MAPPING AMBIENT URBAN AIR POLLUTION AT THE SMALL AREA SCALE: A GIS APPROACH

KIRSTY LOUISE SMALLBONE

Department of Geography
The University of Huddersfield

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"People look down on stuff like geography and meteorology, and not only because they are standing on one and being soaked by the other. They don't look quite like real science. But geography is only physics slowed down and with a few trees stuck on it, and meteorology is full of exciting fashionable chaos and complexity"

(Prachett 1996).

ABSTRACT

Air pollution is an emotive and complex issue, affecting materials, vegetation growth and human health. Given that over half the world's population live within urban areas and that those areas are often highly polluted, the ability to understand the patterns and magnitude of pollution at the small area (urban environment) level is increasingly important. Recent research has highlighted, in particular, the apparent relationship between traffic-related pollution and respiratory health, while the increasing prevalence of asthma, especially amongst children, has been widely attributed to exposure to traffic-related air pollution. The UK government has reacted to this growing concern by publishing the UK National Air Quality Strategy (DOE 1996) which forces all Local Authorities in England and Wales to review air quality in their area and designate any areas not expected to meet the 2005 air quality standards as Air Quality Management Areas (AQMAs), though what constitutes AQMAs and how to define them remains vague.

Against this background, there is a growing need to understand the patterns and magnitude of urban air pollution and for improvements in pollution mapping methods. This thesis aims to contribute to this knowledge. The background to air pollution and related research has been examined within the first section of this report. A review of sampling methods was conducted, a sampling strategy devised and a number of surveys conducted to investigate both the spatial nature of air pollution and, more specifically, the dispersion of pollution with varying characteristics (distance to road, vehicle volume, height above ground level etc). The resultant data was analysed and a number of patterns identified. The ability of linear dispersion models to accurately predict air pollution was also considered. A variety of models were examined, ranging from the simplistic (e.g. DMRB) to the more complex (e.g. CALINE4) model. The model best able to predict pollution at specific sites was then used to predict

concentrations over the entire urban area which were then compared to actual monitored data. The resultant analysis indicated that the dispersion model is not a good method for predicting pollution concentrations at the small area level, and therefore an alternative method of mapping was investigated. Using the ARC/INFO geographical information system (GIS) a regression analysis approach was applied to the study area. A number of variables including altitude, landuse type, traffic volume and composition etc, were examined and their ability to predict air pollution tested using data on nitrogen dioxide from intensive field surveys. The study area was then transformed into a grid of $10m^2$, regression analysis was performed on each individual square and the results mapped. The monitored data was then intersected with the resultant map and monitored and modeled concentrations compared. Results of the analysis indicated that the regression analysis could explain up to 61 per cent of the variation in nitrogen dioxide concentrations and thus performed significantly better than the dispersion model method. The ease of application and transferability of the regression method means it has a wide range of applied and academic uses that are discussed in the final section.

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Table of Contents

List of Tables

List of Figures

CHAPTER 3 POLLUTION MONITORING

CHAPTER 4 SURVEY DESIGN

CHAPTER 5 SOURCES, PATTERNS AND MAGNITUDE OF VARIATION

CHAPTER 6 DISPERSION MODELING

CHAPTER 7 REGRESSION ANALYSIS

1. INTRODUCTION

The 'London Smog' of 1952 dramatically focused both public and political attention on the problems of air pollution and health. Between December 4th and 7th, the daily death rate in the capital rose from ca. 120 to over 500, as pollution levels rose in association with a stable high pressure front over south-east England. During the week ending on December 13th, 2484 people died, some 4.5 times the rate the previous month. Applications for hospital admission for respiratory illness grew three-fold over the period; emergency admissions for cardiovascular diseases doubled; applications for sick benefit rose 50% (Ministry of Public Health 1954, quoted in Schwartz 1994).

Since then, much has changed. Technological advances, economic restructuring and environmental policy have combined to reduce levels of many traditional air pollutants, such as black smoke and sulphur dioxide. Over the same period, however, new concerns have arisen, particularly about the apparent link between rising levels of traffic-related pollution and increases in respiratory and cardio-respiratory illness (e.g. Britton 1992; Lean 1993; Parliamentary Office of Science and Technology 1994; Royal Commission on Environmental Pollution 1995).

In recent years, these concerns have driven the search for both technological and legislative solutions which could reduce levels of air pollution and related health risks. Nevertheless, the scientific basis for intervention remains weak. Whilst a growing number of studies have demonstrated links between traffic-related air pollution and respiratory health, these have been hampered by a number of factors not least the limited knowledge about spatial patterns of air pollution, the limited availability of monitored pollution data, and consequent poor estimates of exposure (Briggs 1992). As a result, it has proved difficult to quantify the true risks to health posed by traffic-related and other air pollutants or to establish definitive air quality standards and control strategies (Committee on the Medical

Effects of Air Pollutants 1995). In recommending air quality standards for particulates, for example, the Expert Panel on Air Quality Standards (EPAQS) stated:

> *"Because of the many uncertainties surrounding the evidence upon which our recommendations are based ..... we believe that the recommended Air Quality Standards should be reviewed in the light of United Kingdom experience and of any new data, within the next five years"* (Expert Panel on Air Quality Standards 1995).

Similarly the National Air Quality Strategy, launched in 1996, notes that:

> *"Central to the further development of air quality policy, ... is an understanding of the relationship between the different levels at which air pollution is generated and, in consequence, controlled"* (DoE 1996).

The Royal Commission on Environmental Pollution set up by the UK government concluded that :

> *"We recommend that further research be carried out into the health effects both of individual transport-related pollutants and substances in combination. This research should include further epidemiological (and) further study of the effects of pollutants"* (Royal Commission on Environmental Pollution 1994).

Such statements indicate that there is a recognised need for further investigation into spatial variation of air pollution, particularly in urban areas, for use in epidemiological studies. A particular need is the ability to map air pollution at the small-area scale. Air pollution maps are potentially powerful tools. They can help to identify 'hotspots' in need of special intervention or monitoring; they can help to design and implement monitoring networks; they can provide a basis for evaluating the effects of management or policy; they can help to estimate personal exposure to air pollution, and thus provide valuable data for epidemiological studies and health risk assessments. They can also be an effective means of communicating information on air pollution to users, whether researchers, policy-makers or members of the public. In recent years, the potential for air pollution mapping has advanced considerably, as a result of improvements in methods of dispersion modelling and in the use of GIS. Nevertheless, the ability to produce detailed air pollution maps, at a scale and level of accuracy which can meet these needs, remains undeveloped.

1.1 AIMS AND OBJECTIVES

The project reported in this thesis was aimed at addressing the lack of detailed pollution data at the small area level by investigating patterns and sources of air pollution at the small area level, and by developing and testing a range of mapping methods, including dispersion models and GIS-based methods. The specific aims were as follows:

- *To examine the magnitude, source and patterns of small area spatial variation in traffic-related air pollution in an urban environment.*

- *To investigate methods of mapping traffic-related air pollution at a small area scale.*

- *To evaluate the implications of small area variations in air pollution for the design of pollution monitoring networks and air quality management areas.*

To this end, the study involved the following objectives:

- the collection of monitored data for a dense network of sites within a mixed urban-rural study area (Huddersfield, UK).

