 5.2 Coefficients of variation of the monthly/annual mean of eight instruments as an estimate of the average pollution of Sheffield over different periods (Clifton *et al.*, 1959)

Period	*Mean values, 28 sites*		*Coefficient of variation* (%), *mean of eight instruments*	
	Smoke (mg/100 m³)	SO_2 (*pphm*)	*Smoke*	SO_2
July 1958	16	5.0	13	16
Sept. 1958	19	5.4	11	12
Nov. 1958	64	15.8	8	12
Year ending Jan. 1959	36	9.1	8	11

Table 5.3 Coefficients of variation of monthly mean values for smoke and sulphur dioxide at different distances (Clifton *et al.*, 1959)

Distance between sites (km)	*Number of pairs used*	*Coefficient of variation* (%)	
		Smoke	SO_2
0.8	6	19	7
1.6	11	25	26
3.2	13	25	31

Table 5.4 Coefficients of variation of daily measurements of smoke and sulphur dioxide at different distances (Clifton *et al.*, 1959)

Month	*Number of instruments*	*Mean distance apart* (m)	*Number of days covered*	*Means of daily values*		*Coefficient of variation* (%)	
				Smoke (mg/100 m³)	SO_2 (*pphm*)	*Smoke*	SO_2
1957							
May/June	4	Same window	12	13	4.9	8	5
Apr./May	4	5.5 (vertical)	16	31	8.2	6	5
Nov.	4	203	22	57	15.0	9	9
Nov.	3	486	22	60	15.0	19	16
1958							
Jan.	3	486	23	53	13.3	12	21
Jan.	3	1191	21	40	11.4	54	83

Finally, Clifton *et al.* studied some of the microscale variations in daily mean values of smoke and SO_2. *Table 5.4* shows that when four instruments were sampling air through the same window, the coefficient of variation was about the same (5–8%) as when the intake tubes were placed above one another at heights of 3, 6, 9 and 12 m above ground level.

A difficulty with both the Nashville and the Sheffield data is that urban air pollution patterns are not random. The usual statistical significance tests therefore cannot be applied, although the results are believed to be at least qualitatively correct.

5.2.3 The use of structure functions

Some of the earliest statistical studies of network design were for the meteorological elements and were undertaken by Gandin (1963, 1970). Gandin's ideas were applied to air pollution problems by Goroshko (1971), Bezuglaya and Klingo (1973) and Gorshenev *et al.* (1975). Because this approach has not been widely referenced in the air pollution literature outside the USSR, the method will be described in some detail here. The treatment will be simplified to emphasise the main points.

Consider a series of consecutive measurements of concentrations (C_0, C_1, $C_2, \ldots, C_i, \ldots C_n$) of a pollutant. Let the mean value of C_i be $\bar{C}$, let the departure of C_i from the mean be C'_i, i.e. $C_i = \bar{C} + C'_i$, and let the variance be σ^2, denoted notationally by $\overline{(C_i - \bar{C})^2}$.

Next, a *structure function* $S(t)$ is defined as the mean square of the differences in values of C for various time lags:

$$S(t) = \overline{(C'_i - C'_j)^2} \tag{5.4}$$

for i and $j = 0, 1, 2, \ldots, n$. In practice, the structure function is computed only for values of t less than about $n/10$, because the statistics become too irregular with smaller sample sizes. $S(t)$ may be normalised to $S(t)/\sigma^2$ if desired.

The structure function has a value of zero for $t = 0$, and increases with increasing t unless the series of values is uncorrelated, in which case:

$$S(t) = \begin{vmatrix} 0 & \quad t = 0 \\ k & \quad t > 0 \end{vmatrix}$$

where k is a constant whose numerical value depends on σ^2.

Suppose now that there is a concurrent series of measurements of concentrations D_i made at a second monitoring station separated from the first one by a distance x. A *space structure function* $S(x)$ can be defined:

$$S(x) = \overline{(C'_i - D'_i)^2} \tag{5.5}$$

At $x=0$, $S(x)=0$. The function may be normalised by dividing by the standard deviations σ_C, σ_D of the two time series. When the space and time fields are uncorrelated

$$S(x) = \begin{cases} 0 & t=0 \\ k & t>0 \end{cases}$$

This is rarely the case for environmental data.

In meteorological applications, an assumption is often made that the structure function field is *homogeneous* and *isotropic*, i.e. that the statistics do not depend on position but only on separation distance. Such an assumption simplifies the subsequent analysis but needs to be checked in each case.

Random errors are usually present in measurements of C'. Assuming that errors at different points are correlated neither with each other nor with the true values of C', it may be shown (Gandin, 1970) that the numerical value of the space structure function computed from equation (5.5) is too large by an amount equal to the sum of the variances of the errors at the two points. If the error variance is denoted by α^2, then the true value of the structure function $S(x)$ is related to the observed value $S_0(x)$ as follows:

$$S_0(x) = S(x) + 2\alpha^2 \tag{5.6}$$

It should be noted that α^2 includes not only observational errors but also 'noise' which arises from microclimatic irregularities, poor siting of stations with respect to local pollution sources, etc.

In principle, the fact that $S(0)$ is zero may be used to estimate α^2, by extrapolating $S(x)$ back to $x=0$. Alternatively, the assumption may be made that

$$\alpha^2(\text{time}) = \alpha^2(\text{space})$$

Then $S(t)$ is computed for small values of t, and extrapolated back to zero time lag.

Consider next the problem of interpolating the value of $C'(x)$ at a point on a line intermediate between $x=0$ and $x=d$. The linear interpolation formula is

$$C'(x) = (1 - x/d)C'(0) + (x/d)C'(d) \tag{5.7}$$

A measure of the goodness of the interpolation is given by the root-mean-square difference E between the actual and the interpolated values of $C'(x)$. For a rather smooth concentration field, the maximum value of E occurs at the mid-point, $d/2$. For this point, it may be shown (Gandin, 1970) that

$$E^2 = S(d/2) - 1/4\, S(d) + 1/2\, \alpha^2 \tag{5.8}$$

Equation (5.8) contains the implicit assumption that the field of $S(x)$ is homogeneous and isotropic.

The application of equation (5.8) to the design of monitoring networks is as follows. Given, (a) the numerical value of S (the structure function) in the region being studied, (b) the numerical value of α^2 (the error variance), and (c) the maximum value of E (the interpolation error) acceptable by the programme manager, then the maximum acceptable distance d between monitoring stations may be computed from equation (5.8). In meteorological applications, an arbitrary rule has been used that the value of $[S(d/2) - 1/4\ S(d)]$ in equation (5.8) should be no larger than α^2, and thus that E should be no larger than $3/2\ \alpha^2$ (Gandin, 1970). In an urban pair pollution application, Bezuglaya and Klingo (1973) have suggested that E should be no larger than 20% of the maximum permissible concentration of the pollutant being considered.

This rather simple view of space and time fields can be extended in a number of important ways. Before doing so, however, it is useful to illustrate the technique with some examples by Bezuglaya and Klingo (1973), who investigated the SO_2 and NO_2 fields in five cities in the USSR, from individual observations averaged over 20-min periods, the total lengths of record being from one to two years. Data were grouped for distances between pairs of monitoring stations of 2.1–4.0, 4.1–6.0, 6.1–8.0, and 8.1–10.0 km. No stations were closer than 2 km from one another. A homogeneous isotropic field was assumed.

The value of α^2 was estimated by extrapolation of the $S(t)$ curve back to zero time lag. This yielded α^2 values in various cities of from 0.0004 to 0.0006 for SO_2 and from 0.0002 to 0.0004 for NO_2 (in units of $(\text{mg m}^{-3})^2$). The resulting structure functions are given in *Figure 5.2*; the solid line is the empirical curve

$$S(x) = Ax^{0.75} \tag{5.9}$$

where A has values of 0.0023 and 0.0025 for SO_2 and NO_2, respectively. It can be seen that the empirical fit is reasonable.

As an example of the variability of $S(x)$, *Table 5.5* presents the $S(x)$ data for one city, Sverdlovsk, and shows that the root-mean-square variability of $S(x)$ within each distance range was rather small.

Bezuglaya and Klingo then examined the implications of their calculations for network design. The first step was to assign a value for E, and they chose a value equal to 20% of the maximum permissible concentration of the pollutant being studied. In the case of SO_2, this yielded a value of 0.01 $(\text{mg m}^{-3})^2$ for E, and a separation distance of 10–16 km for the cities under consideration. In contrast, the separation distance for the NO_2 monitoring stations was estimated to be only 2 km.

The following additional comments should be made about the use of equation (5.8) for network design (Gandin, 1970; Bezuglaya and Klingo, 1973).

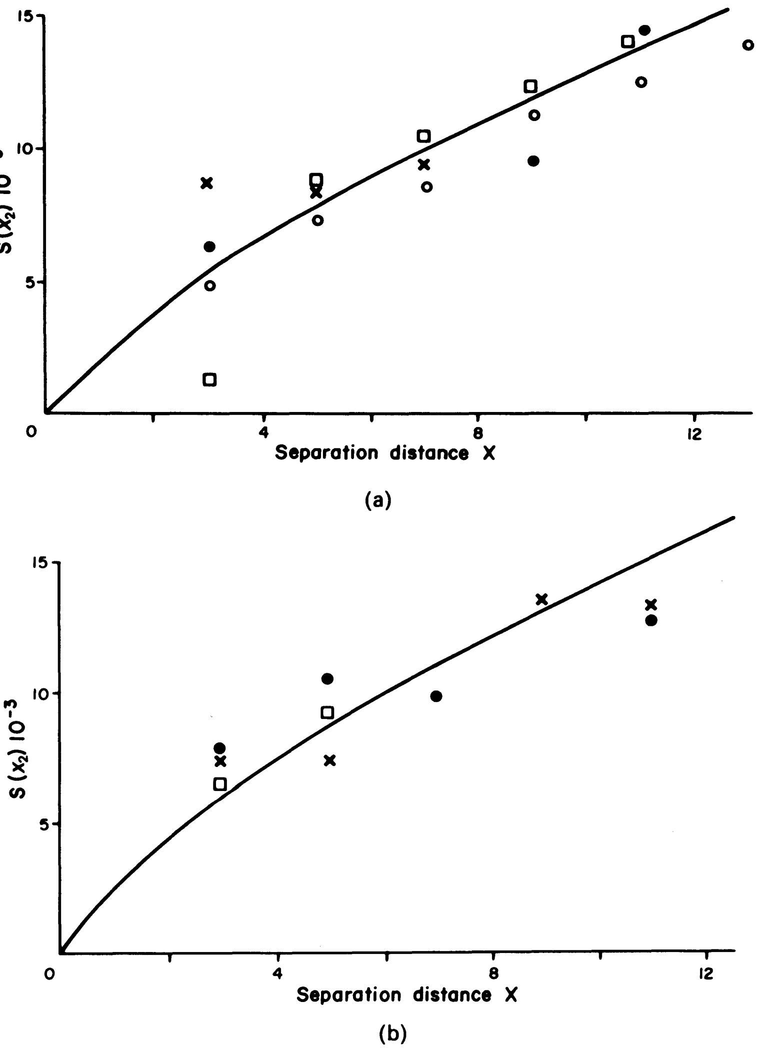


Figure 5.2 Structure function $S(x)$ for several cities in the USSR (Bezuglaya and Klingo, 1973). The solid curves are obtained from equation (5.9). (a) Structure functions for SO_2 concentrations: ● Chita; ○ Sverdlovsk; × Irkutsk; □ Dnepropetrovsk. (b) Structure functions for NO_2 concentrations: □ Dnepropetrovsk; × Sverdlovsk; ● Omsk

Table 5.5 Values of the non-normalised structure function of SO_2 concentrations for various distance ranges between monitoring points in Sverdlovsk (Bezuglaya and Klingo,1973)

Distance (km)	2–4	4–6	6–8	8–10	10–12
$S(x)$	0.0048	0.0072	0.0087	0.0112	0.0124
σ	0.0002	0.0003	0.0004	0.0001	0.0001

(1) The linear interpolation technique can only be applied in cities with relatively uniform distributions of emissions.
(2) The technique provides guidance on separation distances of order of magnitude of half the distance between existing stations, i.e. the technique can be used to locate new stations on the neighbourhood scale but not on the microscale. To undertake the latter would require a microscale network of monitoring stations.
(3) The optimal separation distance depends not only on the value assigned to E but also on the measurement error α^2. A city with high air pollution concentrations generally has larger values of α^2 than cities with low concentrations. The network density should therefore increase with increasing air pollution concentrations, for the same E. (In some cases, the assigned numerical value of E might itself be a function of city size, air pollution concentrations, and/or some other factors.)
(4) The value of $\bar{C}$ must be obtained from the data sample and not from some other source such as an air pollution annual report.
(5) In some cases, optimum network density may prove to be different in winter and summer.
(6) The possibility exists of using the Gandin approach to compare the cost-effectiveness of reducing α^2 versus increasing network density. In one application, Steinitz *et al.* (1971) studied the rawinsonde network in the tropical portion of the northern hemisphere (145 stations). It was inferred that: (a) for interpolating 500-mb heights, an increase in measurement accuracy would be more effective than an increase in station density; (b) for interpolating 500-mb winds, an increase in measurement accuracy would be less effective than an increase in station density provided that separation distances between stations were not too large. In data-sparse regions, the rate of decrease in interpolation error with increasing accuracy or increasing network density is very small.

The linear interpolation approach described above has been extended by the Soviet scientists in several important ways.

(1) Interpolation at the midpoint of a line can be replaced by interpolation at the centre of an n-sided polygon. For an equilateral triangle, for example, equation (5.8) is replaced by

$$E = S(d/3^{1/2}) - 1/3S(d) + 1/3\alpha^2 \qquad (5.10)$$

As n increases, the formulations become more complex but they can be specified without difficulty. From a practical point of view, however, only a slight increase in accuracy is to be gained from using a large value of n (Gandin, 1970).
(2) An alternative approach is the method of optimal interpolation which uses weights chosen not in advance but during the course of an analysis; the weights are such that the standard error of interpolation

is less than it would be with any other set of weights. *See* Gandin (1970) for details. Optimal interpolation is preferable to linear interpolation in the following cases: (a) when the space correlations are small; (b) when the distribution of monitoring stations is highly asymmetrical with respect to the interpolation point; (c) when the value of α^2 varies substantially across the region; and (d) when the value of α^2 is of the same order of magnitude as the value of σ^2.

(3) In some applications, the main interest is in estimating an areal average rather than point values of the pollutant concentrations. This problem is solved by a variant of the method of optimal interpolation, and is not difficult; *see* Gandin (1970, pp. 14–16).

(4) Time series frequently contain gaps. Gorshenev *et al.* (1975) suggest techniques to minimise the effects of gaps on the statistical parameters computed from series of air quality measurements. *See* also Pimental (1975).

5.2.4 The use of correlation functions

For a network of air quality monitoring stations, correlation coefficients between every pair of stations may be computed, as has been done, for example, for New York City (Goldstein *et al.*, 1974) and Tucson, Arizona (Moyers *et al.*, 1977). Information of this type may be used in several ways to aid network design.

5.2.4.1 The quasi-intuitive approach. A simple technique is to increase network density in areas where correlation coefficients between adjacent stations are near zero, and to decrease densities where correlation coefficients are near ± 1. In some applications, this method works best with selected subsets of data: (1) data in which the concentrations are moderate to high (inclusion of many zero or trace values could inflate the correlation coefficients); (2) data which are separated in time so that the autocorrelation coefficients at individual stations have dropped to zero (according to Tennekes and Lumley (1972), this time separation is equal to twice the integral time scale, i.e. twice the area under the autocorrelation coefficient in *Figure 3.1* (solid line), for a stationary time series); and (3) data measured during similar meteorological conditions (*see*, for example, Munn, 1975).

5.2.4.2 Use of the space correlation function σ^2. A spatial correlation coefficient is sometimes computed as a function of separation distance, assuming that the field is homogeneous and isotropic. By finding a best-fit curve for the σ^2 function, the average separation distance between stations to ensure that σ^2 is larger than some designated value can be estimated. In many practical cases, this will require modest extrapolation of the σ^2 function inward to separations smaller than those which actually occur in the network.