- examination of sources of variation in air pollution concentrations within the area.

- testing and comparison of different methods of pollution mapping, including dispersion modelling, interpolation and empirical techniques.

- on the basis of these results, production of a 'best approximation' pollution map for the study area.

The project was carried out partly in association with an EU Third Framework funded project entitled SAVIAH (Small Area Variation In Air pollution and Health). The aim of the SAVIAH study was to develop and test methods for examining the relationship between chronic respiratory symptoms in children and environmental (air) pollution. The study was carried out in four European countries: Amsterdam (Netherlands), Huddersfield (United Kingdom), Prague (Czech Republic) and Poznan (Poland). The study employed a range of techniques including: questionnaire surveys to obtain data on health, family background and home circumstances of children aged 7-11 years; low-cost passive sampling devices to monitor air pollution levels at a dense network of sites in each study area; GIS methods for the modelling and mapping of air pollution and to determine personal exposure at the individual level; small-area statistical methods to analyse spatial patterns in health outcome and relationships between exposure and health. Results of the SAVIAH study are reported by Briggs *et al.* (1997), Lebret *et al.* (in press), van Reeuwijk *et al.* (in press) and Pikhart *et al.* (in press). The research reported here includes work undertaken both within the context of the SAVIAH study and outside that study (see, also, Collins *et al.* 1995).

The thesis is arranged as follows:

Chapter 2 reviews the history of air quality legislation in Britain, examines existing knowledge concerning the relationship between air pollution and health, looks at possible mapping techniques and identifies key research needs.

Chapter 3 describes the study area, outlines the atmospheric processes involved in air pollution, evaluates the available monitoring technology and identifies the most suitable sampling methodology which fulfils the aims and objectives of this project. The sampling procedures used in the study are described in detail.

Chapter 4 describes the various surveys used in the project. The sampling protocol used in each survey is also described.

Chapter 5 examines and quantifies sources of variation in pollution levels in both a spatial and temporal framework. The contribution of traffic volume, distance from road, land cover, sampling height and measurement error are all investigated.

Chapter 6 investigates the capability of traditional methods of dispersion modelling to describe these variations in air pollution at the small area scale. A number of different dispersion models are used and compared, and the results are validated against a subset of the pollution data obtained in the pollution surveys. One method is then applied to map pollution levels across the study area.

Chapter 7 develops and evaluates the use of GIS-based regression analysis as a basis for air pollution mapping.

Chapter 8 discusses the relative merits and disadvantages of each of the techniques and considers the implications of the results of the study for air pollution management and monitoring, and for environmental epidemiological research. The extent to which the aims and objectives of this project have been achieved is examined and the conclusions discussed.

2. *BACKGROUND TO AIR POLLUTION*

Air pollution is an emotive and complex issue. Historically, air quality has been controlled by the use of emission standards based on available abatement technology and taking account of the economic viability of the industry. Recently, however, emission standards in the UK have been replaced by the use of 'proactive' air quality standards which have attempted to prevent certain pollutants (e.g. benzene and 1-3 butadiene) from becoming an air quality issue and to lower overall ambient concentrations of various other pollutants (e.g. nitrogen dioxide, sulphur dioxide and smoke). To set such standards, it is essential to understand the risks to human health and the environment of exposure to certain pollutants. Research into the implications of air pollution on human health are therefore considered essential in setting air quality standards at sensible levels. These two issues are examined in this chapter. In addition, methods of mapping air pollution will be considered. Mapping air pollution is an important part of current air quality legislation (DOE 1996) and also essential for identifying the 'at-risk' population of an urban area. Actual mapping of air pollution, however, is not straightforward and as yet there is no prescribed method of mapping. Current methods of mapping from other disciplines will therefore be examined and any possible techniques identified for more detailed investigation.

2.1 BACKGROUND TO AIR QUALITY LEGISLATION

Poor air quality has long been a cause for public concern and has necessitated the introduction of legislative controls to resolve the problem. The first recorded legislation in the United Kingdom was in the thirteenth century when the use of coal was prohibited in London in 1273 due to the effect it was perceived to have on human health (NSCA 1997). The next significant piece of air pollution

legislation in the UK was not introduced until the nineteenth century and followed the realisation that crops, vegetation, human health, materials and tools were severely damaged by emissions from alkali works. The 1863 Alkali Act thus required a 95 per cent reduction in emissions from alkali factories, and the dilution of the remaining 5 per cent before release to the atmosphere. It also instituted the National Inspectorate of Pollution and gave them powers of enforcement. Emissions from alkali works subsequently fell from 14,000 tonnes to 45 tonnes per year (NSCA 1997, Elsom 1992, Colls 1997).

Attempts to control the ever changing problems of air pollution, especially within urban areas, have been based on a number of different philosophies. In Europe and the USA, legislative air quality standards are set. Emitters must show that their emissions would not cause air quality standards to be exceeded. Conversely, the UK has historically relied on emission standards to control air pollution, the assumption being that if controls were set on emissions, ambient air quality targets would therefore be achieved. Emission standards for the UK have been based on the pragmatic concept of '*Best Practicable Means (BPM)*' as stated in the 1874 second Alkali Act. This allowed the economic viability of the industry concerned to be considered in deciding the level of abatement technology necessary (Colls 1997; NSCA 1997).

The concept of best practicable means in controlling air pollution continued until the 1980s when heightened interest in the environment, combined with new EU legislation, forced recognition of the cross-media movement of pollution: i.e. that air pollution had implications for water quality and land contamination. Consequently, it was felt that an integrated approach to pollution control would be more able to control the movement of pollution across different media. This concept entered British law in the 1990 Environmental Protection Act. The Environmental Protection Act (1990) resulted in the replacement of BPM by BATNEEC (best available techniques not entailing excessive cost). As with the BPM approach, however, the concept of BATNEEC and the inclusion of the words '*best*' and '*excessive*' naturally entails a subjective judgement to be made on the part of the assessor and thus is open to appeals and abuse.

Legislation to control air pollution within the UK could therefore be considered as reactive instead of proactive in approach. The situation changed, however, with the introduction of the UK National Air Quality Strategy in 1996. This strategy drew together current thinking on air quality management and for the first time set down national standards for air quality in the UK. The strategy identified standards for nine pollutants based on the effects of human health (see Table 2.1). Furthermore, the strategy stated that Local Authorities should review pollution levels and identify possible 'hotspots' or 'Air Quality Management Areas' where it was thought the air quality standards would not be met by 2005. Once identified, a management plan for that area would then be drawn up to take account of local factors such as meteorology, topography, population density, vehicle volume and composition and specialised sources (e.g. airports) and then implemented within a given time period (DOE 1996).