Probably because the field was not homogeneous and isotropic, this approach was not useful in the case of a 40-station SO_2 network in New York City (Goldstein and Landovitz, 1977). Correlation coefficients were almost independent of distance between 0 and 3 km and 51 and 54 km, average values being near 0.5 but with great scatter. In fact, Goldstein and Landovitz are of the opinion that a single station should not be used to represent either the whole metropolitan area or even the surrounding neighbourhood. This may be true in cities where SO_2 emissions are mainly from a few point-sources, but is not necessarily so in other cases.

5.2.4.3 The minimisation of interpolation errors. Having determined the space correlation function, the interpolation error at any point in a pollution field can be estimated; *see*, for example, Gandin (1963), Buell (1975). The several ways in which this information can be applied to network design will be described in the following subsections. The resemblance with techniques arising from a knowledge of structure functions (section 5.2.3) should be noted.

5.2.5 The method of Buell (1975)

Buell (1975) has considered the problem of locating monitoring stations one at a time to supplement an existing network. His method is to determine the magnitudes of the interpolation errors throughout the region, and to select the location with the largest interpolation error as a monitoring site.

Buell begins with a discussion of the space correlation function, and notes the following points.

(1) The root-mean-square error of interpolation depends on the shape of the spatial correlation function and on the distance of the interpolated point from the data points.

(2) If the spatial correlation function drops to zero over a distance that is less than the distance between data points, interpolation is not practicable. Buell refers to the *range of influence* of a correlation function as the distance over which the function is significantly different from zero.

(3) The interpolation error also depends on the variability of the observations: the more variable the data, the closer must be the sampling stations necessary to achieve the same root-mean-square error of interpolation.

(4) Provided that the correlation field is reasonably well behaved (e.g. no discontinuities), the maximum interpolation error between two points occurs half-way between them.

Buell considers the simple example of a correlation function which decreases linearly to a value of zero at distance g. If g is larger than the distance d between two observation points, and if the variance σ^2 of the concentrations is approximately the same at the two observation points, then the maximum mean-square interpolation error E^2 is at $d/2$:

$$\bar{E}^2 = \sigma^2 d/2g \tag{5.11}$$

If the value of E^2 is specified, then the distance between data points may not exceed

$$d = 2gE^2/\sigma^2 \tag{5.12}$$

This suggests that if g is everywhere the same, the separation distance varies inversely as the variance.

In general, the correlation function does not decrease linearly with distance. For engineering applications, however, g might be considered to be related approximately to the area under the correlation function: this area is sometimes called the *correlation distance*. Equation (5.12) might then be applied, but the underlying assumption of a homogeneous isotropic field must not be forgotten.

Buell next derives a general method for estimating the interpolation error at a point P from a linear combination of observations made at points P_i $(i = 1, \ldots, n)$:

$$E^2 = [\sigma^2]_p - \sum_i \sum_j g_i a^{ij} g_j \tag{5.13}$$

where σ^2 is the variance at point P, g_i is the covariance between the concentrations at P and at P_i, and a^{ij} is the element from the inverse of the matrix of the covariance between the concentrations at P_i and P_j.

In principle, equation (5.13) could be used to map the field of E^2 and thus to select an additional site for a monitoring station at the point where E^2 is largest. However, Buell has not provided a practical example.

5.2.6 The design of precipitation chemistry networks

There have been several studies of network design for WMO regional precipitation chemistry stations (Karol and Myatch, 1972; Granat, 1974; Granat, 1976). At the outset in the 1960s, the WMO specified that about 200 stations would be needed worldwide, but there was no firm basis for this view.

Karol and Myatch (1972) have studied this problem, seeking to determine the minimum number of stations that would permit: (1) interpolation of the monthly concentrations and depositions of selected trace substances in precipitation to any point in the field with specified accuracy; and (2) estimation of total areal deposition of a given constituent of monthly precipitation, with specified accuracy. By way of introduction, it should be noted that because the turbulent wind varies greatly near buildings and trees (and near rain-gauges!), so also do measured values of precipitation and of wet and dry deposition of particles. In the case of wet deposition, the difficulty may be partially overcome by measuring concentrations of trace substances rather than depositions. Then from networks of rain-gauges, a smoothed areal mean precipitation amount can be estimated, and the deposition of pollutants can be inferred. This procedure is widely adopted.

The data used by Karol and Myatch consisted of monthly concentrations and depositions of Ca^{2+}, SO_4^{2-}, Na^+ and the sum of the ions at twenty-eight stations in the European territory of the USSR for the months April–September (1958–65 at eleven stations; 1962–65 at an additional seventeen stations). The space correlation functions were computed according to the method of Gandin *et al.* (1968), extrapolating the functions to zero separation to estimate α^2, the random observational error (*see* section 5.2.3, equation (5.6)). The ratio α^2/σ^2 was about 0.15–0.20. The random error term was then subtracted from the computed space correlations, and the integral scales of these functions were determined. The results given in *Table 5.6* show that correlation distances were greater for concentrations than for depositions. The values were generally of the order of a few hundred kilometres.

Finally, interpolation errors at fixed grid points were minimised, by the method of Gandin (1963). Assuming that the interpolation error should not exceed the observational error (0.20), the analysis indicated that the mean distance between stations should not exceed 100 km. This contrasts with the results of a study, with the same methodology, of the network density required for actinometric stations (Vinnikov and Dvorkina, 1970); in that case, a separation distance of about 500 km was found.

For the chemical constituents of precipitation, areal averages are more important than point values. From a method described by Gandin *et al.* (1968) for estimating areal averages, the result was obtained that 2–3 stations should be located in each square of 300×300 km^2 if areal monthly averages of wet deposition were to be measured with an error of estimate not exceeding the observational error.

These results are for monthly mean values and do not necessarily apply in the case of event sampling, which should be studied separately. Karol and Myatch also believe that a mesoscale precipitation chemistry network should be established in order to permit better estimates of α^2 to be made.

Table 5.6 Correlation distances (in km) for various constituents in precipitation (Karol and Myatch, 1972)

	Ca^{2+}	SO_4^{2-}	Na^+	*Sum of ions*	*Precipitation amount*
Concentration	270	300	120	450	430
Deposition	240	250	90	330	

Granat (1974, 1976) in fact studied the mesoscale variability of wet deposition but his general approach to network design was rather different from that of Karol and Myatch.

For a region in central Sweden about 100 km in diameter, Granat (1976) analysed monthly precipitation samples from a network of 45–70 stations. The ratios of standard deviation to mean are given in *Tables 5.7* and *5.8* for precipitation events and monthly samples, respectively. For event samples (*Table 5.7*, part A), the ratios vary from 0.1 to 1.2; these values are larger than the ratios for pairs of collectors located a few metres apart (*Table 5.7*, part B).

When the area covered by the data in *Table 5.7* was subdivided into five subareas, the ratios of areal monthly standard deviations to areal monthly mean values ranged from about 0.1 to 0.3 (*see Table 5.8*).

Granat used these and other data to compute the correlation function for separation distances up to 550 km. A typical decrease of correlation with

Table 5.7 Areal variability of chemical composition and amount of precipitation in event samples in an area of about 100 km in diameter in central Sweden[a]

	Event number	*Precipitation*	SO_4^{2-}	Na^+	*Number of collectors*
A	1	0.26	0.33	0.68	62
	2	0.67	0.51	0.56	57
	3	0.54	0.37	0.77	46
	4	0.10	0.40	0.62	66
	5	1.19	0.13	0.44	68
	6	0.16	0.12	0.60	70
	7	0.40	0.20	0.57	66
B	1–7	0.09	0.12	0.19	7 pairs

[a] A gives the ratio of standard deviation and event mean value for the area, and B the ratio for pairs of collectors a few metres apart (Granat, 1976).

Table 5.8 Areal variability of chemical composition and amount of precipitation in monthly samples in five areas of about 50 km in diameter in central Sweden. Variability is calculated as root-mean-square deviation within each area, month by month, and is given as a ratio to the average for the whole period (Granat, 1976)

Area	*Precipitation*	SO_4^{2-}	Na^+
Fo	0.21	0.15	0.25
Sn	0.31	0.18	0.30
Pl	0.26	0.14	0.21
Sm	0.14	0.12	0.31
Ap	0.19	0.16	0.33

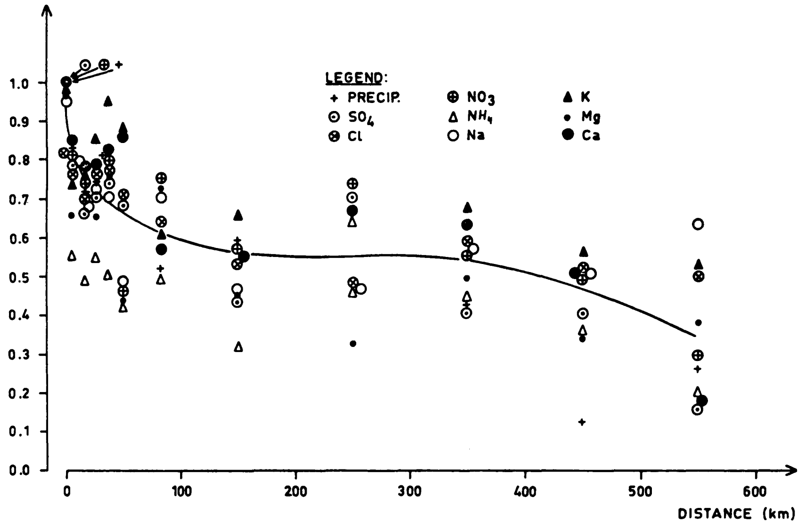


Figure 5.3 Correlation coefficients (ordinate scale) for monthly concentrations in precipitation for various separation distances (abscissa) (Granat, 1976)

separation distance was found, but the variability was rather large (*see Figure 5.3*).

There is little comparable information about space–time correlations in eastern North America, the second major region subject to acid rain. However, Pack (1978) analysed monthly data from a small wet deposition network (Washington, D.C.; Charlottesville, Virginia; Penn State University; Cornell University; Whiteface Mountain, N.Y.). He found that sulphate correlations remain high at distances of 600 km while nitrate correlations become small beyond 150 km. It seems that sulphate concentrations are affected significantly by large-scale meteorological patterns whereas nitrates are more dependent on local conditions.

5.2.7 The design of a turbidity network

For the area of interest shown in *Figure 5.4* (the north-eastern United States), Shannon and Wesely (1976) and Shannon *et al.* (1978) have sought to optimise the siting of ten turbidity sensors, five of the sites having been preselected for logistic reasons. The approach that was used is as follows (*see* also Eddy, 1974).

(1) With historical data from twenty-four stations within and near the area of interest, correlation matrices were computed for designated time and space separations (80 equidistant grid points were used).
(2) A continuous function with adjustable coefficients was fitted to the 'raw' correlations, using a non-linear programming technique. The

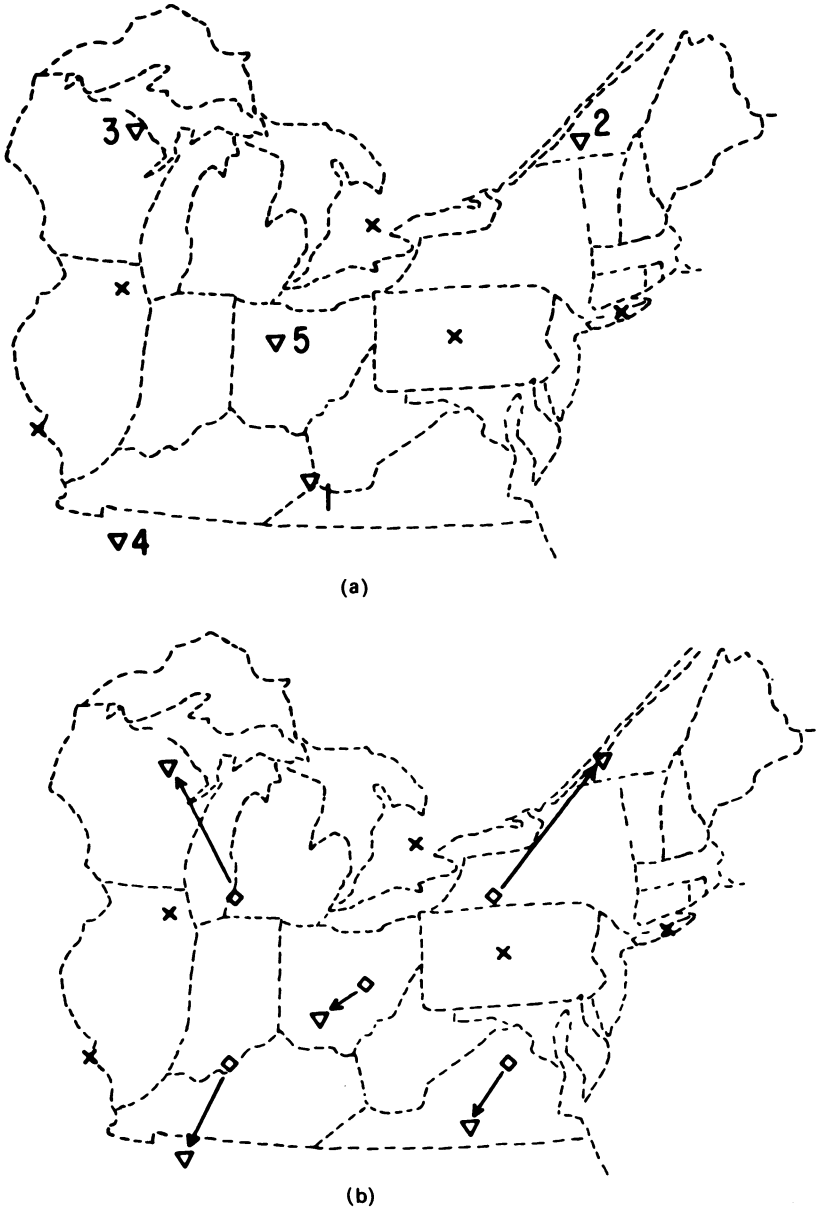


Figure 5.4 Optimal patterns determined by: (a) Sequential optimisation; × = preselected site, ∇ = optimised site. The numbers indicate the order in which the latter were selected. Modelled variance explained 24.5%. (b) Simultaneous optimisation; × = preselected site, □ = initial location of a shiftable sensor, ∇ = optimised location of a shiftable sensor. Modelled variance initially explained 20.4%. Modelled variance optimally explained 25.0%. Arrows indicate net shift of stations (Shannon and Wesely, 1976)

function explained 45% of the 24-station variance: this percentage was small because the monitoring stations were too widely separated. However, data from the five preselected sites explained even less, only 15% of the 24-station variance.

(3) A first guess was made of the best positions for the additional five sites.

(4) The locations were then optimised by a standard non-linear programming technique.

The final positioning of stations is shown in *Figure 5.4*. This network increased the percentage of variance explained from 15% to 25%.

The method used by Shannon and Wesely has recently been extended by Brady (1978) to include the optimal design of a sampling network for two cross-correlated variables, e.g. surface rainfall amounts and radar reflectivity, turbidity, and suspended particulate concentrations. A non-linear programming algorithm permits comparisons to be made of networks with different mixes of station locations and variables sampled.

5.2.8 Rank-ordering of stations in a monitoring network

A simple way of determining the relative worth of each station in a network is to compute the statistics of interest, first using all stations, and then removing one member in turn. Horie and Stern (1976) have rank-ordered 130 suspended particulate stations in the New York–New Jersey–Connecticut region, by three different schemes. (I) For each actual station, the root-mean-square departure of interpolated from observed values was computed. (The measurements at the three nearest stations were used for interpolation.) (II) For designated grid points, the root-mean-square difference was determined between the interpolated values using all and all but one of the stations. (Actual measurements at nearest stations were used to interpolate a grid-point value.) (III) As in (II) except that when the highest ranking station had been chosen, that station was removed from the subsequent analysis, which then proceeded. Some results are given in *Figure 5.5*, which shows the growth of the mean interpolation error with decreasing network density for each of the three schemes. The results are viewed in another way in *Table 5.9*, which shows that all three schemes led to rather similar subsets of the twenty most important stations.