Table 2.1 UK national air quality standards and objectives

Pollutant	Conc	Reference period	Target Date	Exceedence Allowance
Benzene	5 ppb	Running annual mean	2005	
1,3 Butadiene	1 ppb	Running annual mean	2005	
Carbon monoxide	10 ppm	Running 8 hour mean	2005	
Lead	0.5 $\mu g/m^3$	Annual mean	2005	
Nitrogen dioxide	104.6ppb	1 hour mean	2005	8 hours exceedence allowed per year
	20 ppb	Annual mean	99.9th percentile by 2005	
Ozone	50 ppb	Running 8 hour mean	97th percentile by 2005	10 day exceedence allowed per year
Particulates (PM_{10})	50 $\mu g/m^3$	Running 24 hour mean	99th percentile by 2005	4 day exceedence allowed per year
Sulphur dioxide	100 ppb	15 minute mean	99.9th percentile by 2005	99.9 per cent of measurements below 100ppb

(DOE 1996)

2.1.1 European Influence on UK Legislation

The European Union has historically adopted a proactive approach to air quality and, instead of setting emission standards, chose to control air pollution by the introduction and enforcement of air quality standards. This was undertaken by the introduction of a series of directives into European Community Law in the 1980s which have since passed into law in the respective countries.

The first standards introduced into law were as a result of increasing concern regarding the effects of sulphur dioxide and black smoke on the environment, particularly the influence of acid rain on vegetation and fresh water lakes. The sulphur dioxide and suspended particulate directive (80/779/EEC) set both limit values (mandatory) and guide values (non-mandatory) for these pollutants, both of which are detailed in Table 2.2. This directive has since been renegotiated in the Helsinki Protocol and the UK has agreed to reduce sulphur emissions from 1980 levels by 50 per cent by 2000, 70 per cent by 2005 and 80 per cent by 2010 (NSCA 1997).

Similarly a directive detailing air quality standards for nitrogen dioxide (85/203/EEC) was introduced in 1985 and has been renegotiated in 1991 following the ratification of the 1988 Sofia Protocol (see Table 2.2). Similar standards for ozone, carbon dioxide, carbon monoxide and volatile organic compounds (VOCs) have been set or are due for adoption (NSCA 1997).

The influence of the European community on UK legislation should not be underestimated, however, and has played a great part in the change in UK legislation from standards based on emission levels to those based on air quality standards summed up in the recent UK National Air Quality Strategy (DOE 1996).

Table 2.2 EU Air Quality Standards

	Limit Value	Guide Value
Sulphur Dioxide	80μg/m^3 if smoke > 40μg/m^3 or 120 μg/m^3 if smoke ≤ 40μg/m^3 (as the median of daily mean values taken annually)	100-150μg/m^3 as a 24 hour mean
	180μg/m^3 if smoke > 60μg/m^3 or 130 μg/m^3 if smoke ≤ 60μg/m^3 (as the median of winter daily values)	40-60μg/m^3 as an annual mean
	250μg/m^3 if smoke > 150μg/m^3 or 350 μg/m^3 if smoke ≤150μg/m^3 (as the 98th percentile of daily values annually)	
Nitrogen Dioxide	200μg/m^3 at the 98th percentile calculated from the mean values per hour annually.	50μg/m^3 at the 50th percentile calculated from the mean values per hour annually
		135μg/m^3 at the 98th percentile calculated as above
Lead	2μg/m^3 as an annual mean	

(NSCA 1997)

Finally it should be noted that, although possessing no powers of enforcement, the World Health Organisation (WHO) has also published recommended air quality guidelines which have been used as a basis for the EU air quality standards. Although not mandatory, WHO guidelines are generally accepted as levels which should not be exceeded if healthy air is to be maintained.

These 'agencies' have been fundamental in shaping air quality legislation in the UK and the replacement of emissions standards by air quality standards in the 1990s. Adoption and enforcement of the UK National Air Quality Strategy is not yet complete, however, owing to the recent change in government, although it is generally accepted that the strategy will by implemented with only minor alterations.

2.2 AIR POLLUTION AND HEALTH

2.2.1 TRENDS

The implications of the effects of air pollution on human health have been of growing concern in recent years. This concern is reflected in both the number and subject of recent epidemiological studies. Many researchers have noted that there has been a gradual rise in the prevalence of respiratory illness, particularly asthma and wheeze, concurrent with increases in road traffic volume over the last 20 or so years (Anderson *et al.* 1994; Britton 1992; Burney 1988; Burney *et al.* 1990; Haathela *et al.* 1994; Oosterlee *et al.* 1996; NILU 1991; Wardlaw 1993). During the same time period there has been a dramatic increase in the incidence of acute asthma attacks. For example, the rate of reported attacks in the population as a whole more than doubled from 10.7 per 100,000 patients per week in 1974 to 27.1 in 1991; the rate among 0 - 4 year old children increased more than five-fold, from 13.5 to 74.4 per 100,000 per week (Action Asthma 1991). In addition, the Committee on the Medical Effects of Air Pollutants (1995) notes that:

> *"with regards asthma, it is probable that a substantial proportion [of the population] remain undiagnosed."* (Committee on the Medical Effects of Air Pollutants, 1995).

These increases in asthma are paralleled throughout the developed world and cannot therefore be dismissed as the result solely of changes in diagnosis or reporting strategies (Britton 1992). Along with increases in respiratory illness, there have been reported increases in mortality rates linked to air pollution and specifically to increased road traffic volumes. For example, during 3 days in December 1991, the death rate in London increased by 10% concurrent with extremely high air pollution levels linked to a traffic-induced smog (Association of London Authorities *et al.* 1994). This and similar reports (e.g. Pope *et al.*

1992, Dockery *et al.* 1989; 1993) are put into perspective when it is considered that, in western society, four out of five people live and work in urban conurbations and that it is in these urban areas that air pollution levels are highest. As a result, a large percentage of western society is potentially exposed to high levels of air pollution whether at school, work or home.

As noted earlier, traditional concern about links between air pollution and health have focused on pollutants such as smoke and sulphur dioxide, carbon dioxide and lead. Restructuring, of heavy industry, improved pollution abatement technologies and the introduction of emission legislation (e.g. The Clean Air Acts of 1956, 1968 and 1993, the Control of Pollution Act 1974 and the Environmental Protection Act 1990) have helped reduce levels of many of these pollutants. This decline in traditional pollutants has been offset by increases in the levels of a range of 'new' pollutants including nitrogen dioxide, ozone, non-methane volatile organic compounds, carbon monoxide and fine particulates, largely as a result of increasing levels of road transport (QUARG 1993). In 1991, for instance, vehicle pollution in the UK was responsible for almost 90 per cent of all emissions of carbon monoxide in the atmosphere, just over half of all emissions of nitrogen oxides, 36 per cent of all volatile organic compounds emissions and 2 per cent of sulphur dioxide emissions. This effect is more pronounced in urban areas, where road traffic contributes as much as 99 per cent of carbon monoxide emissions, up to 76 per cent emissions of nitrogen dioxide and 22 per cent of sulphur dioxide emissions. Notwithstanding efforts to improve vehicle fuel and engine design, levels of traffic-related air pollution seem likely to increase, for UK predictions for the next 20-30 years suggest a further growth of at least 40% in traffic volume (Gillham *et al.* 1992; QUARG 1993; Royal Commission on Environmental Pollution 1995). Furthermore, although all new cars manufactured after January 1994 have had to be fitted with catalytic converters, nearly two thirds of all pollutants are emitted in the first few minutes of the journey when the catalysts are still cold (Lean 1993; Russell-Jones 1987; Royal Commission on Environmental Pollution 1995). Thus the effect of catalytic converters on reducing air pollution will be limited. With regards to health, pollution emitted from vehicles is of more concern than that emitted from

industrial sources as industrial releases are emitted at a higher level and therefore have less impact on local air quality (Read 1994).