This technique could be easily modified to meet related network design criteria, e.g. to select a network giving the best estimate of the spatial mean value.

5.2.9 A comparison of variances of measurements of several trace substances

Moyers *et al.* (1977) have examined suspended particulate data from a network of eight urban and three rural stations in Tucson, Arizona.

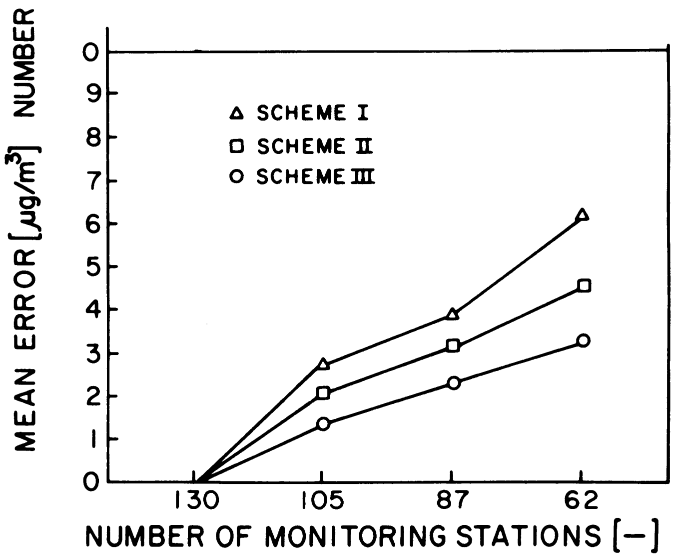


Figure 5.5 The growth of mean interpolation error as the number of monitoring stations for suspended particulate matter in the New York–New Jersey–Connecticut region was reduced from 130 to 62 (*see* text for further details) (Horie and Stern, 1976)

Table 5.9 Selection of the 20 most important stations from a network of 130 stations (Horie and Stern, 1976)[a]

Chosen by all 3 schemes	5 stations
Chosen by schemes I and II	2 additional stations
Chosen by schemes I and III	1 additional station
Chosen by schemes II and III	10 additional stations

[a] *See* text, section 5.2.8, for details.

Information was available on the total mass and on the concentrations of SO_4^{2-}, NO_3^{2-}, Al, Pb, Cd, Zn and Cu. The following analysis was performed using the eight urban stations: (1) means and variances for each station and each species were calculated; (2) combining the data from all eight stations, means and variances were calculated; (3) for each species and each station, the ratio of the station variance to the city-wide variance was computed; (4) for each station, an average of the eight ratios was calculated; (5) the stations were then ordered according to the numerical value of this average ratio. For the eight stations, the lowest value of the ratio was 0.83 and the highest was 2.19. The authors were of the opinion that the most representative sites were those with low values of the ratio.

This approach has some merit if the objective is to seek the best sub-network of stations for estimating urban mean values of a variety of trace substances.

5.2.10 Cluster analysis

Sabaton (1976) has studied the 24-hourly concentrations of SO_2 measured at thirty stations in metropolitan Paris, using *cluster analysis*, which aims at reducing network density with a minimum loss of information. (For other examples, *see* Hopke *et al.*, 1976, and Moyers *et al.*, 1977.)

Sabaton first subdivided his data into ten classes in ascending ranges of concentrations, and constructed a contingency table of the number of occurrences in each class at each station. In parts of the table where the numbers clustered, the space correlation coefficients were relatively high, thus providing a practical way of subdividing the network into three or four sub-networks, each containing stations that were relatively highly correlated with each other.

In the Paris example, this led to three sub-networks plus two sites (stations 16 and 28; *see Figure 5.6*) which were to be kept for operational reasons. The next step in the analysis was to determine within each group, the station best explained by other members of its group. This station was eliminated, and the analysis was repeated, with the remaining stations in the group. When the remaining members in a subgroup could not explain more than 85% of the variance of the subgroup, the process was arbitrarily stopped. With this criterion, a total of fifteen stations could be eliminated from the Paris network. As can be seen in *Figure 5.6*, most of the stations that were removed were located in the central part of the city.

5.2.11 The method of principal components

Spatial variations in air quality can be represented by a set of orthogonal functions. Because such functions are independent, the contribution of each to the total variance of the field is also independent. This kind of study is called an *eigenvector*, *factor* or *principal component* analysis. The result is usually displayed in a series of maps, each with isopleths that explain fractions of the total variance, the highest fraction being explained by the first map, etc. Peterson (1970) has studied the SO_2 field in St. Louis in this way.

The method may be applied to network design by comparing the maps associated with various sub-networks of stations, and selecting the one which causes the smallest reduction in variance. Sabaton (1976) has used this approach to determine the 15-station sub-network that preserves the most information contained in the existing 30-station metropolitan Paris

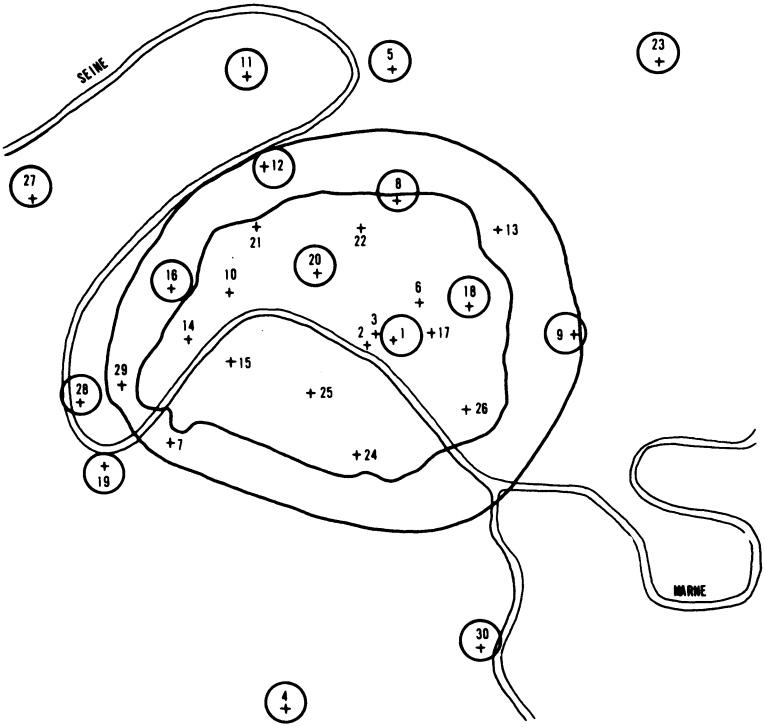


Figure 5.6 Optimisation of network design for Paris, France by cluster analysis (Sabaton, 1976). The circled stations are the ones that have been retained by this technique. Stations 16 and 28 were kept for operational reasons

network. The results are shown in *Figure 5.7.* On average, 82% of the information is retained, although at individual stations, the retention figure is as low as 67%.

Comparing the results (*Figures 5.6* and *5.7*) of the two methods used by Sabaton, cluster analysis produces a sub-network containing many suburban stations while principal component analysis leads to a strategy in which the central stations are kept.

5.2.12 A linear programming method

Darby *et al.* (1974) have examined the effectiveness of an air quality monitoring network in the Boston metropolitan area, in terms of its ability to provide maximum protection against health effects, i.e. in terms of its ability to detect violations of US primary air quality standards, weighted by the numbers of people affected. A linear programming optimisation model was used in the following way.

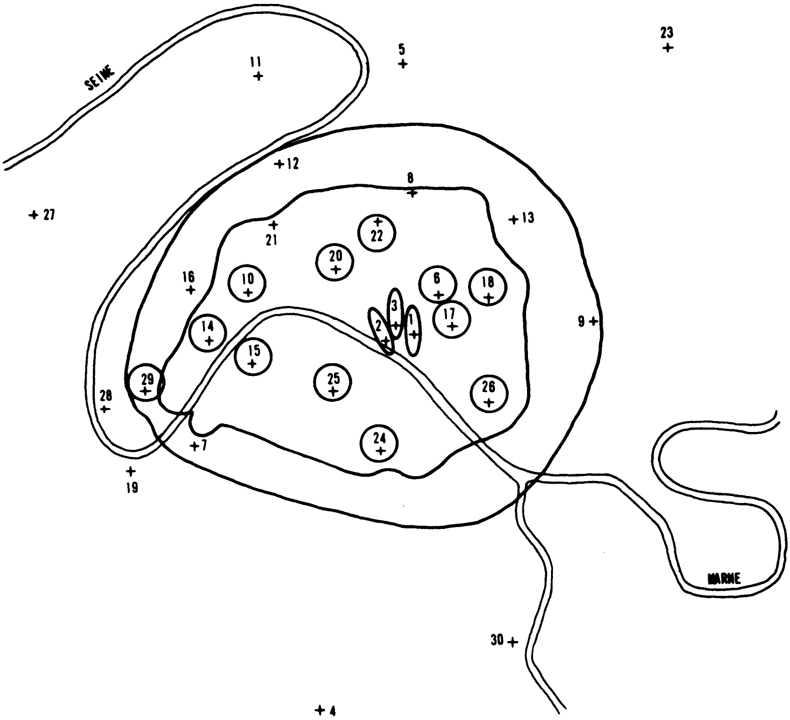


Figure 5.7 Optimisation of network design for Paris, France by principal component analysis (Sabaton, 1976). The circled stations are the ones that have been retained by this technique

(1) The pollution time-averaged concentrations were assumed to be log-normally distributed at each monitoring station/grid point of interest.
(2) The metropolitan area was subdivided into grid squares, and the population in each square was estimated. These subpopulations were allowed to vary, with high values during the daytime in the business/commercial zones, and at night in the residential areas.
(3) The population within each grid square was adjusted to give additional weight to children and elderly people.
(4) As constraints on the network, (a) a minimum number of stations was specified, *viz.* the number required by the US Environmental Protection Agency, and (b) a maximum budget was imposed, which limited the number of stations that could be operated.
(5) Three pollutants were considered: suspended particulates, sulphur dioxide and oxides of nitrogen.
(6) Only hours when the US primary and secondary air quality standards were exceeded were deemed to be significant.

The results are expressed in terms of a *network effectiveness function*, which is defined as the probability (ranging from 0 to 1) that the pollutant concentration exceeds an air quality standard for a given length of time, and that the susceptible fraction of the population is greater than that of some 'standard' population, i.e. a population based on US Census Bureau data for 201 metropolitan statistical areas. The effectiveness function will be greater than zero whenever in any of the Boston grid squares (a) the air quality standard is exceeded, (b) the population contains a larger fraction of children and elderly people than does the 'standard' population.

The linear programming method seeks to optimise network effectiveness for various densities of stations. The results given in *Figure 5.8* show that the effectiveness increases with increasing numbers of stations, and also show that the existing network is only about one-half as effective as it might be for health-related purposes (0.58 versus 0.85). As Darby *et al.* note, however, the Boston network was established for other reasons, and therefore should not be expected to be optimal for health-related monitoring.

Figure 5.8 also suggests that very little is to be gained, in terms of meeting the objectives specified by Darby *et al.*, by increasing the number of monitoring stations beyond about eight.

5.2.13 Statistical significance

For many of the methods described above, statistical significance tests are difficult to find. A recommended alternative is to subdivide the monitoring data into two or more subsets, replicating the analysis with each. Comparison of the results (e.g. ordering of stations, selection of the best location for a new station, etc.) should then provide some qualitative information on reproducibility. This question has been little studied to date.

5.3 Modelling methods

5.3.1 Introduction

There are many different kinds of air quality models. The most familiar are the transport–diffusion types, sometimes broadened to include chemical transformation and deposition terms. However, air quality can be modelled in other ways, e.g. by using Markov chains.

The usual purpose of a model is to make predictions. Provided that the forecasts are better than might be expected through chance, they can help in the siting of stations. Indeed if the model predictions show high skill, the need for a monitoring network diminishes, and stations may be required only to demonstrate that the 'calibration' of the model remains unchanged.

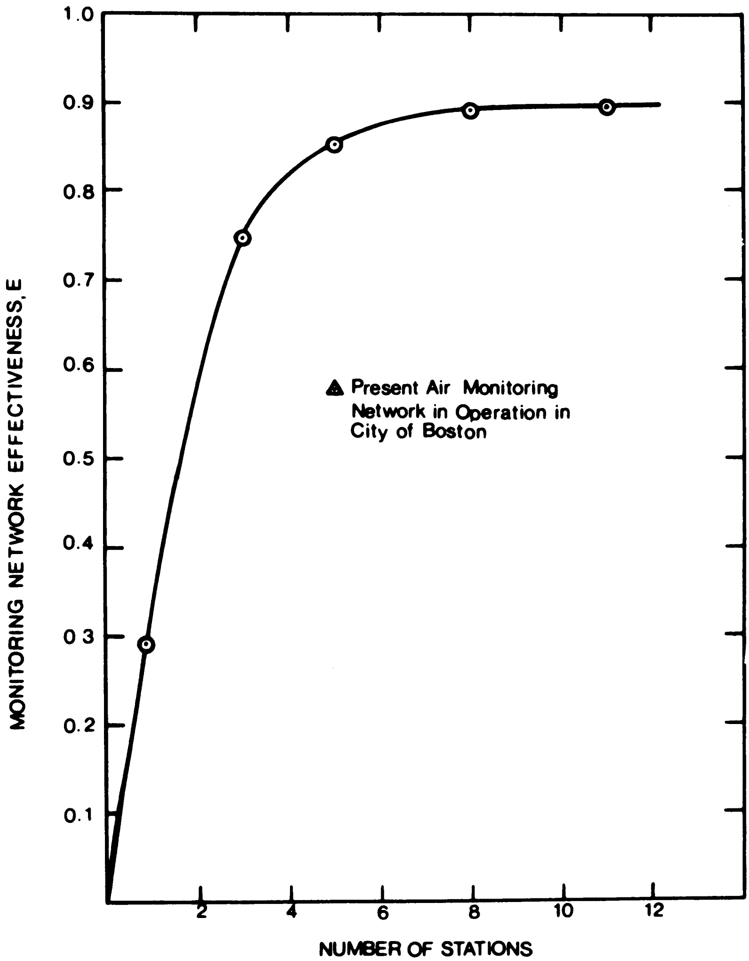


Figure 5.8 Monitoring network effectiveness versus number of optimally placed air sampling stations (Darby *et al.*, 1974). The triangle shows the effectiveness (0.58) of the present network (5 stations)

5.3.2 The design of monitoring networks from point-source models

5.3.2.1 Introduction. The statistical methods described in section 5.2 can rarely be used for network design when a single strong point-source of pollution predominates. As an alternative, however, models of the concentration field may provide guidance on the selection of monitoring stations, but several limitations should be noted.

(1) Predictions of ground-level concentrations from a point-source do not include the background component of pollution. If an objective of monitoring is to ensure that air quality standards are met, then

predictions of concentrations downwind of point-sources must be supplemented by upwind measurements. Since the wind direction changes from day to day, it will usually be necessary to establish four background monitoring stations at the vertices of a square or rectangle aligned along the most important wind direction (not necessarily the most frequent wind direction) (Pooler, 1974). If the wind is constrained to blow in a canyon, only two background stations will be required.

(2) Point-source diffusion models provide predictions of concentrations at 'roof-top' level, and should not be applied to urban canyons or to the open spaces below forest canopies.

(3) Although the concentration isopleths downwind of a point-source can often be predicted rather well, the orientation of these isopleths is more difficult to estimate. An error of 20–30° in wind direction can make an order-of-magnitude difference in observed concentrations at a fixed point, even when the general isopleth pattern is predicted correctly. This is a particular problem when the only wind information is from a weather station located several kilometres away.

(4) Although the skill in predicting a pollutant concentration at a fixed monitoring station may be low, the frequency distribution of concentrations predicted by the model may match those observed. Provided that this is verified at a few points, the predicted frequency distributions can provide the basis for designing a monitoring network in some cases.

(5) There is also the problem of selecting a climatologically representative period of meteorological observations. In classical statistics, an increase in sample size reduces the error of estimate of a mean. In meteorology, however, this is not true. Statistics obtained from measurements made over the last few years may not be good predictors of conditions over the next few years.