2.2.2 Acute Studies

In the last decade, a number of epidemiological studies have investigated the health effects of exposure to a wide range of traffic-related pollutants. Particular attention has been focused on fine particulates, ozone and nitrogen dioxide. Many of these studies have focused on short term (acute) effects of exposure to brief periods of moderate or high levels of pollution. This concentration on acute health effects is due to a number of factors, not least the relative ease of collecting the necessary health data. Long term studies, conversely, require health data to be collected over a long period (e.g. 1-10 years) with increased risk of non-co-operation by subjects, high drop-out rates and the subjects moving out of the study area. Recent research, conducted both in Europe and the USA, has suggested that at acute concentrations below the current air quality guidelines, air pollution concentrations may be associated with rising mortality, hospital admissions, respiratory symptoms (such as bronchitis, asthma, wheeze) and decreasing lung function (Dockery and Pope 1994; Dockery *et al.* 1993; Wardlaw 1988). More specifically, studies in Finland indicated an association between nitrogen dioxide levels and hospital admissions for respiratory disease and asthma (Ponka 1991; Rossi *et al.* 1993). Short term increases in NO_2 have been shown to be associated with decreasing respiratory function (Brunkreef *et al.* 1989; Goldstein *et al.* 1988; WHO 1987). Schwartz *et al.* (1990) found an association between ambient NO_2 levels and sore throats, phlegm and eye irritation in healthy student nurses in Los Angeles. Relationships were also identified between reduction in peak flow and increases in symptoms and use of respiratory medication and daily levels of PM_{10} particulates (Brunkreef *et al.* 1989; Hoek *et al.* 1992; Pope *et al.* 1992). Furthermore, research in the USA by Dockery *et al.* (1992) and Pope *et al.* (1992) suggested that there was a 16-17 per cent rise in the overall death rate for every $100\mu g/m^3$ rise in particulate concentrations.

Ozone is a secondary pollutant, the health effects of which have also been noted by a number of researchers. Again, results from studies in the US and Europe have been remarkably consistent in demonstrating reductions in pulmonary functions at ambient ozone levels of between 80 and 250 ppb (Hoek *et al.* 1993; Lioy *et al.* 1985; Spektor *et al.* 1988). Interestingly, it has been noted that, unlike most other pollutants, the effects of ozone are not confined to those who already suffer respiratory problems (Spektor *et al.* 1988).

2.2.3 Chronic Studies

In contrast, there have been relatively few studies which attempt to examine the effects of long term exposure to low levels of air pollution. Most of those which have been conducted tend to have small sample sizes and compare areas of low pollution with areas of high concentrations of numerous pollutants, thus making it difficult to determine which pollutant is responsible for any observed effects and to remove the confounding effects of difference in lifestyle, social conditions and health service provision (Read 1994). The various studies have also used different measures of exposure to different pollutants, and therefore comparisons are difficult.

Chronic studies are especially severely affected by problems of confounding factors. Confounding factors may either dilute or artificially inflate the correlation between air pollution and health. Thus relationships between a specific pollutant and an aspect of human health may be incorrectly identified. The most obvious confounding factor which may effect health is smoking (Hawthorne 1978; Lambert *et al.* 1970; McCarthy *et al.* 1985). Children whose parents smoke are 50 per cent more likely to be admitted to hospital with bronchitis and pneumonia (USDHHS 1986). Similarly, a cohort study of 10,000 British children found that there was a 14 per cent increase in childhood wheezy bronchitis and asthma when mothers smoked (Neuspiel *et al.* 1989). Other factors which affect respiratory function, especially asthma and wheeze, are exercise (Coughlin 1988), type and age of housing (McCarthy *et al.* 1985), damp housing

(Strachen and Sanders 1989), and dust (Anto and Sunyer 1990; Sunyer *et al.* 1989a; 1989b). People who suffer from allergic asthma may also be affected by animal fur or feathers, dust mites, mould, and a range of pollen including birch spores and timothy grass.

In order to circumvent some of the influence of confounding factors, a number of studies have examined the specific effects of long-term exposure to traffic-related pollution and health. Occupational studies of those working in confined spaces with vehicles such as police (Speizer *et al.* 1973), tunnel workers (Evans *et al.* 1988), bus garage workers (Gambel *et al.* 1987) and ferry vehicle workers (Ulfvarson *et al.* 1990) demonstrated either an increased prevalence of respiratory symptoms or a reduction in lung function or both.

2.2.4 Nitrogen Dioxide

Nitrogen dioxide is a known oxidant, which can reduce airway capacity and pulmonary function in susceptible individuals at high concentrations. At ambient concentrations, however, the effects are less clear and results of recent studies have been somewhat contradictory. Several studies reported no overall effect on the prevalence of respiratory disease of NO_2 (Dockery *et al.* 1989; Euler *et al.* 1988; van Mutius *et al.* 1992). Other studies, however, have shown an increase in prevalence of respiratory disease in polluted areas, though this is not specific to NO_2 (Detels *et al.* 1991; Jaakola *et al.* 1991). A national study in 44 cities in the USA showed an association between particulates, nitrogen dioxide and ozone and the risk of low lung function when adjusted for confounding factors (Schwartz 1989).

2.2.5 Ozone

Ozone is a powerful oxidant, which can cause significant impairment of pulmonary function at high concentrations (WHO 1987). In addition, 10 per cent of the population are particularly susceptible to the effects of ozone and may

suffer headaches, eye and throat irritation at ambient concentrations (EPAQ 1994; Elsom 1992). As with nitrogen dioxide, relatively few long term studies have been conducted to investigate the health effects of ozone. Detels *et al.* (1991) found that, in general, the prevalence of respiratory symptoms was higher and the lung function lower in more polluted areas. Abbey *et al.* (1991) demonstrated an association between prevalence of asthma and ozone levels in excess of 100 ppb. Studies by Zwick *et al.* (1991) also identified an association between levels of ozone and lung function and bronchial reactivity.