5.3.2.2 The use of wind-direction frequencies. A simple approach to network design is obtained by using direction frequencies. There are several possible variants, each suited to a particular monitoring objective. Hougland and Stephens (1976) have suggested the following approach.

(1) The first step is to designate potential monitoring sites, e.g. at fixed grid points.

(2) A *coverage factor* is then defined, and its value is computed for each potential site:

$$A_{jk} = \mathrm{FREQ}(k)*[1/(1+D_j)] \tag{5.14}$$

where A_{jk} is the coverage factor for the jth monitoring site in the kth downwind sector from the source; FREQ(k) is the frequency of the wind direction in the kth sector; and D_j is the distance from site to source. (The quantity $1/(1+D_i)$ is used instead of $1/D_i$ to prevent the coverage factor from becoming large as D_i approaches zero.)

(3) The sites with largest values of the coverage factor are then candidates for monitoring stations. This yields a monitor-oriented network, as contrasted with a source-oriented one (*see* section 5.3.3.2).

In this procedure, there is an implicit assumption that pollution concentrations decrease linearly with distance from a source. This is not correct, particularly in the case of a tall chimney; with increasing distance, the concentration first increases, and then decreases in that case. However, the bracketed term on the right-hand side of equation (5.14) could readily be replaced by a function whose value was given in a nomogram or table.

Other variants of the use of wind-direction frequencies in network design include (a) the replacement of surface wind by a mean transport wind through the mixed layer, and (b) restriction of the data sample to hours when high concentrations are most likely to occur, e.g. during fumigations and other limited mixing conditions.

5.3.2.3 The use of a point-source climatological dispersion model. Employing a Pasquill–Gifford or similar dispersion model together with a representative wind climatology, the frequency distributions of hourly or daily concentrations of a specified pollutant can be estimated at any point in the field. Assuming that the objective for monitoring is the detection of violations of air quality standards, the number of times that a standard will be exceeded at each grid point during a year or a decade can then be counted. The sites with the largest numbers of violations would be selected for monitoring.

Alternatively, a computer could be programmed to determine the coordinates of the point where the maximum ground-level concentration was predicted to occur each hour, and to map the locations of the 24×365 such points associated with a year of data. The zones with highest densities of points would be preferred sites for monitoring. If desired, only the points associated with ground-level concentrations exceeding designated limits would be counted. Several other related strategies are possible.

In the following paragraphs, two methodologies will be described, by Godfrey *et al.* (1976) and by Noll *et al.* (1977). In the former case (Godfrey *et al.*, 1976) the details are as follows.

(1) A coal-fired power station with two stacks operating was used as an example.
(2) Some thirty-six azimuthal angles and five distances (2, 3, 5, 7 and 10 km) from the source were selected, yielding $36 \times 5 = 180$ grid points.
(3) A Gaussian-type diffusion model was employed, in conjunction with one year of meteorological surface and upper air data.
(4) A random digit was generated, to be added to the azimuthal angle every hour.

(5) For each of the 180 grid points, a count was made of the number of occurrences when (a) the 24-hourly concentrations were above the primary United States SO_2 standard of 365 $\mu g\ m^{-3}$, and (b) the 3-hourly concentrations were above the secondary SO_2 standard of 1300 $\mu g\ m^{-3}$.

(6) From this information, sampling networks of various sizes and configurations were selected, independently for the two time periods. Locations with the largest numbers of violations were selected first as monitoring sites, except that adjacent locations would be excluded, in order to provide a broader coverage.

(7) After selecting 5, 7, 10, 12, 15, 18 and 20 stations, a count was made of the number of times that a violation occurring at any of the 180 sites was detected by each sub-network.

The results are summarised in *Figures 5.9* and *5.10.* As the number of sampling stations increased, the percentage of violations detected also

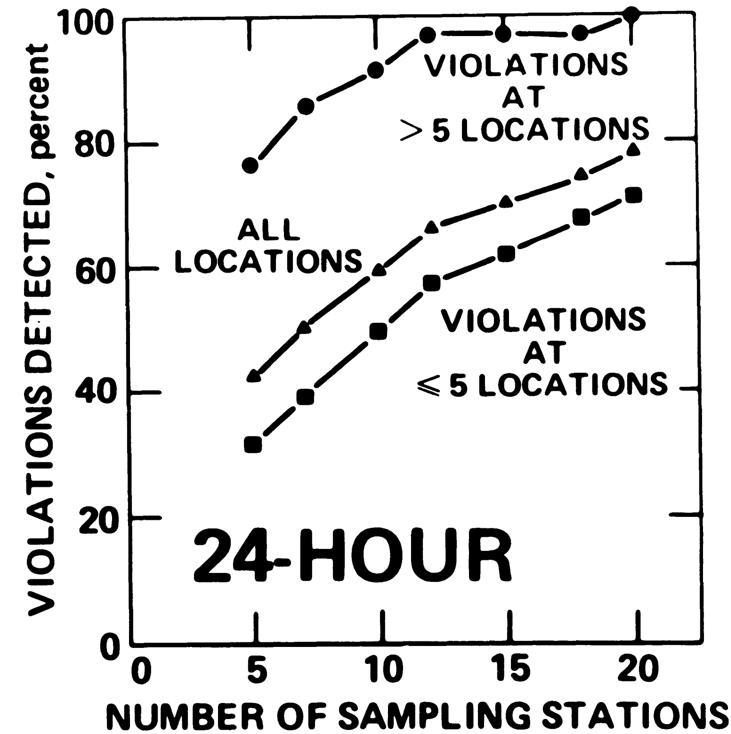


Figure 5.9 Percentage of detected violations of the 24-h SO_2 air quality standard as a function of the number of sampling stations (Godfrey *et al.*, 1976). *See* text for further details

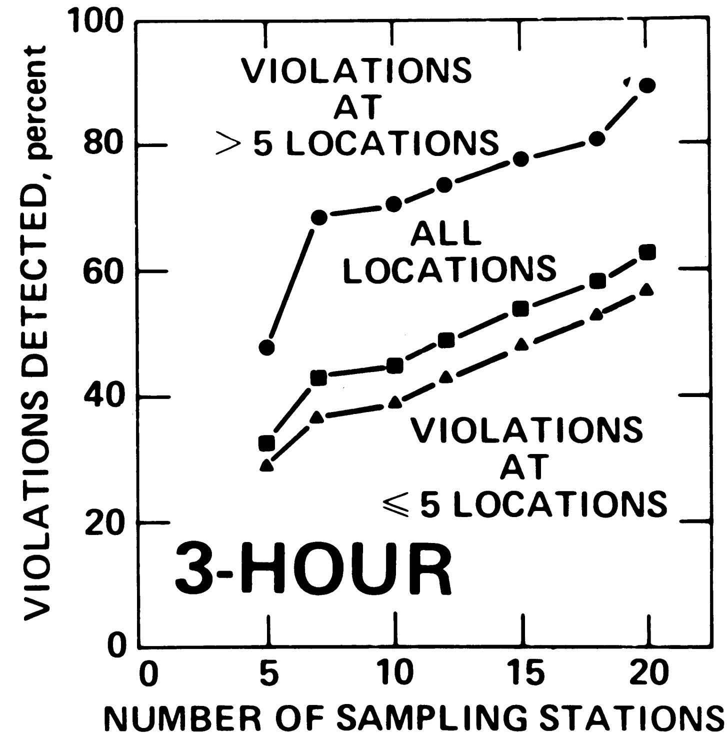


Figure 5.10 Percentage of detected violations of the 3-h SO_2 air quality standard as a function of the number of sampling stations (Godfrey *et al.*, 1976). *See* text for further details

increased, as would be expected. For occasions when violations occurred concurrently at more than five of the 180 sites (uppermost curves), the detection frequency was much greater than on occasions when there were violations at less than five sites (lowermost curves).

Finally, Godfrey *et al.* compared their 12-station and 18-station networks with networks of similar sizes but with all the stations equidistant on a circle 2 km from the source. The results given in *Table 5.10* indicate that for this simulation, a ring of stations 2 km from the source performed as well as the carefully selected network. However, the authors do not wish to speculate on whether this result can be generalised.

A second methodology has been described by Noll and Miller (1977) and Noll *et al.* (1977). In this case too, a large power station was used as the example, and an associated climatology was available. The first step in the analysis was to identify the meteorological situations that caused high ground-level concentrations (*see Figure 5.11*), and to estimate their

Table 5.10 Violations detected with selected sampling locations compared with uniformly spaced sampling locations (Godfrey *et al.*, 1976)

	24-hour		*3-hour*	
No. of days (periods) with violations	139		521	
	Number of days detected	*Percentage detected*	*Number of periods detected*	*Percentage detected*
Twelve selected locations[a]	93	66.9	252	48.4
Twelve uniformly spaced (every 30°) locations[b]				
starting with 10°	73	52.5	258	49.5
starting with 20°	82	59.0	274	52.6
starting with 0°	92	66.2	282	54.1
Eighteen selected locations[a]	104	74.8	301	57.8
Eighteen uniformly spaced (every 20°) locations[b]				
starting with 10°	95	68.3	330	63.3
starting with 0°	105	75.5	353	67.8

[a] At various downwind distances. [b] At a downwind distance of 2 km.

frequencies of occurrence for each wind direction. As indicated in *Figure 5.11*, there is a range of distances associated with each kind of meteorological condition, and this leads to the schematic representation of a single situation shown in *Figure 5.12.* For a single meteorological case and wind direction, the zone within which a maximum concentration might occur is represented by the shaded area (plus the enclosed part of the ellipse). This is called a *potential monitoring zone* by Noll *et al.* But one station located in the centre of this zone will not cover the entire zone; in fact, even if a tolerance of 20% is permitted in the estimate of predicted maximum concentration, a single station will cover only the area given by the ellipse, called the *coverage area of the station.* The tolerance value of 20% can of course be modified as desired, with a consequent change in the size of the ellipse.

Next a *coverage ratio* is defined, *viz.* the ratio of the *coverage area* to the *area of the potential monitoring zone.* This ratio gives the probability that a monitoring station located within the coverage area will have a concentration of at least 80% of the predicted maximum concentration.

Suppose now that this particular meteorological situation occurs N times a year, and that the monitoring station is to be sited in such a way that it will detect 80% or more of the peak concentration n times ($n < N$) with 99% confidence. The solution to this statistical problem is straightforward (*see*

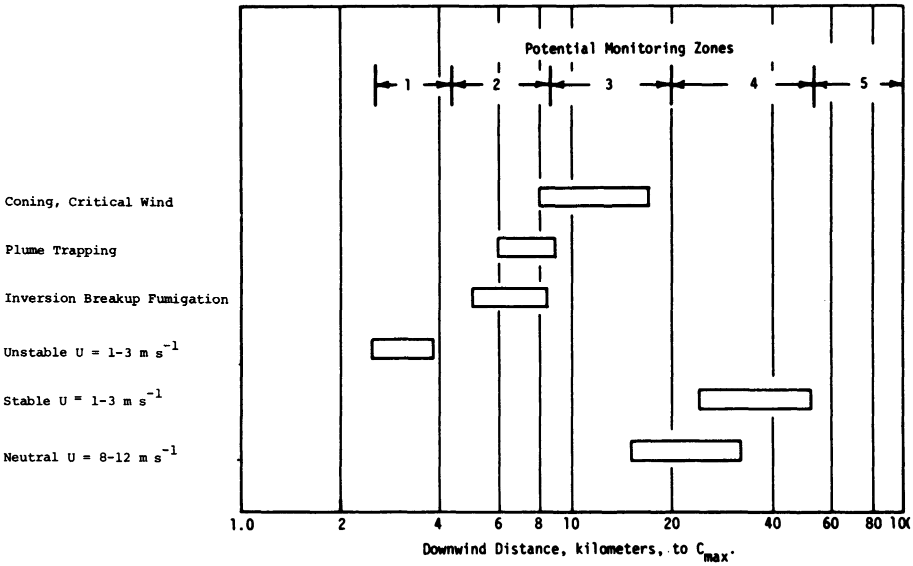


Figure 5.11 Identifying potential zones of maximum ground-level centre-line concentrations C_{max} downwind of a point-source (Noll and Miller, 1977). U is the wind speed

Noll *et al.*, 1977; Noll and Miller, 1977) using the Gaussian approximation to the binomial distribution. The results can be presented in the form of a nomogram such as *Figure 5.13*. For example, if a fumigation occurs 20 times a year with a given wind direction, then a monitoring station located as in *Figure 5.12* will detect at least 80% of the predicted maximum concentration about 2, 8 and 16 times for coverage ratios of 0.35, 0.7 and 0.95, respectively, with 99% confidence.

Some interesting applications of Noll's method have recently been given (Hilst, 1978). With respect to the design of a monitoring network around a power station, the following question is of importance: what are the number and locations of stations required to detect hourly average maximum concentrations to within ±20% of their true values for 80% of the time? Noll's technique leads to the conclusion that a fixed network of 40 stations within 20 km of the source (assuming uncomplicated terrain) would suffice. (But *see* also Chapter 6, section 6.1, in which it is suggested that the number could be reduced by using mobile samplers.)

Based on one year of hourly meteorological observations, and for a plume model at distances of up to 30 km from a chimney, Noll's method was used to determine the reduction in the frequency with which maximum concentrations would be observed as grid points were selectively removed from the

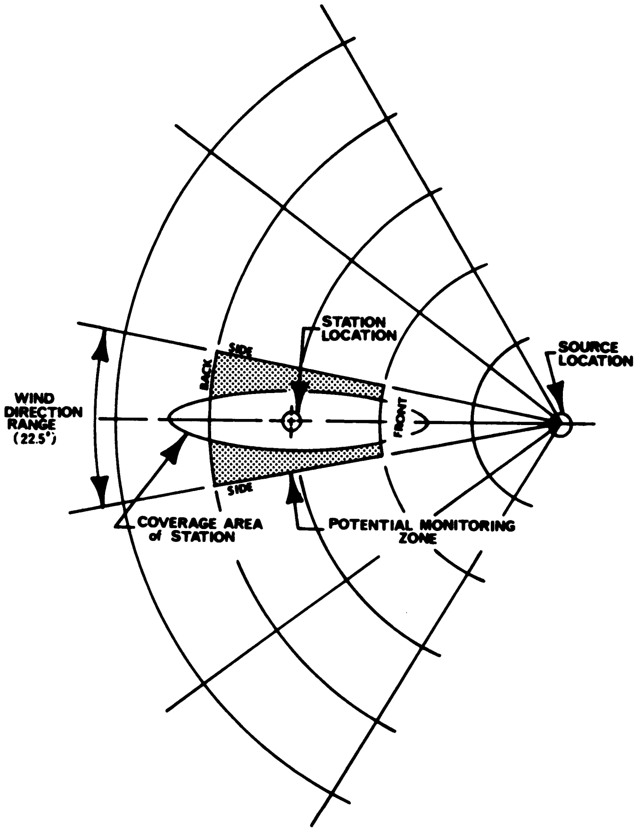


Figure 5.12 Schematic representation of the coverage area of a single monitoring station directly downwind of a point-source, for one of the potential zones shown in Figure 5.11 (Noll *et al.*, 1977). *See* text for further details

network. The basis for removing grid points was the frequency with which maxima occurred at a grid point; that location with the lowest frequency was removed first, etc.

Figure 5.14 shows the frequency with which hourly average concentrations exceeding 600 $\mu g\ m^{-3}$ (0.20 ppm) would have been detected by a network of N stations, $N = 0, 1, 2, \ldots, 26$). The figure indicates that a network of 20–25 stations would have detected these maxima (within ±20%) for 80–90% of the time.

Figure 5.15, based on data for a different chimney, assesses the number of stations, N, required to measure any designated maximum concentration (χ_{max}) to within a fixed fraction (ε) of its true value for any selected percentage of the time $f(\tau)$, where $\tau = 1$, 3 and 24 h (Hilst, 1978). For example, a network of forty stations detects the maximum hourly and 3-hourly concentrations within 20% of their true values for 80% of the time.

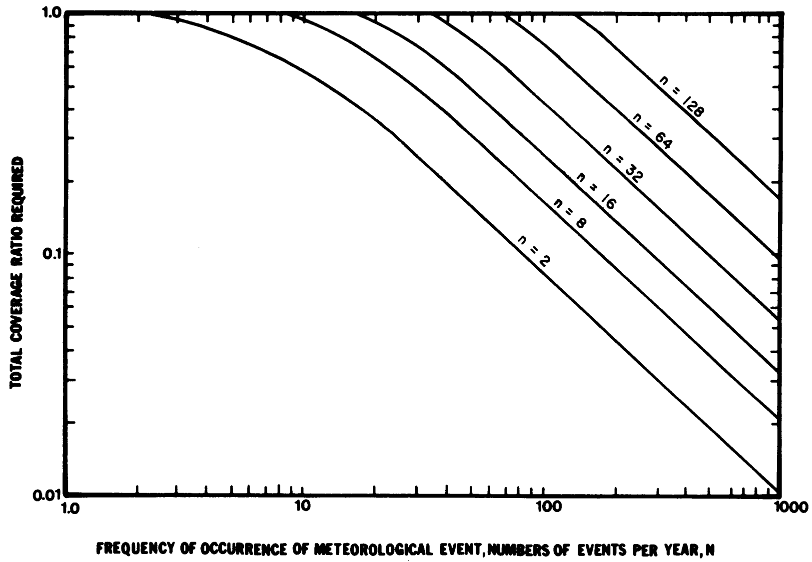


Figure 5.13 Nomogram giving the coverage ratio required to observe a maximum ground-level concentration a total of n times per year with 99% confidence versus the number N of occurrences of meteorological conditions that cause this maximum (Noll *et al.*, 1977)

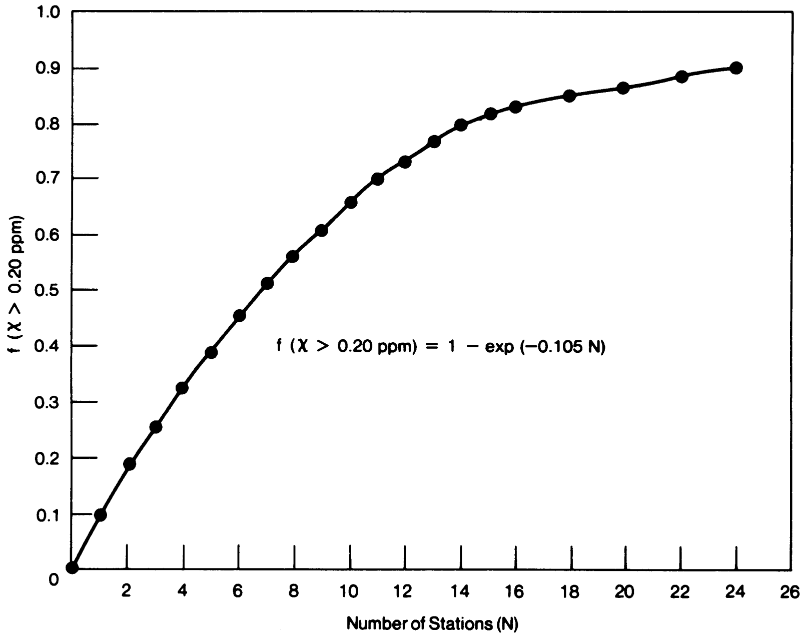


Figure 5.14 The frequency $f(\chi)$ with which hourly average concentrations χ exceeding 600 $\mu g\ m^{-3}$ (0.20 ppm) would be detected by a network of N stations within 30 km of a power station chimney (Hilst, 1978)

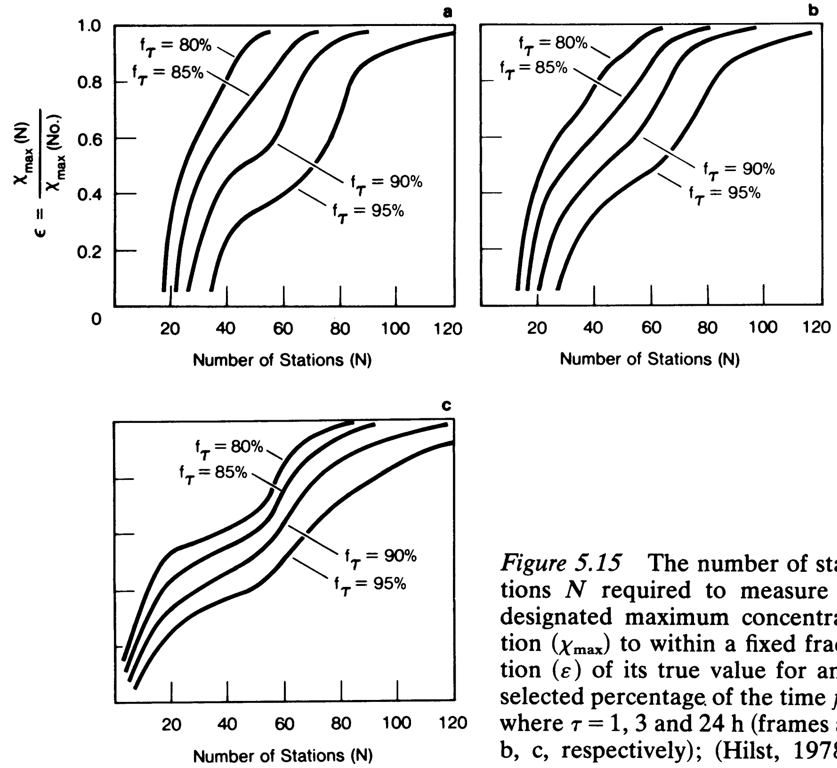


Figure 5.15 The number of stations N required to measure a designated maximum concentration (χ_{max}) to within a fixed fraction (ε) of its true value for any selected percentage of the time f_τ, where $\tau = 1$, 3 and 24 h (frames a, b, c, respectively); (Hilst, 1978).

Provided that the mesoclimate can be modelled, this approach to network design could be used over irregular terrain.

5.3.3 The use of multiple-source models in designing monitoring networks

5.3.3.1 Introduction. In principle, the methods described in section 5.3.2 can be applied to multiple as well as to point-sources. The ground-level concentration field resulting from each source can be determined, and the total loading at any given monitoring station or grid point can be found by summation.

In practice, several difficulties arise: (1) emission inventories are somewhat inaccurate as input for models predicting hourly concentrations; (2) multiple sources are usually associated with built-up areas, where the regional flow patterns are often distorted.

5.3.3.2 The use of wind-direction frequencies. The method of Hougland and Stephens (1976) described in section 5.3.2.2 can be extended to the case of multiple sources. The calculations described there are repeated at each grid point in relation to each source. Equation (5.14) is then modified to

$$A_{ijk} = \mathrm{FREQ}(k) * \mathrm{STR}(i) * [1/(1+D_{ij})] \qquad (5.15)$$

where A_{ijk} is the coverage factor for the ith source, the jth monitoring site and the kth downwind sector from source i; STR(i) is the strength of source i. When the grid point is within an area source, D_{ij} is set equal to zero.

The sites with the largest values of A_{ijk} could be selected for monitoring (a *monitor-oriented procedure*). To improve the geographic distribution, monitors would not be placed at adjacent grid points.

An alternative is the *source-oriented procedure*. For each source and wind direction, the grid point with the largest value of A_{ijk} is determined. Then with the restriction that there can be only K stations, where K is smaller than the number of sources, an optimal solution is sought. Hougland and Stephens make use of the Ignizio procedure, which selects sites one at a time, and then applies a technique that removes stations no longer justified because of subsequent additions. A computer program is available.

Examples are shown in *Figures 5.16* and *5.17* of source-oriented and monitor-oriented networks for suspended particulate matter. The wide distribution of stations in the source-oriented case is to be noted. The objective then is to give the best possible indication of general air quality throughout the region. For the monitor-oriented strategy, on the other hand, the objective is to maximise the likelihood that the highest concentrations will be detected by the network.

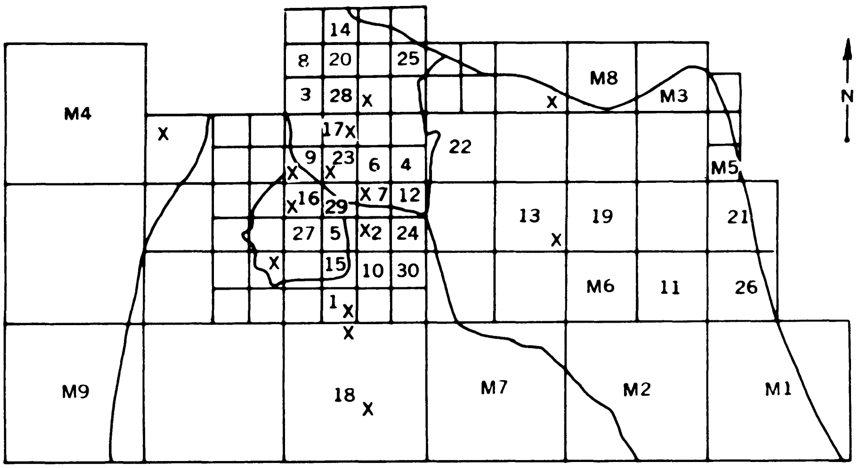


Figure 5.16 A source-oriented monitoring network in Virginia. Crosses represent locations of existing stations and numbers indicate priorities in selecting stations. Symbols M1, M2, . . . , M9 represent sites with the smallest coverage factors, M1 being the very smallest; these locations would not be selected for monitoring (Hougland and Stephens, 1976)

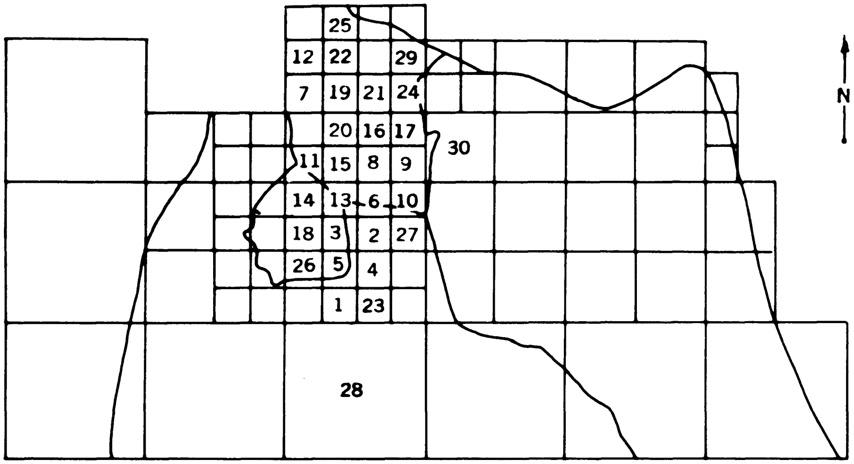


Figure 5.17 A monitor-oriented network in Virginia. Numbers indicate priorities in selecting stations (Hougland and Stephens, 1976)

5.3.3.3 The use of diffusion–transport models. Diffusion–transport models can be applied to network design in the following four ways, the most appropriate approach depending on individual circumstances (particularly the objectives for monitoring).

(1) The weighting of concentrations by frequencies. Liu *et al.* (1977) have designed a CO monitoring network for regulatory purposes. The objective was to minimise the possibility of non-detection of a violation in air quality standards.

Emissions of CO were estimated from traffic density data for a hypothetical urban area 5 km × 5 km. This information was used in a multiple-source diffusion model to estimate the spatial field of CO concentrations for each of various hours of the day and various meteorological patterns.

Liu *et al.* (1977) then defined a *Figure-of-Merit* function $F(i, j)$ as follows:

$$F(i,j)=\sum\begin{pmatrix}\text{concentration at grid point } i, j\\ \text{under meteorological pattern } k\end{pmatrix}\cdot\begin{pmatrix}\text{probability of}\\ \text{meteorological pattern } k\end{pmatrix} \quad (5.16)$$

F is thus the mean CO concentration weighted according to its frequency of occurrence at each grid point. In some applications, only cases in which air quality standards are exceeded may be important; equation (5.16) is then modified by counting violations.

The next step was to plot grid-point values of F on a map, and to draw isopleths. Preferred monitoring sites were then those locations with high F values which were not adjacent to other high values. In the Liu *et al.* application, the entire process was computerised.

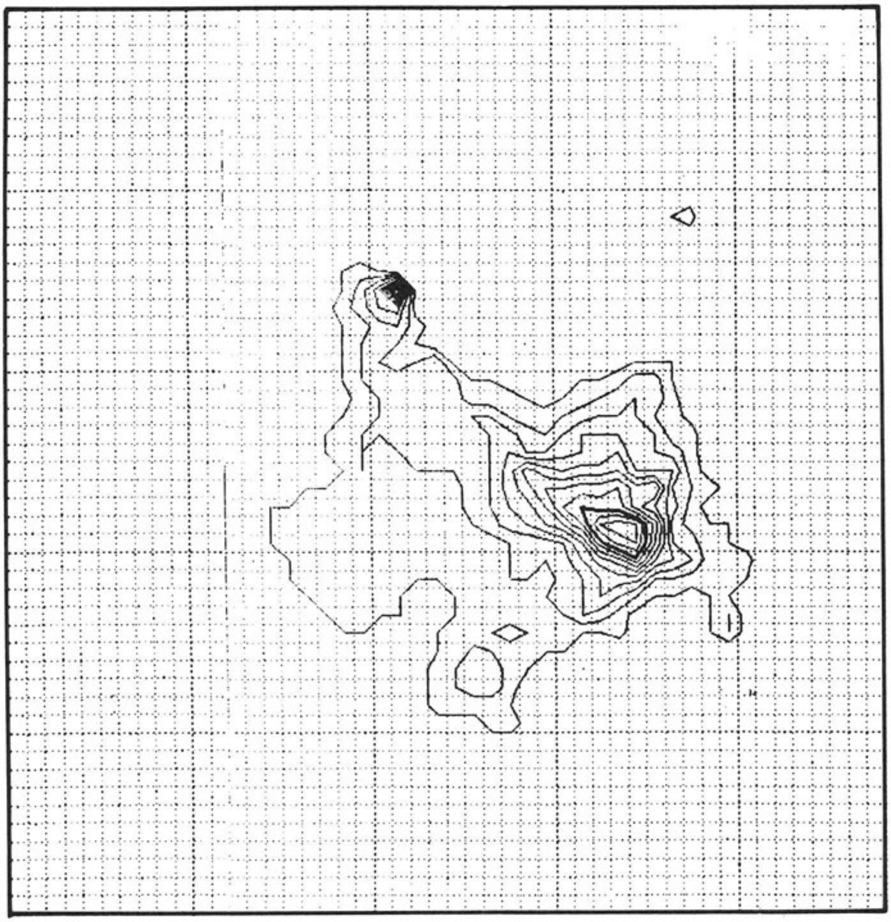


Figure 5.18 A hypothetical Figure-of-Merit diagram; *see* equation (5.16) in text. The area in the diagram is 5 km × 5 km. Isopleths are in increments of 1 ppm of CO (Liu *et al.*, 1977)

A hypothetical example of a Figure-of-Merit diagram is given in *Figure 5.18*. The resulting choice of monitoring sites (ranked alphabetically) is shown in *Figure 5.19*.

Behar *et al.* (1975) have considered this same problem and pollutant. They began by selecting a few critical meteorological episode situations, and they estimated their relative frequencies of occurrence. A multiple-source diffusion model was then applied to each set of circumstances, and the ground-level concentration patterns were estimated. The method of Liu *et al.* was then used.

This variant reduces computer costs.