2.2.6 PARTICULATES

The effects of exposure to particulates on human health is of growing importance, demonstrated by the recent introduction of an air quality guideline for PM_{10} in 1996 by the UK government. Examination of literature indicates that a number of studies identified an association between levels of particulates and respiratory symptoms (Melina *et al.* 1981; Euler *et al.* 1988). Chronic cough, bronchitis and chest illnesses were found to be associated with particulates (PM_{15} and $PM_{2.5}$) in six cities in the USA (Dockery *et al.* 1989). A significant association was also demonstrated between mortality (particularly from cardiopulmonary disease) and $PM_{2.5}$ in adults (Dockery *et al.* 1993). Similar results were found in the Czech Republic by Bobak *et al.* (1992). Generally, recent research has suggested that the finer particulates ($PM_{2.5}$), which are more reactive and can penetrate further in to the lungs, are more important in terms of their health effects.

2.2.7 PROXY EXPOSURE INDICATORS

In almost all the epidemiological studies undertaken to investigate relationships between air pollution and health, the main limitation is the lack of accurate exposure data. This shortcoming is mainly due to the limited availability of nationally measured pollution data (e.g. there are only 26 automatic NO_2 monitoring stations, 31 O_3 monitoring stations and only 14 PM_{10} monitoring

stations for the whole of the UK), and the high cost of conducting purpose-designed surveys to obtain the relevant data. In many cases, therefore, proxy indicators of traffic-related pollution levels have been used. Studies in Germany, for example, found a significant relationship between respiratory function and the prevalence of recurrent wheeze and breathlessness and traffic flow (see Table 2.3). Residential distance to road was used as an estimate of pollution in other studies (see Table 2.3). Nitta *et al.* (1993), for example, reported increased levels of respiratory and allergic symptoms in areas of high exposure to vehicle emissions. Similarly Wichmann *et al.* (1989) found a raised prevalence of asthma in areas of high concentrations of NO_2 and CO associated with road traffic. Use of proxy indicators such as distance from road or traffic volume inevitably generates uncertainties in exposure estimates, and may act to dilute or distort relationships with health outcome.

Direct measurements of exposure, however, are generally impracticable due to their costs and problems of recruiting volunteers. Improved estimates of exposure are thus likely to come mainly from the use of methods to model air pollution levels at the small area level. Indeed, two recent studies (Oosterlee *et al.* 1996; NILU 1991; Pershagen *et al.* 1994) have already used such methods to provide exposure estimates in studies of traffic-related pollution and respiratory health and identified significant relationships (see Table 2.3).

2.3 METHODS OF MAPPING

From the above research it is clear that there is a need for a method of mapping air quality and thus providing better estimates of exposure to air pollution. Use of dispersion models provides one means of mapping, and in recent years a wide range of models have been developed, some with inbuilt graphical capabilities, for both point and line sources. Application of dispersion modelling, however, is

Table 2.3 Use of proxy indicators of pollution in epidemiological research.

Proxy indicator	Author	Date	Location	Exposure Indicator	Health outcome
Residential distance to road	Blumer & Reicht	1980	Switzerland	Particulates/ Lead	Occurrence of cancer
Residential distance to road	Edwards *et al*	1994	UK	Traffic-related pollution	Asthma
Residential distance to road	Elliott *et al*	1992	UK	Industrial emissions	Cancer of Larynx and Lung
Residential distance to road	Ishizaki *et al*	1987	Japan	Traffic-related pollution	Respiratory symptoms
Residential distance to road	Livingstone	1996	UK	Traffic-related pollution	Respiratory symptoms
Residential distance to road	Murakami *et al*	1990	Japan	Traffic-related Pollution	Respiratory symptoms
Residential distance to road	Nitta *et al*	1993	Japan	Traffic-related Pollution	Respiratory symptoms
Residential distance to road	Waldron *et al*	1995	UK	Traffic-related pollution	Asthma
Residential distance to road	Wichman *et al*	1989	Germany	Traffic-related Pollution	Prevalence of croup Syndrome
Residential distance to road	Whitelegg	1994	UK	Traffic-related Pollution	Respiratory symptoms
Traffic flow	Edwards	1993	UK	Traffic-related Pollution	Respiratory symptoms
Traffic flow	Romieu *et al*	1992	Germany	Traffic-related Pollution	Prevalence of recurrent wheeze & breathlessness
Traffic flow	Wjst *et al*	1993	Germany	Traffic-related Pollution	Respiratory function
Traffic density	Weiland *et al*	1994	Germany	Traffic-related pollution	Wheeze & allergic Rhinitis
Residential distance to industry	Halliday *et al*	1993	Australia	Industrial emissions	Wheeze & respiratory symptoms
Residential distance to industry	Shy *et al*	1970	USA	NO_2, Particulates	Respiratory functions
Occupation	Hall & Wynder	1984	USA	Traffic-related pollution	Lung cancer
Air pollution models	NILU	1991	Norway	Traffic-related Pollution	Respiratory symptoms
Air pollution models	Oosterlee *et al*	1996	Netherlands	NO_2	Respiratory symptoms
Air pollution models	Pershangen *et al*	1995	Sweden	NO_2	Occurrence of Wheezing Bronchitis
Air pollution models	Pönka	1991	Finland	NO, CO, Ozone	Asthma

often limited by the availability of the required input data (e.g. on emissions, meteorology, topography) as well as the inherent limitations of the models themselves. Although often used for specific site-level investigations (e.g. highway development), they have been less extensively used to map air pollution for entire towns or cities. Alternatively, pollution surveys can be generated by spatial interpolation techniques. Interpolation can be defined as;

> 'the estimation of the values of an attribute at an unsampled location from measurements made at surrounding sites' (Burroughs 1986)

Interpolation from a point (or monitoring site) to an area (in which people may live and work) is not as straightforward as it may first appear and has long been a source of interest and research for geographers and cartographers. Many methods of interpolation have been developed and have, in recent years, been enhanced by the development of Geographical Information Systems (GIS) such as ARC/INFO, SPANS and MAPINFO which enables the spatial handling, manipulation and analysis of vast amounts of data. In addition there is a wide range of spatial interpolation techniques which are available as part of statistical packages (such as Splus, Minitab and SPSS). These include triangulation, thin plate spline techniques (Hutchinson 1982; Dubrule 1984), moving window methods (Jones 1996; Bailey and Gatrell 1995), trend surface analysis and various methods of kriging (Oliver and Webster 1993; Myers 1995;). These methods have been widely used in environmental mapping, including air pollution (e.g. SEIPH 1996; 1997; Dorling and Fairbain 1997), though interestingly few attempts have been made to use them for air pollution mapping in urban areas. Several studies have also compared the different methods of interpolation (e.g. Burroughs 1986; Lam 1983), albeit without any definitive conclusions: in general, performance varies according to the quality of the data and the nature of the underlying spatial patterns being investigated. In addition, the more sophisticated techniques pose severe demands of data quality and uniformity of distribution which cannot always be met in natural sampling situations.