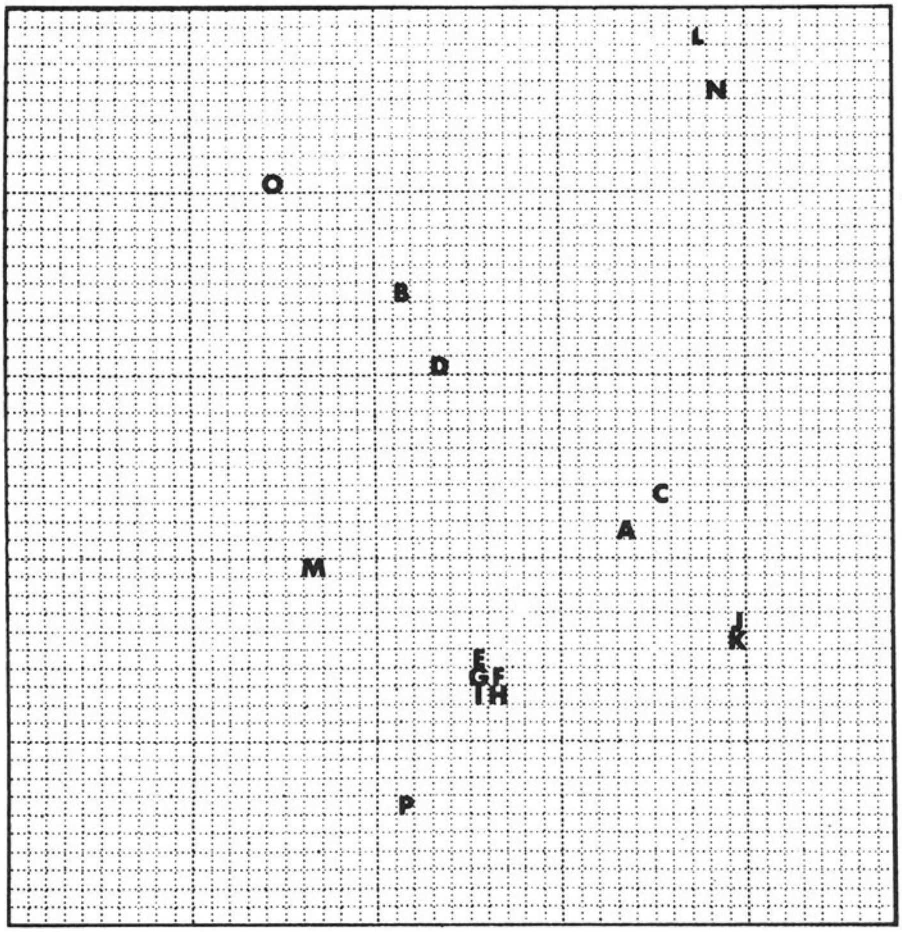


Figure 5.19 Alphabetical ranking of potential monitoring sites for data in Figure 5.18. Preferred sites are those with high values in Figure 5.18 and which are not adjacent to monitoring sites already selected (Liu *et al.*, 1977)

(2) *Comparisons of sets of validation statistics.* After a multiple-source air pollution model has been calibrated and validated with data from a network of stations in a given area, the following strategy could be employed to reduce the number of stations in that area. With the same data base but with one station in turn removed from the network, the model could be recalibrated and revalidated. The stations could then be ranked according to their relative effects on validation statistics. This approach has not been tried and is not very practical because of excessive computer costs.

(3) *Ability of a monitoring network to detect trends.* Questions like the following are sometimes posed. (a) Given an existing network, which station or group of stations is most sensitive to changes in emissions? (b) What are

the most appropriate design criteria for a network established to detect long-term trends in air quality? In both these cases, the site predicted to have the largest net change may not necessarily be the best one to choose; if its variance is also large, the detection of a trend may be statistically difficult.

A recommended approach is to undertake a sensitivity analysis, which requires only that a validated multiple-source air pollution model be available for the region. The analysis consists of simulating changes in emissions such as a reduction in CO emissions from automobiles, the establishment of a new industrial zone, or a change from oil to gas or coal as a major energy-source for the region. The output of the simulation is a frequency distribution of concentrations, one set for each of a designated number of grid points. For these data, mean values and variances for present and simulated future emissions are then compared. The simulation may also provide an answer to the following type of question: how many measurements must be made in order to detect a change of x% in source strength, with a statistical confidence of y%?

(4) Ability of a monitoring network to detect a phenomenon of a particular scale. Related to (3) is the question of whether an existing air quality network is capable of detecting an unusual event of a particular scale, e.g. a forest fire or an accidental release, for only an hour or so, of major quantities of pollutants from a chimney. An answer to this question will of course be given in probabilistic terms.

Eddy (1974) has suggested that the best strategy is to simulate the phenomenon being investigated with a numerical model to estimate the diffusion of the plume or cloud through the region of interest. On averaging the results over several repetitions, the detection capability of an existing network can be estimated.

5.4 Combination methods from both statistical and prediction techniques

5.4.1 A general method

The general method described in this subsection requires a data base of predicted and observed concentrations from a network of stations. The way in which the predictions are made is unimportant, the only requirement being that the forecasts be better than those arising by chance. Prediction schemes include the following: (1) predictions obtained from multiple-source models; (2) predictions based on 'climatological' average concentrations for the site, the time of day, the day of the week, and the month; (3) predictions based on persistence (the concentration field for the next time step is assumed to be the same as the present field); (4) predictions based on Markov chains, autocorrelations, or other time and space interdependencies.

The general method consists of (a) computation of variances of the differences between predicted and observed concentrations, and (b) the construction, wherever possible, of smoothed isopleths of this variance field. If isopleths can indeed be drawn, then they provide a basis for modifying (expanding, contracting, relocating stations) the network to meet almost any objective and criterion.

In the more likely case in which network density is insufficient to permit construction of isopleths, a comparison of variances will still provide guidance in network design. For example, stations with the largest (smallest) variances are probably the most (least) important.

Several variations of this methodology have been described, e.g. by Seinfeld (1972), Brewer and Moore (1974), Eddy (1974), Vukovich (1975), Shannon (1976), Gribik *et al.* (1976) and Gustafson *et al.* (1976). As an example, Seinfeld (1972) has considered a network that should be as sensitive as possible to changes in emissions from major sources. From a transport–diffusion model, Seinfeld computed the differences between predicted and observed concentrations, assuming that the differences were normally distributed with zero mean, and that differences at different locations but at the same time, or at the same location but at different times, were independent. Seinfeld then proposed a computational algorithm that would permit monitoring stations to be withdrawn from or added to a network in such a way as to provide optimal least-square estimates of source strengths.

Seinfeld did not apply this method to a multiple-source problem. However, he did include two illustrative examples.

(a) In a one-dimensional heat flux system, in which the objective of monitoring was to minimise the error of estimate of the numerical value of the thermal diffusivity, the method predicted that if a single additional sampling station were to be added, it should be located exactly half-way between two existing stations; if two stations were to be added, they should be one-quarter and three-quarters of the way along the line joining the two existing stations.

(b) For an elevated line source of pollution, assuming power-law forms for the vertical profiles of wind speed and eddy diffusivity, the optimal location for a single monitoring station was predicted to be at the downwind position where the maximum ground-level concentration would occur. This prediction is as might be expected, which lends support to the method.

As another example, Vukovich (1975) developed design criteria for deciding upon a network density in St. Louis, Missouri. Applying the method to wind observations, Vukovich first used a regression equation to predict the wind field, and then he computed the correlation coefficients between predicted and observed values. *Table 5.11* shows that the correlation coefficient increased in value from 0.5 to 0.67 as the number of anemometer stations increased from thirteen to nineteen.

Table 5.11 Correlation coefficient (R) between predicted and observed wind speeds versus station number where a thirteen-term model was used to describe the wind field (Vukovich, 1975)

Number of stations in optimal network	R
13	0.50
14	0.63
15	0.65
16	0.65
17	0.66
18	0.67
19	0.67

5.4.2 The use of a multiple-source model to estimate the space correlation function

Buell (1975) has suggested that a multiple-source model might be suitable for estimating the form of the space correlation function, which in turn could be used to select an optimal network design: *see* section 5.2.5. To test his ideas, Buell used a simplified model of St. Louis, Missouri, which contained only twenty-one sources. Even so, however, the correlation field was so irregular that the raw statistics had to be smoothed. At this point in the analysis, Buell's interest shifted to a determination of the measurement error α^2, and of the importance of small-scale siting effects. This led to general considerations of statistical significance and of the applicability of factor analysis (section 5.2.11) to problems of this type. Although the original goal was not achieved, *viz.* estimation of the space correlation function with sufficient precision to be useful in network design, the approach is worth further consideration.

Not only space correlations but also structure functions (section 5.2.3) should be studied in this way. In particular, the assumption of a homogeneous isotropic field could be tested for various simple configurations of ground-level sources. This would be a valuable analysis to undertake.

A possible complication has been pointed out by Seinfeld (1972), *viz.* that the error field for multiple-source models may not be normally distributed. This could lead to bias in the estimates of the space correlation and structure functions.

5.4.3 Optimisation of networks to detect multiple point-source violations

Given the locations and approximate strength of major point-sources within a region, Bronin (1979) has considered ways of optimising an air quality network in terms of its capability to distinguish the relative contributions of individual sources. In particular, an ability to detect violations in emission standards is required.

Bronin assumes that the following information is available for the analysis: (1) locations and approximate strengths of major point-sources; (2) an existing air quality monitoring network; (3) meteorological information, particularly the wind field; (4) a multiple-source air pollution model. For each monitoring station, the first step is to formulate a set of source-oriented diffusion equations, each with source strength Q_i and each contributing C_i to the observed concentration C at that station. The unknowns are Q_i and C_i; the known quantity is C, the sum of C_i. The next step is to seek a combined solution for all equations at all monitoring stations, the source strengths being treated as unknowns but the emission inventory providing an initial guess to reduce the computer time required to solve this 'inversion'-type problem numerically. After several iterations, the source-strength field should begin to converge.

The investigator is now ready to consider the problem of optimising the existing network, assuming that only one monitoring station is to be located in a grid square, and that the total number of stations is finite (equal to or slightly greater than the present number). First, the inferred source strengths Q_i, together with the meteorological fields, are used to obtain a predicted concentration field throughout the region. Then the siting of the monitoring stations is changed randomly, and additional estimates of the array of source strengths are obtained. A root-mean error is estimated for each permutation of the siting of sampling stations, the minimum error case being identified with optimal network design. This analysis is repeated for each of several meteorological situations, and the results are compared. (Presumably the network design could vary significantly from one weather pattern to another.)

Bronin (1979) has not provided any experimental validation of his proposals but, in principle, the methodology is worth pursuing.

5.5 Design of monitoring networks to meet multiple objectives

Smith and Egan (1979) have considered an extremely important question: the optimisation of monitoring networks to meet multiple objectives. Frequently, a programme manager has budgetary restrictions, which require, for example, that pollutants with quite different source characteristics be monitored at the same sampling stations, or that multiple-source pollution models be validated with data collected for the quite different purpose of detecting violations in air quality standards.

Smith and Egan list some of the factors to be considered when studying this difficult problem:

regional background air quality
number of major sources

separation distances between sources
complexity of meteorological flow
pollutants to be monitored
averaging times of air quality standards most appropriate for each pollutant
objectives (separately for each pollutant)

As additional considerations, the following factors may limit the availability of sites:

inaccessibility
lack of power
inadequate security
unavailable private property

Finally, the following factors should be added, but should be given less weight:

comparative maintenance costs
public relations aspects

For many of these factors, overlay maps can be prepared to help in the identification of exclusion zones and of preferred grid squares to meet single monitoring objectives. But there remains the problem of ranking grid squares with respect to multiple monitoring objectives.

Smith and Egan (1979) suggest that optimisation be undertaken for each objective; hopefully, there will be a small common subset of grid squares where sampling stations could be located to meet most if not all of the objectives. In the Smith–Egan system (1979), a simplification of the Miller and Noll (1976) method is used (*see* section 5.3.2.3), followed by application of the Hougland and Stephens (1976) monitor-oriented procedure (*see* section 5.3.3.2).

For multiple objectives, the relative importance of each objective must be specified, and a weighting scheme assigned. In this connection, there is value in performing a *sensitivity analysis* to determine if a change in weights has an effect on the ordering of preferred monitoring sites. This technique is widely used in the fields of industrial engineering and applied system analysis.

6

Other topics

6.1 Portable and mobile monitoring systems

Networks of fixed sampling stations may be supplemented with semi-portable trailers or automobiles. Even bicycles have been used in some cases (Kleiner and Spengler, 1976). These supplementary systems can help in meeting the following objectives: (1) the investigation of very localised complaints; (2) the selection of permanent monitoring stations; (3) the comparison of air quality levels before and after a new source is introduced into a region, or an existing source is modified; (4) plume chasing; the determination of cross-wind spread of pollution from a point-source, and the detection of maximum ground-level concentrations; and (5) studies of health effects (personal monitors are sometimes carried by groups of volunteers).

Some of the difficulties associated with such systems include the following. (a) Measurements can usually be made only on roads, which may not be at right angles to the average centre-line direction of a plume. (b) For pollutants emitted from automobiles and trucks, the concentrations vary greatly along and across the road. (c) The moving vehicles stir the air and cause re-entrainment of particulate matter. (d) Because of meteorological variability, the problem of obtaining representative space and time 'snapshots' of the pollution field requires careful consideration. In automobile sampling, the traverses may need to be repeated several times before smooth isopleths can be drawn.

Referring back to Noll's technique for designing a monitoring network around a power station (Chapter 5, section 5.3.2.3), it will be recalled that forty stations would be required (assuming uncomplicated terrain) to meet the design specifications for the system (Hilst, 1978). However, Noll estimates that this network could be reduced to about fifteen stations if three mobile stations could be added to the system, each mobile operating at a site chosen daily on the basis of the weather forecast (Hilst, 1978; Noll, 1978). Mobile monitoring is particularly effective at sites where high concentrations occur only infrequently. For each site, however, the relative cost-effectiveness of fixed versus mobile stations would need to be determined.

In another application, Jacko (1976) has studied five power stations in Indiana, with four portable trailers each equipped to measure suspended particulates, SO_2, wind and temperature. The design strategy was to deploy all four trailers around one power station for a week, and then to move on to another plant. Over a one-year period, ten weeks of data were obtained in the vicinity of each plant.

The four trailers were sited so that one was upwind and three were downwind of a power station. As the wind direction shifted, the trailers were moved to keep them aligned with the plume centre-line. In this way, sufficient data were collected to demonstrate the log-normal nature of the SO_2 frequency distributions and to distinguish different power stations and downwind distances.

For multiple-source monitoring, Stratmann and Exfeld (1968) used a random sampling strategy in the Nordrhein-Westfalen region. Sulphur dioxide was monitored with a portable sampler at sites selected randomly from grid points spaced at 1-km intervals. (The data from this network were used to estimate area-mean values and variances.)

Finally, mention should be made of a study by van Egmond *et al.* (1976) in The Netherlands, for which there was already a network of about 220 fixed stations for monitoring SO_2 over an area of $200 \times 300\ km^2$. A van for monitoring SO_2 was equipped with a navigational system that permitted the position of the vehicle to be known accurately. In the particular study described here, the objective was to determine the form of the space–time correlation functions across the region for separation distances ranging from 0.6 km to 40 km, to provide a rational basis for interpolation. For a few initial experiments undertaken during steady-state conditions, the results were encouraging, but were strongly dependent upon the synoptic weather pattern. On 18 February 1976, for example, the regional flow was south-easterly, and the space correlation function was relatively high; on 26 February 1976 the flow was south-westerly, and the correlations were low, never exceeding 0.4.

6.2 Remote sensing

Supplementary monitoring can be undertaken with remote sensing devices such as lidar, sodar and laser; *see*, for example, Perry and Young (1977). The advantages of remote sensors are that (1) space-integrated values can sometimes be measured over relatively long path-lengths, (2) vertical profiles can sometimes be obtained—this could not otherwise be done without costly balloon, aircraft or rocket soundings, (3) remote sensors can help in 'plume chasing' and in estimating source strengths.

The disadvantages are that (a) because remote sensors generate large masses of data very quickly, careful consideration must be given to questions of data assimilation and analysis, (b) in some cases, frequent instrument calibration is required, and there is need for special training in electronics, (c) data from remote sensors cannot be related directly to air quality standards or criteria (the literature on effects relates mostly to air quality measurements made at fixed stations).

6.3 Health-related monitoring

6.3.1 Introduction

Human populations are mobile, and some members spend more than 80% of their time indoors. The design of health-related air quality monitoring systems therefore introduces special complexities. Several of the methods described in Chapter 5 are sometimes relevant, e.g. that of Darby *et al.* (1974) in section 5.2.12. Before designing a network, however, the goals of the epidemiological study should be carefully reviewed. This should take place at a very early planning stage.

The research methods used in epidemiology are of three main types: (1) retrospective analysis, (2) prospective analysis, and (3) interventions (*see* below for descriptions of these terms). The most appropriate air quality monitoring system will clearly be different in each case, although design criteria are still rather uncertain.

6.3.2 Retrospective analysis

In this approach, readily available data banks are examined for possible relationships between health indicators and air quality. The analysis usually proceeds in one of the following two ways.

6.3.2.1 Multivariate analysis. Multivariate analysis is frequently used in epidemiological research. Large numbers of variables are cross-correlated in searches for significant statistical relations between air pollution and health. The study populations are drawn from different cities or from different parts of the same city. The health indicators are obtained from mortality records, national censuses, medical data, hospital admission records, etc. The air quality measurements are from single sites or from networks of stations, usually operated by air pollution control agencies.

6.3.2.2 Episode analysis. Air quality frequently varies less from place to place than it does from day to day at a single place. It is therefore sometimes productive to identify spells of unusually poor air quality lasting several days, and to search for short-term anomalies in the behaviour of various health indicators. Because episode conditions usually extend over whole cities or regions, the design of the air quality monitoring network is not very critical; one representative station might be sufficient in some applications.

6.3.3 Prospective analysis

A prospective study is based on sound physiological principles rather than on the availability of historical data banks. Existing monitoring programmes may of course be utilised where relevant but a prospective study may also include the following.

Health-related information
physiological measurements
questionnaires
indirect indicators (e.g. absenteeism from school or work)

Air-pollution information
upgrading of existing networks
personal monitors
indoor monitors
smoking history

Other related information
meteorological
concentration of pollen, spores, etc.
concentration of trace substances in food and drinking water
lifestyle indicators

As in the case of retrospective studies, the emphasis may be either on episode events or on long-term exposures.

6.3.4 Interventions

An example of the intervention technique is the chamber experiment in which the physiological responses of volunteers to controlled exposures of pollutants are measured. The method has not been used outdoors to any extent although in a town with a single major industry (smelter, pulp and paper mill, etc.), the temporary closure of the industry during an industrial strike would permit an intervention-type study. Of course, the socio-economic environment would also be affected by the strike, and this might confound the analysis.

6.3.5 Some further remarks

The design of health-related air quality monitoring systems is still rather uncertain. In particular, because of inadequate information about the personal exposures of people moving about in the urban environment (both indoors and outdoors), the epidemiological literature on exposure–response relations is somewhat blurred. Replicate studies are urgently needed in order to calibrate data obtained from fixed networks of stations in terms of data obtained from personal monitors and from representative indoor environments.

For air pollution control purposes, in which one of the goals is to protect human health, air quality as measured by routine networks of monitoring stations may provide, in some crude sense at least, relevant data for health-protection purposes. The somewhat circular reasoning is as follows: (1) in selecting numerical values for air quality standards, the standard-setters have taken account of the epidemiological evidence about health effects; (2) the epidemiological evidence comes mainly from multivariate regression analyses; (3) routine air quality data have been inputs to these analyses; (4) routine air quality data therefore implicitly relate to standards and to air pollution control programmes.

6.4 Effects-related monitoring (non-human)

A plant physiologist can make a valuable contribution to the process of siting air pollution monitoring stations. Sometimes in fact, vegetation monitoring can supplement or even replace conventional mesoscale and neighbourhood monitoring networks (Harney *et al.*, 1973; Craker *et al.*, 1974; Prinz, 1974; Gruber and Jutze, 1976). Four general approaches are used.

(1) In polluted areas, the degree and areal extent of vegetation damage can be mapped. Some species (sentinels) are more sensitive than others, and/or respond only to specific pollutants.

(2) The absence of particular species may be an indicator of the occurrence of high air pollution concentrations. Lichens and mosses have frequently been used for this purpose; *see*, for example, Hawksworth (1971).

(3) Samples of leaves or needles may be chemically analysed to map the spatial distribution of concentrations of particular substances of interest. Some species (accumulators) have more rapid uptake rates than others. Moss (1975) examined the excess sulphur in arboreal and herbaceous samples at various distances from a source area, although he did not find a single relation between concentrations and distance.

(4) Moss bags are efficient and economical collectors of particulate matter. It has been found that they may be used to obtain the fine-scale detail of the weekly or monthly depositions (rather than the

concentrations) of many trace substances, e.g. lead, nitrates (Goodman and Roberts, 1971).

In all these cases, a number of problems must be admitted, and biological information must usually be regarded as supplementary, requiring confirmation by other means.

(a) Even when grown under identical conditions, a single-species population has inherent variability in its response to pollution.
(b) On the mesoscale and even on the neighbourhood and microscales, there are significant gradients in all the environmental variables, e.g. hours of sunlight, soil texture and moisture, air temperature, humidity, and wind. The effects of pollution on vegetation are modulated by these factors. (Some of the confounding influences may be removed by growing plants in uniform soils that are regularly fertilised and moistened at the same rates.)
(c) Without direct monitoring of wind and air quality, the plant physiologist often has difficulty in knowing whether vegetation damage is due to a single fumigation event or to more modest stresses persisting through a growing season.
(d) Vegetation damage may be caused by several pollutants, sometimes acting synergistically; for example, the threshold for SO_2 damage is lowered by the presence of NO_2 or O_3. Injury is therefore not a certain predictor of concentrations of a specific substance.

In addition to vegetation surveillance, other kinds of effects may be monitored. The rate of cracking of rubber strips is an indicator of oxidant concentrations while the tarnishing or peeling of certain kinds of paint can reveal the presence of specific pollutants such as fluorides or H_2S. An 'effects package' is included in some monitoring programmes (Prinz, 1974; Gruber and Jutze, 1976), the objective being to obtain an indication of the long-term impact of the urban and/or industrial atmosphere on materials.

6.5 Monitoring of the meteorological fields

For regional and global scale studies, meteorological networks are already in place through the WMO World Weather Watch (WWW). Although these networks may not be optimal for air quality applications, they are not readily modified, the primary subscribers to WWW being the national weather forecasting services.

For mesoscale and urban studies, special meteorological networks may be required. After reviewing the objectives of the programme, the meteorologist can begin to develop an optimal system, with the aid of many of the methods and rules-of-thumb described earlier for the design of air quality networks.

6.6 Monitoring of emissions

Source-strength inventories are important components of air quality management and network design strategies. The inventories usually have a rather coarse time resolution (average annual or seasonal emissions, and perhaps a weekday versus weekend comparison). Hour-by-hour changes in emissions from multiple sources cannot be estimated with sufficient accuracy to be considered as a useful part of the monitoring programme.

On the continental and global scales, natural emissions often become important. But in this case, too, the task of estimating source strengths, except possibly in terms of average seasonal or annual values, has not yet been solved.

For a strong point-source (smelter, power station, etc.), hourly emissions can be estimated with reasonable accuracy by various emission-factor techniques. From a knowledge of meteorological conditions, the concentration pattern around the chimney could then be predicted, in principle, without a ground-level air quality monitoring programme, except for occasional measurements to verify that the model continues to behave satisfactorily. In practice, this approach has rarely been used, has not yet been demonstrated to be cost effective, and does not allay the concerns of citizen groups where they exist.

6.7 Cost effectiveness

Several scientific papers, e.g. those by Hickey *et al.* (1971), Brewer and Moore (1974), Miller and Noll (1976), Pickett and Whiting (1978a,b), deal with the problem of minimising the costs of air quality monitoring systems, while at the same time meeting specific goals and tolerances. When there is a requirement to monitor several pollutants and/or to consider more than one objective, the optimisation problem becomes difficult but, in principle, the methods described in Chapter 5 may be applied. An additional consideration in some cases is the frequency of observations, e.g. whether to measure suspended particulate concentrations every day at only a few stations or once a week at many stations.

If the terms of reference for a network design study are carefully specified at the outset, the investigator will have taken a major step forward in seeking a solution. This is the missing link in most attempts at optimisation of networks.

6.8 Integrated multi-media monitoring

There are a number of applications in which the atmosphere is only one of a number of biospheric compartments of interest. For example, heavy metals enter the human body not only by inhalation but also in food and water. In such cases, the idea of an integrated multi-media monitoring system is attractive. The main benefits are (1) usefulness in the development and testing of environmental models, e.g. of dose–response relations, or of biogeochemical cycling, and (2) cost effectiveness. For example, in studies of the effects of acid rains on biological life in a lake, it is easier to interpret the data if wet deposition rates are measured at the site rather than interpolated from a network of precipitation chemistry gauges, the nearest station being 100 km away.

On the global scale, design criteria for integrated multi-media monitoring systems are already being considered. Scientists in the USSR have been particularly active in this field (Izrael, 1980), and the WMO has held an International Symposium on Multi-Media Global Monitoring of Environmental Pollution (at Riga in December 1978).

7

Some practical guidelines on network design in urban and rural areas

7.1 Introduction

Judicious selection from amongst the methods and techniques contained in Chapters 4 and 5 may assist in the design of air quality monitoring systems. The aim of this chapter is to further this process, the subject matter being organised according to specific classes of pollutants, and particular objectives.

7.2 Monitoring for CO

Concentrations and concentration gradients of CO are highest in the vicinity of busy streets, tunnels and highways. The gradients vary in both time and space, on the micro and indeed also on the neighbourhood scale. This creates siting problems even when monitoring objectives are carefully specified.

An example of a concentration field in a city canyon was given in Chapter 4, section 4.4.3, while in Chapter 5, section 5.3.3.3, two methods for designing a CO monitoring network were described, those by Liu *et al.* (1977) and by Behar *et al.* (1975). Other relevant papers are by Ott and Eliassen (1973), Perkins (1973), Harrison (1974), Patterson and Record (1974), Ludwig and Kealoha (1975), EPA (1975a), Gilmore and Hanna (1976), Kleiner and Spengler (1976), Miller and Noll (1976) and Ott (1977). Many of these authors have been preoccupied with health-related monitoring, which is beyond the scope of the present review. However, some of the observed and/or modelled microscale and neighbourhood variations in CO concentrations are of direct interest to the problem of site selection. As an example, in the case of a highway in open countryside, with the wind at right angles to the road and for slightly unstable meteorological conditions (Pasquill–Gifford C stability), a line-source model predicts that the concentration of CO diminishes downwind to 80, 60, 40, 20 and 10% of its curbside value at distances of 2, 6, 25, 200 and 625 m, respectively (Miller and Noll, 1976).

Ott (1977) has recently surveyed the mass of experimental data existing for CO and has made some recommendations. Ott visualises a concentration field as in *Figure 7.1*, and he proposes the six types of monitoring stations described in *Table 7.1.* Not all types will be required in every air quality management programme. However, the network designer should be aware of Ott's classification, and should not compromise by choosing a site that is intermediate between any of the types listed in *Table 7.1.* In this connection, the WHO (1977) guidelines mention that for comparability of data from different stations (of the same type), the siting criteria must be strictly followed. If deviations are unavoidable, they should be the same at all stations (of the same type).

7.3 Monitoring for SO_2 and particulates

7.3.1 Emissions from tall chimneys

Some methods for designing a monitoring network in the vicinity of a tall chimney have been described in Chapter 5, section 5.3.2. If the objective is to have a high success rate in detecting air quality violations, then the network must be relatively dense. However, if the control officer needs only

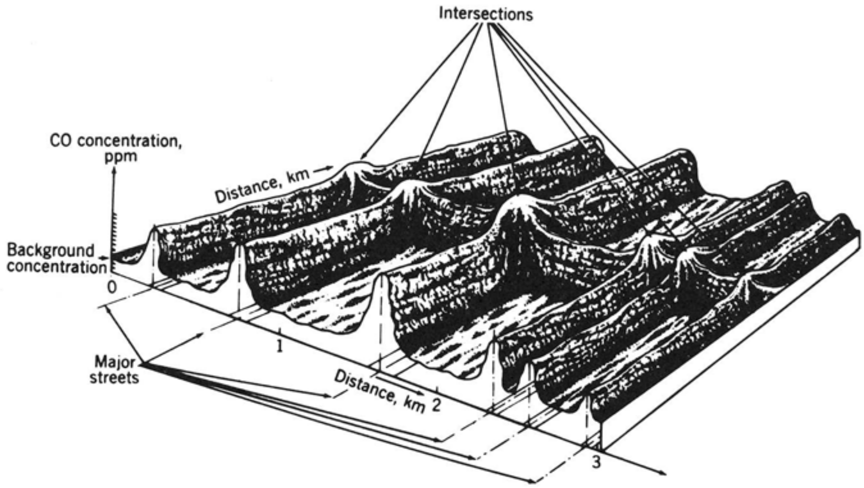


Figure 7.1 Schematic representation of a CO concentration field in an urban area (Ott, 1977)

Table 7.1 Recommended criteria for siting monitoring stations (Ott, 1977)

Station type	*Description*
Type A	*Downtown pedestrian exposure station.* Locate station in the central business district of the urban area on a congested, downtown street surrounded by buildings (i.e. a 'canyon' type street) and having many pedestrians. Average daily travel on the street should exceed 10 000 vehicles/day, with average speeds of less than 6.7 m s^{-1}. Monitoring probe is to be located 0.5 m from the curb at a height of 3 ± 0.5 m[a]
Type B	*Downtown neighbourhood exposure station.* Locate station in the central business district of the urban area but not close to any major streets. Specifically, no street with average daily travel exceeding 500 vehicles/day should be closer than 100 m from the monitoring station. Typical locations are parks, malls, or landscaped areas having no traffic. Probe height is to be 3 ± 0.5 m above the ground surface
Type C	*Residential population exposure station.* Locate station in the midst of a residential or suburban area but not in the central business district. Station should be more than 100 m from any street having a traffic volume in excess of 500 vehicles/day. Station probe height must be 3 ± 0.5 m
Type D	*Mesoscale station.* Locate station in the urban area at appropriate height to gather meteorological and air quality data at upper elevations. The purpose of this station is not to monitor human exposure but to gather trend data and meteorological data at various heights. Typical locations are tall buildings and broadcasting towers. The height of the probe, along with the nature of the station location, must be carefully documented in each case
Type E	*Non-urban station.* Locate station in a remote, non-urban area having no traffic and no industrial activity. The purpose of this station is to monitor for trend analyses, for non-degradation assessments, and for large-scale geographical surveys. The location or height must not be changed during the period over which the trend is examined. The height of the probe must be documented in each case. A suitable height is 3 ± 0.5 m
Type F	*Specialised source survey station.* Locate station very near a particular air pollution source under scrutiny. The purpose of the station is to determine the impact on air quality, at specified locations, of a particular emission source of interest. Station probe height should be 3 ± 0.5 m unless special considerations of the survey require a non-uniform height

[a] In contrast, WHO (1977) guide lines specify that the probe should be 1 m from the curb.

to demonstrate the occurrence of at least one violation per month or per year, then design requirements may be relaxed. In either case, air pollution control agencies should promulgate guide lines for monitoring programmes around strong point-sources (number of samplers and locations; number of permissible violations of designated values per month or per year, per sampler). In fairness to industry, the methods of analysis and of interpretation of monitoring data should be public information.

The design of monitoring systems for distances of more than 50 km downwind of tall chimneys will be discussed in section 7.4.

7.3.2 Multiple low-level sources of SO_2 and particulates

For areas with multiple low-level emissions of SO_2 and particulates, various methods are available for assisting in network design. After deciding on an objective and a tolerance, the user may select a method(s) from those described in Chapter 5. In making his decision on network design, the user will also be guided qualitatively by: (1) an emission inventory, even if it is only a subjective one; (2) information on the mesometeorological wind fields in the area; (3) topography; (4) population (in some cases); (5) projected land-use changes; (6) budget constraints. These items have been expanded into check lists by Hamburg (1971), Price *et al.* (1975) and Ludwig *et al.* (1976).

For health-related studies, particulate sampling should preferably include measurements of size distributions. Because this is frequently not possible, Ludwig *et al.* (1976) recommend that special care should be taken to select monitoring sites that will be relatively free of large particles, re-entrained, for example, in the swirling wakes of moving vehicles.