The rational behind most methods of spatial interpolation is that, on average, points closer together are more likely to have similar values than those further

apart. Contouring (triangulation), for example, is one of the most widely used methods of spatial interpolation for air pollution. Originally developed as a cartographic technique for indicating terrain elevation, Ostad and Brakensiek (1968) stated that methods of contouring could be transferred to 'concept space' and was not therefore restricted to 'geographic space'. Contouring has been widely used in a number of fields including meteorology, hydrology (Cooper and Burt 1986), geology (Bott and Trantrigola 1987; Reid and McManus 1987); transport studies (Murayama 1994; Dundon-smith and Gibb 1994), location analysis (Haggett, Cliff and Frey 1997) and air pollution (Campbell 1988; Greenland and Yorty 1985; Vit 1995).

Such methods of interpolation, however, suffer from a number of problems when applied to urban air pollution. Maps produced in this way, although allowing for gradation in variation over space, imply linear variation between locations. In addition, the occurrence of closed basins and summits means that the interpolation can become very complex, especially where there is marked local variation in the modelled surface. Furthermore, to achieve a representative pollution surface, a large number of data points with sufficient spatial variation are needed. This is often problematic as the number of monitoring stations for urban areas are few. It should also be noted that many forms of spatial interpolation, by relying solely on monitoring data, fail to consider other potentially useful information such as emission data, local topography and climatic influences, all of which may help to explain and predict variation in urban air pollution (Dorling and Fairbairn 1997).

A final point to consider is the use that such maps will be put to. Increasingly, maps are being used not only to inform research, but also as important tools for management, policy and decision-making. As such, the accuracy of the maps has important implications, both in terms of cost and ultimately, life. A map of flood risk developed by Prof. Clark at Southampton University, for example, was recently used by local insurance companies to control insurance risks and was in danger of creating planning blight in the area labelled as a 'high risk zone' (Clark

1997). The public perception of an air pollution map and the fact that many people believe maps without question, should also be considered and every effort made to ensure that the mapping technique chosen represents the actual spatial distribution of air pollution as accurately as possible.

2.4 SUMMARY

This chapter has shown that there has been significant changes in the policy and philosophy behind air pollution legislation, culminating in a shift away from emission standards and towards air quality standards as used by the European Union and the World Health Organisation. This change in policy can be attributed in part, to developments within the EU and increasing concern about the possible links between air pollution and health in recent years, most notably as a result of increasing volumes of road traffic and an apparent increase in respiratory illness. To date, epidemiological studies have been hampered by the difficulty in obtaining reliable measures of exposure at the small area of individual level. To a large extent, this reflects the limited spatial resolution of routine pollution monitoring, and thus the need to rely on exposure proxies. Finally methods of air pollution mapping to date were examined as a basis for further work which will be undertaken within this thesis. This research is aimed at examining the magnitude and patterns of small area spatial variation in air pollution within an urban environment and at developing and testing interpolation and dispersion based methods of pollution mapping, through a detailed investigation in the Huddersfield area, in West Yorkshire, UK.

3. *POLLUTION MONITORING*

3.1 THE STUDY AREA

The research project was conducted in the Huddersfield area of West Yorkshire. The area chosen for study was that of the, now defunct, Huddersfield Health Authority boundary (Figure 3.1). This area was chosen for a number of reasons. Firstly it was expected to facilitate the collection of medical statistics if required. Secondly, the area provided a good example of a medium sized provincial town in the UK, with large variations in pollution levels and a wide range of emission sources. Thirdly, good working links had been formed between the centre of study (The University of Huddersfield) and Kirklees Metropolitan Council and West Yorkshire Health Authority. Both of these were considered essential in order to allow data access and information exchange. Finally the area was convenient to the centre of study. Subsequently, the study area was selected as one of the four centres for the SAVIAH study – an EU-funded project which aimed to investigate the relationship between air pollution and respiratory health of children and allowed the comparison of prevalence of childhood respiratory symptoms and its determinants across countries based on a standardised method (Fischer *et al. In press).*

The study area is 305 km^2 and topographically very complex. It ranges from the Pennine Hills in the west to the margins of the Vale of York in the east. Geologically, the area is underlain by rocks of Carboniferous age which form a sequence of gently dipping strata, inclined to the west, and dissected by a number of deep river valleys (e.g. the Holme and Colne). The area ranges in altitude from