7.4 Pollutants associated with atmospheric chemical reactions

For substances such as oxidants and sulphates that are produced by atmospheric chemical reactions, high ground-level concentrations may occur tens to hundreds of kilometres downwind from sources. The scope of the monitoring grid is thus expanded considerably. Quite often, however, because the source of photochemical products is regional, the sampling problem is simplified in comparison with that downwind of a tall chimney because the cross-wind variation in concentrations is not great; indeed, many of the cross-wind gradients that do exist at these downwind distances are due to local variations in sink strengths.

Ludwig *et al.* (1976) have reviewed the literature on photochemical pollutants, and have produced a taxonomy of monitoring sites. Their classification is shown in a slightly modified form in *Table 7.2*, which may be helpful in network design.

Finally, Sheih *et al.* (1978) have considered the design of a network for regional-scale studies of atmospheric transport and transformation of sulphur dioxide in eastern North America. The following design criteria were specified.

(1) The number of stations should be sufficiently large to detect the general pattern.

Table 7.2 Monitoring site types for precursors and photochemical pollutants (after Ludwig *et al.*, 1976)

General site type	*Characteristic*	*Scale to be represented*	*Other important factors*	*Pollutants to which site is applicable*	*Remarks*
Neighbourhood	Source-oriented	Smaller end of the neighbourhood scale, 1–2 km	Areas where measurements will identify contributions of specific sources	NO_2, NMHC[a], NO, SO_2	
Neighbourhood	General	Neighbourhood	Areas where measurements dominated by single sources are to be avoided	NO_2, NMHC, O_x NO, SO_2	Similar to source-oriented site, but not as restrictive
Urban	Important reactant area	Urban/regional, tens of km	Precursor areas where reactants contribute importantly to photochemical air quality in region	NO, NMHC, SO_2, NO_2	
Regional	Important product area	Regional, hundreds of km	Areas where important photochemical pollutant products are expected to occur	O_x, NO_2, sulphates, nitrates	
Traffic effects	Street canyon or traffic corridor	Micro, on the scale of streets	Must be a large traffic source of NO nearby	NO, NO_2, O_x	Specifically to assess the reactions among NO, NO_2, and O_x

[a] Non-methane hydrocarbons.

(2) The network should be capable of detecting maximum concentrations.
(3) The network should be capable of giving the background concentration.
(4) The separation distance between sampling stations should be proportional to the distance between successive contours of pollutant concentration in the neighbourhood of the stations.
(5) The network should provide an array of stations in the direction of the prevailing wind for assessing the effects of chemical transformations.

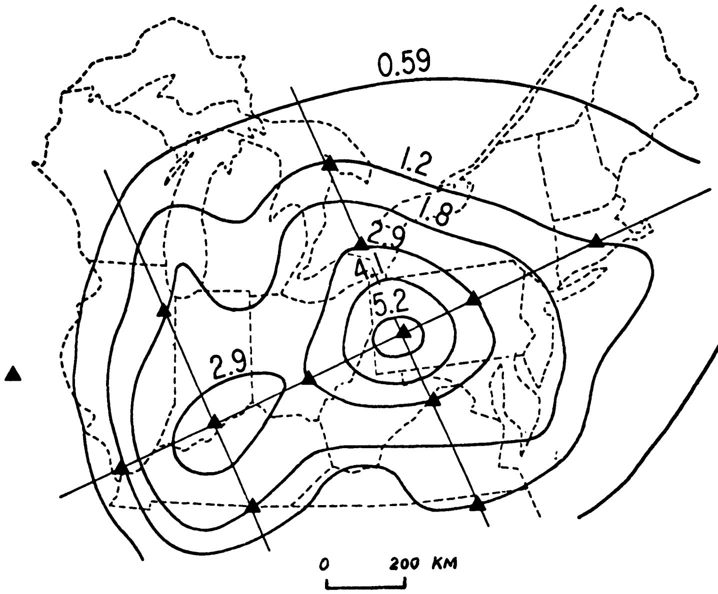


Figure 7.2 Isopleths of SO_2 ($\mu g\,m^{-3}$) obtained from a long-term statistical trajectory model. The 13 sites selected for monitoring stations are indicated by triangles (Sheih *et al.*, 1978)

(6) The network should have an array of stations in the direction perpendicular to the prevailing wind for evaluating the effects of horizontal turbulent diffusion. (In the area of interest, the general wind direction was WSW.)

To meet design criterion (6), 'climatological' isopleths of SO_2 concentrations were computed; *see Figure 7.2.* The concentrations were obtained from a climatological trajectory model, in which the source inventory was simplified to include only the 53 major power plants in the area of interest.

The resulting network of thirteen stations (shown by triangles in *Figure 7.2*) seems to meet the six design criteria listed above, if the assumption is valid that the isopleths are close to their long-term positions. On individual days, when wind patterns are quite different from normal, this fixed-station network is of course not optimal.

7.5 Rules-of-thumb on network density

In 1971, the United States EPA published guidelines for air quality surveillance networks (EPA, 1971). Two empirical methods for estimating network density were given: one based on population, the other based on area and on the present level of pollution in the region.

7.5.1 A criterion based on population

Figure 7.3, a nomogram relating numbers of stations to population, is intended as a general guide only. In cities where emissions of a particular pollutant are small, network density may be drastically reduced.

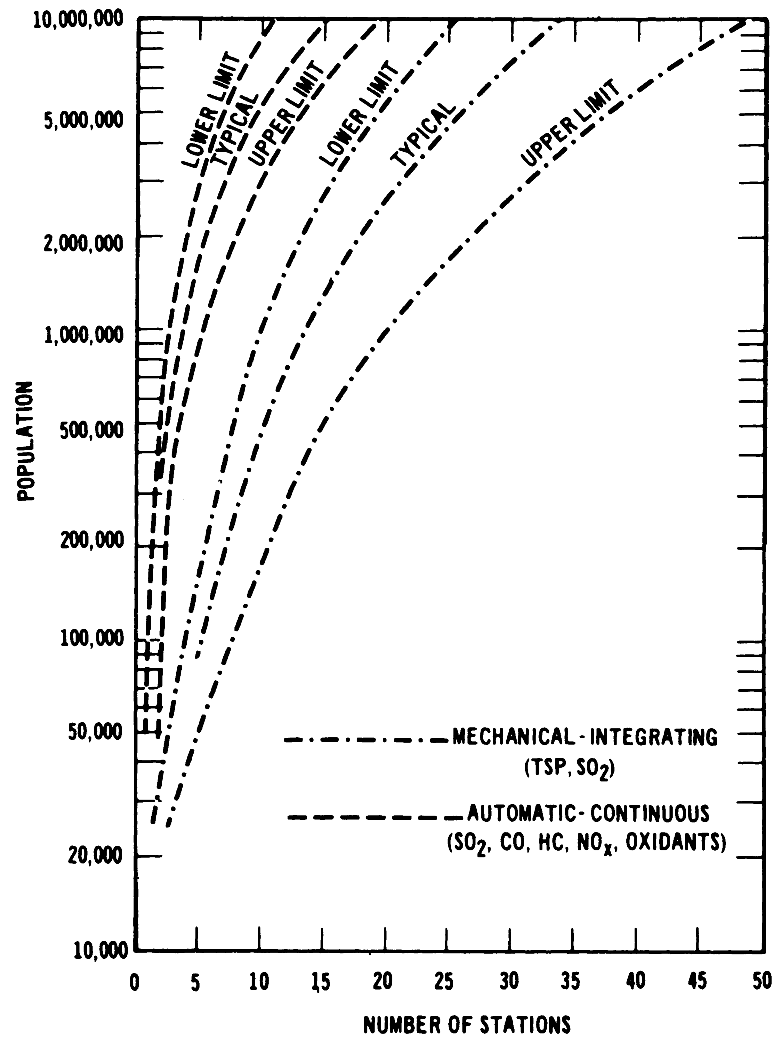


Figure 7.3 Nomogram providing guidelines for network density (EPA, 1971)

Table 7.3 Regulatory minimum number of monitoring sites (EPA, 1975b)

Classification of region	*Pollutant*	*Region population*	*Minimum number of air quality monitoring sites*[a]
I	Suspended particulates	Less than 100 000	4
	hi-vol	100 000–1 000 000	4 + 0.6 per 100 000 population
		1 000 001–5 000 000	7.5 + 0.25 per 100 000 population
	tape sampler	Above 5 000 000	12 + 0.16 per 100 000 population
			One per 250 000 population up to eight sites
	Sulphur dioxide	Less than 100 000	3
	bubbler	100 000–1 000 000	2.5 + 0.5 per 100 000 population
		1 000 001–5 000 000	6 + 0.15 per 100 000 population
		Above 5 000 000	6 + 0.05 per 100 000 population
	continuous	Less than 100 000	1
		100 000–5 000 000	1 + 0.15 per 100 000 population
		Above 5 000 000	6 + 0.05 per 100 000 population
	Carbon monoxide	Less than 100 000	1
		100 000–5 000 000	1 + 0.15 per 100 000 population
		Above 5 000 000	6 + 0.05 per 100 000 population

	Photochemical oxidants	Less than 100 000	1
		100 000–5 000 000	1 + 0.15 per 100 000 population
		Above 5 000 000	6 + 0.05 per 100 000 population
	Nitrogen dioxide[b]		
	continuous		3
	bubbler	Less than 100 000	3
		100 000–1 000 000	4 + 0.6 per 100 000 population
		Above 1 000 000	10
II	Suspended particulates		3 hi-vols
			1 tape sampler
	Sulphur dioxide		3 bubbler
			1 continuous
III	Suspended particulates		1 hi-vol
	Sulphur dioxide		1 bubbler
	Nitrogen dioxide[b]		2 bubblers

[a] In interstate Air Quality Control Regions, number of samplers to be distributed among states on the basis of population.
[b] Will be proposed as new requirements.

7.5.2 A criterion based on concentrations and area

The total number of samplers N required for a given region may be estimated in this case from an empirical equation

$$N = N_x + N_y + N_z$$

where x, y, z refer to areas of dimensions X, Y, Z, in which pollution levels are higher than the annual air quality standards, intermediate between air quality standards and background levels, and at background levels, respectively.

The values of N are given by

$$N_x = 0.0965 \frac{C_m - C_s}{C_s} X$$

$$N_y = 0.0096 \frac{C_s - C_b}{C_s} Y \qquad (7.1)$$

$$N_z = 0.0004\, Z$$

where C_m = numerical value of the maximum isopleth, to the nearest 10 $\mu g\,m^{-3}$; C_s = numerical value of the minimum isopleth, again to the nearest 10 $\mu g\,m^{-3}$. Equation (7.1) applies for both SO_2 and suspended particulates.

More recently, the United States EPA has specified minimum numbers of monitoring stations for its Air Quality Control Regions (EPA, 1975b). The regulatory requirements are given in *Table 7.3*, which shows that population is a major factor to be considered when designing an urban network in the USA.

The EPA has also issued guide lines for monitoring around point-sources (EPA, 1976). In order to meet the requirements of the United States Energy Supply and Environmental Coordination Act of 1974, a minimum of three stations is suggested (*see Table 7.4*).

These rules-of-thumb are inconsistent neither with the WHO proposal (WHO, 1977) shown in *Table 7.5*, nor with the guidelines used in the USSR (Zaitsev and Yankovskii, 1977). The WHO proposal relates to air quality trend analysis, the main criterion for network density being population. For the Soviet Union, a city with a population of from 500 000 to 1 million must

Table 7.4 Minimum network for monitoring around designated sources (EPA, 1976)

Pollutant	*Sampling frequency*	*Minimum number of sites*
SO_2	Continuous	3
Total suspended particulates and/or sulphates	Once every 3 days	3

Table 7.5 Suggested average numbers of stations for air quality trend monitoring in urban areas of given populations[a] (WHO, 1976)

Urban population (million)	*Average number of stations per pollutant*					
	Total suspended particulate matter	*Sulphur dioxide*	*Nitrogen oxides*	*Oxidants*	*Carbon monoxide*	*Wind speed and direction*
<1.0	2	2	1	1	1	1
1.0–4.0	5	5	2	2	2	2
4.0–8.0	8	8	4	3	4	2
>8.0	10	10	5	4	5	3

[a] Modifying factors are as follows. (1) In highly industrialised cities, the number of stations for suspended particulate matter and sulphur dioxide should be increased. (2) In areas where large amounts of heavy fuel are used, the number of stations for sulphur dioxide should be increased. (3) In areas where not much heavy fuel is used, the number of stations for sulphur dioxide may be reduced. (4) In regions with irregular terrain, it may be necessary to increase the number of stations. (5) In cities with extremely heavy traffic, the number of stations for nitrogen oxides, oxidants and carbon monoxide may need to be doubled. (6) In cities with a population of 4 million or more, with relatively low traffic, the number of stations for nitrogen oxides, oxidants and carbon monoxide may be reduced.

have 5–10 monitoring stations, distributed so that one station represents 10–20 km^2. In cities with a larger population, with complex topography or with an unusually large number of pollution sources, one station per 5–10 km^2 is recommended.

7.6 Urban reference stations

An *urban reference station* is an air quality/meteorological monitoring station located within an urban area but not near sources of pollution or obstructions to the wind. Siting criteria for such stations have not yet been developed, but suitable locations might be found in large urban parks, e.g. Kensington Gardens, London; Central Park, New York; Mount Royal, Montreal.

A station of this type would be established for the following reasons: (1) to assist in the estimation of long-term trends in urban air quality and climate; (2) to study the transport and diffusion of plumes from tall chimneys, within the metropolitan area but away from the disturbing effects of urban buildings and canyons. The instrumentation to be used could be similar to that recommended for the WMO regional stations with expanded programmes (WMO, 1976).

Associated with the urban reference station should be a precision air quality laboratory (not necessarily at the same site).

8

Conclusions and recommendations

The design of air quality monitoring networks is 'an exceptionally difficult and subtle problem that continues to be of major importance' (Calder, 1975). Some of the difficulties and subtleties have been described in this volume, and a number of research gaps have been identified. A further point that should be stressed is the desirability of making an inventory of existing air quality and meteorological stations before beginning to design or redesign a network.

The main conclusions are as follows.

(1) Atmospheric scales of motion range from the micro to the global. In siting a monitoring station, the scale of the phenomenon or process to be observed should be designated, and the siting criteria should be such that the effects of all smaller scales will be suppressed insofar as possible.

(2) The objectives of a monitoring network, as well as the tolerances, should be decided in advance. These considerations have a tremendous effect on network design.

(3) Methods that may help in network design are of three general types: statistical, modelling and combination statistical–predictive. The most appropriate method will depend on the objectives, the tolerances and the data-base available.

(4) Where possible, several methods should be applied and the results compared. A valuable tool is a sensitivity analysis, in which the relative importance of various assumptions and inputs is assessed with respect to the outputs of the study.

The main research gaps are as follows.

(a) Usually an air quality monitoring network is already in place, and the only possible modification may be incremental in nature, the major constraint being that only modest changes in operating costs are permitted. However, given a network of stations, an interesting inverse problem could be examined: what kinds of questions is an existing network capable of answering, and with what confidence? No such study has yet been undertaken.

(b) With respect to network design, there is need for comparative studies in which (i) several methods are applied to the same data set, and (ii) a single method is applied to data from several cities or regions.

(c) There is need for statisticians to become more interested in significance tests for data that contain random errors and that are correlated in both time and space.

(d) There is need for experimental pilot studies, particularly on the micro and neighbourhood scales. An objective should be to search for general results insofar as possible, rather than to make a large number of interesting but unrelated observations. A suggestion has been made (Sweeney, 1969) that before a permanent monitoring network be established in an urban area, an intensive pilot study should be undertaken. However, Vukovich (1975) rightly points out that because the fabric of a city is constantly changing (new roads, downtown renewal programmes, etc.), a network based on existing air quality patterns would quickly become outdated. A more meaningful approach would be to design pilot studies that permit general results to be inferred. In a symposium on urban climate (WMO, 1970, p. 377), the suggestion was made that there was need to define 'standard non-standard sites' for urban observations. This need still exists.

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