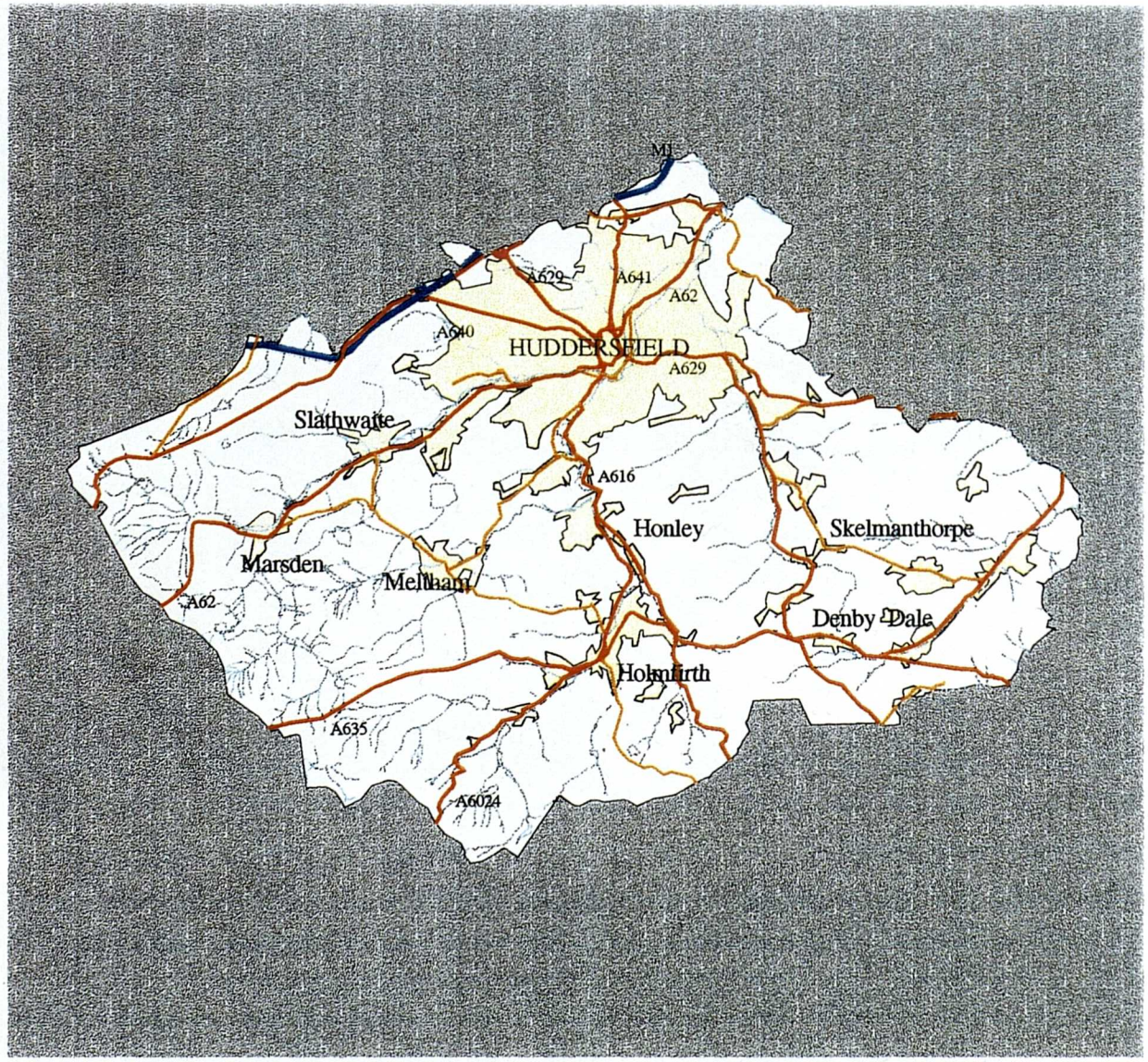


Figure 3.1 Map of the Study Area

Legend

Motorways

A-Roads

B-Roads

Rivers

Urban Areas

-1 0 1 2 3 Km

80m in the east (near Flockton) to 582m in the south-west (Black Hill) and it is this combination of geological structures, river valleys and altitude which have combined to influence the location and nature of the urban settlements.

The traditional industry of the area has been the woollen mills which were concentrated at the headwaters of the river valleys in order to take advantage of the clear, clean Pennine water. Although many of the textile mills have now given way to cloth recycling, dying and chemical industries (e.g. Holiday Dyes and Chemicals, Dawson Dyers and Zenica), many of these are still located in the river valley bottoms. Consequently, the majority of the settlements and infrastructure of the area is located around these industries.

On the plateaux, above the river valleys, much of the land is used for agricultural purposes. In the west of the study area, where the valleys are more pronounced and the soil of a poor quality, most of the land is used for sheep farming. In the east, however, the topography is gently undulating, which produces conditions conducive for arable farming.

The population of the study area was ca. 211,300 in 1991 (OPCS Census 1991), the majority of which is concentrated in the urban settlements of Huddersfield (pop 148,000) and Holmfirth (pop 30,636). The remaining population (32,664) is spread throughout the surrounding satellite villages, (e.g. Slaithwaite and Linthwaite in the Colne valley, Holmfirth and New Mill in the Holme valley and the Skelmanthorpe, Clayton West, Shelley and Denby Dale in the Dearne valley). Most of these villages are now used as commuter centres for people travelling to Huddersfield, Dewsbury, Leeds, Sheffield and Bradford. Major routeways include the A62 which runs along the Colne, the A616/A35, which follows the Holme and the A635 which follows the Dearne. In addition, the M62 provides a major transport link across the north-west of the area.

3.2 SAMPLING METHODS

The primary aim of this project was to investigate the nature of small area variation in traffic-related air pollution in urban areas, and to examine methods of mapping urban air pollution as a basis for exposure assessment. In order to fulfil these aims it was necessary to obtain pollution data on levels of pollution which could be used both to describe and investigate patterns of variation, and to test the accuracy of the resultant maps.

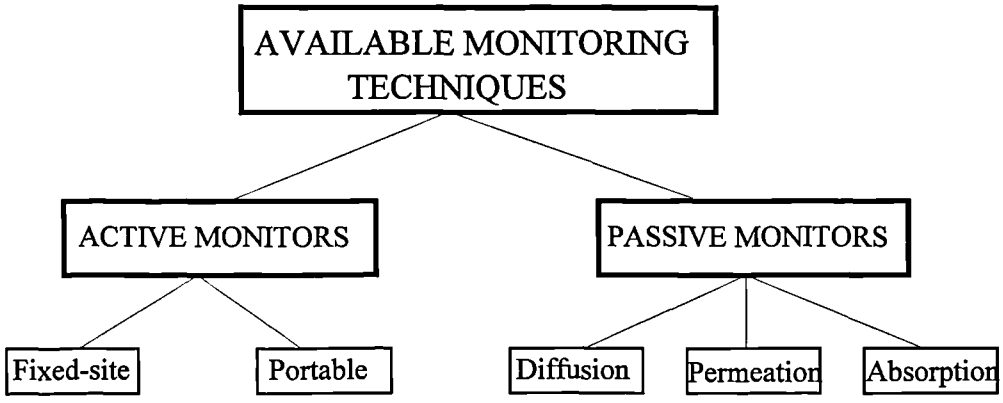
As noted earlier, the study area has a complex topographic and socio-economic make-up. No permanent, fixed site monitoring stations existed in the area (one was added by the local authority, however, towards the end of the project), and although Kirklees Council was conducting some monitoring using passive diffusion samplers, this was considered inadequate for the needs of this study. Obtaining representative detailed pollution data was, therefore, possible only by undertaking an intensive, purpose-designed monitoring programme. The following criteria were considered when selecting the monitoring method for this project:

- within the financial constraints of this project, the sampling technique must provide the best possible spatial coverage of the study area.
- the methods must be accurate, reliable and be a recognised method of air pollution monitoring within the scientific community. Results should be comparable to governmental standards.
- the method should not require extensive maintenance nor expensive calibration due to the possible remoteness of some sites and financial considerations of the project.
- analysis of the samples should be quick and simple.
- samplers must be weatherproof and as far as possible vandal proof.

- the chosen sampling method should be able to be left unattended for significant periods of time at any location and be easy to transport.

Monitoring methods can be divided into active monitors (which physically capture air to be analysed in either real-time or at a later date) and passive samplers (which allow air to diffuse onto/into the sampling medium) on the basis of sampler type and output (Figure 3.2). The choice of monitoring technique was important to the project as it would influence the survey design and the extent of the spatial coverage of data. The remainder of this section examines the range of monitoring techniques available and explores their possible use within the limiting requirements of this study.

Figure 3.2 Schematic diagram of available sampling technology.



3.2.1 Fixed-site Monitors

Fixed-site (or continuous) monitors have been developed for the detection of a range of gaseous pollutants. They provide a continuous readout of pollution levels at a particular site, and are therefore useful for studies requiring data on

detailed variation in pollution levels. Continuous monitors, specific to the measurement of nitrogen dioxide, are based on the gas-phase chemiluminescent method. These monitors records emissions of photons from the gas-phase reaction of NO with ozone. Concentrations of ambient air are drawn into chemiluminescent monitor and the initial amount of NO within the sample of air is determined (V1). The NO_2 in the sample of air is then reduced to NO_x (NO + NO_2) providing a second measurement (V2). The monitor then subtracts V2 from V1 providing a measurement of the volume of NO_2 in the original ambient air sample.

Yocom and McCarthy (1991), Tardiff and Goldstien (1991), Lodge (1989), Harrop *et al.* (1990) and Atkins (1986; 1991) have all noted the numerous advantages and disadvantages of using continuous monitors for measuring pollution. These are summarised in Table 3.1.

In the light of these considerations, it was decided to reject this type of monitor for the sampling required in this project. The primary reasons for this decision were the high cost and the difficulties in siting the equipment, which would seriously reduce the number of possible sampling sites. Although detailed information on the temporal variation of pollution would be obtained, insufficient insight into the spatial variation of NO_2 would be gained. Due to the reliable and accurate nature of continuous monitors, however, it was decided to use this method as a reference for the calibration and validation of the selected monitoring technique.

3.2.2 ACTIVE PORTABLE MONITORS

Portable monitors were first developed for industrial exposure monitoring, but have since been adapted to measure the lower concentrations experienced in

Table 3.1 Assessment of the suitability of continuous monitors.

Advantages	Disadvantages
- provide data on the relationship between NO and NO_2, and NO_2 decay rates	- equipment is expensive to purchase
- well established and acceptable method, for comparison with EU and UK ambient air quality guidelines	- cost of the equipment tends to limit the number of samplers in a network; therefore poor spatial resolution
- provide a continuous record of pollution	- due to cost of monitor, equipment failure becomes significant
- allow short term peaks and troughs in pollution levels to be identified	- location and height of the sampler will affect the results, thus creating sampling biases
- method is highly sensitive, reliable, and accurate	- good ventilation is required due to the by-product of ozone
- results are immediately available	- monitoring sites may be limited in residential areas by the production of audible noise
- when operated in conjunction with relevant technology, can provide real-time data	- monitoring sites must be weatherproof, vandal proof, provide an external dedicated power supply and be large enough to accommodate the monitor
- equipment can be operated unattended for extended time-periods	- if relocated or disconnected from the power supply, the equipment requires recalibration
- can be multiplexed to allow different locations to be sampled thus providing cost-effective use of equipment	- require extensive maintenance

urban areas. Most portable monitors are attached to, or contain, a pump (either battery or manual) which enables them to draw a known volume of air though the sampling device over a known period of time. The sampling device is dependent upon the type of pollutant. It may take the form of an absorbent medium, a membrane containing a reagent, or a liquid through which the air is bubbled.

The quantity of the measured pollutant is determined in the laboratory using standard chemical procedures. As with fixed-site monitoring stations, the use of portable monitors has a number of advantages and disadvantages, as described in Table 3.2

Table 3.2 Assessment of the suitability of portable monitors

Advantages	Disadvantages
- samplers are versatile and can be adapted to monitor a large range of pollutants	- samplers are relatively expensive, reducing the number of monitoring locations
- method is considered sensitive	- samplers provide only an integrated reading
- samplers can be operated unattended for a significant time period	- analysis of the samplers is often time consuming as no automation can be applied to the process
- small size of the equipment allows monitoring in locations inaccessible to continuous monitors	- samplers are reliant on power operated pumps and therefore require either a dedicated power supply or are limited by the battery operation time
- samplers are light and easy to transport	- portable monitors require calibration and maintenance
- can be used as personal monitors to record actual human exposure	- many of the pumps are not weatherproof or vandal proof, thus limiting their use to measure outdoor pollution
- can be moved around, and measurements taken at several geographically distant locations	
- with appropriate technology, monitors can be multiplexed to produce a series of timed samples for later analysis in the laboratory	

Again, the cost of the monitoring equipment and the siting difficulties were considered to be the main constraints on their use in this project.

3.2.3 PASSIVE MONITORS

In the light of the inherent limitations of traditional active, fixed-site and portable monitoring techniques, considerable effort has been devoted in recent years to developing low-cost passive monitors. Passive monitors provide only average pollution data for the full exposure period (Archibold and Crisp 1983; Goodman *et al* 1974; Atkins *et al* 1986). They can be divided into absorption, permeation and diffusion monitors. Each of these will be briefly examined and their suitability for the project assessed.

3.2.3.1 ABSORPTION SAMPLERS

Absorption samplers allow the required pollutant to be absorbed on to the sampling medium with little control over the rate of absorption. Such samplers can in turn be divided into biological and non-biological passive absorption samplers:

a) Biological Absorption Samplers. Biological samplers include devices such as moss-bags, commonly used to measure heavy metals, and lichens used to measure ambient levels of sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) (Treshow and Anderson 1989).

Lichen, sensitive to sulphur dioxide concentrations are a living organism used in many pollution surveys (Hawksworth and Rose 1976; Gilbert 1974; Kauppi and Halonen 1992; Seaward 1992). Different species of lichen have different tolerances to pollution and thus can be used to map approximate levels of air pollution. Unfortunately there are many constraints on the use of lichen as pollution monitors, not least the difficulty in identification, substrate distribution and the time-lag which exists between actual pollution levels and the lichen.

Consequently, lichens therefore only provide an indication of pollution levels at an indeterminate time in the past. Lichen surveys were therefore not considered practicable for this project.

b) Non-Biological Absorption Samplers. Non-biological samplers are based on the principles of absorption and include corrosion plates to monitor rainfall acidity, rubber strips to monitor ozone and the Leclerc apparatus to monitor sulphur dioxide etc. No reliable non-biological sampler suitable for monitoring traffic-related pollution has yet been developed.

3.2.3.2 PERMEATION SAMPLERS

Permeation monitors were developed in the late 1970s and consist of a sampling body (or badge) which is filled with the relevant 'sink' or trapping medium. A permeation membrane is placed between the reactive medium and the ambient air. The membrane, therefore, acts as the diffusion path for the air passing into the reactive medium. Each permeation sampler is calibrated in the laboratory before exposure. The samplers are then exposed for between 1 and 5 days and returned to the laboratory for analysis. Pollution concentrations of the samplers are calculated using Fick's First Law of Diffusion (Section 3.3). Due to the small size and lightweight nature of the samplers they can be placed in a wide range of locations, while the short exposure time and calibration before exposure provides relatively accurate results. The samplers can also be validated and tested against more established methods such as continuous monitors (Fowler 1982). Nevertheless, they are expensive and time consuming to prepare and analyse as each sampler requires individual calibration before exposure. For these reasons they have not been widely used for air pollution studies (Fowler 1982; McGinlay *et al.* 1996; Pio 1992).

3.2.3.3 DIFFUSION SAMPLERS

Diffusion samplers have been developed for a wide range of pollutants, including NO_2, SO_2, benzene and ammonia. Diffusion samplers have been used in a large number of studies (e.g. Bailey *et al* 1992, Hewitt 1991, Loxen *et al* 1988, Martin *et al* 1981, Noy *et al* 1990, Harrop *et al* 1990, Spengler *et al* 1983). Based on Fick's First Law of Diffusion (Section 3.3), the monitors typically consist of a tube or badge, one end of which is exposed to ambient air while the other contains an absorbent reagent on a membrane. A diffusion zone is created by the body of the monitor, through which air passes into the pollution sink (i.e. the reactive material). The rate of pollution uptake can be controlled by altering the dimensions of the sampler, i.e. diffusion width/length (Palmes *et al.* 1973; 1976; Atkins *et al.* 1986; Brown 1981). The problems and advantages of using diffusion samplers have been discussed by a number of researchers (Atkins *et al.* 1986; 1978; Apling *et al.* 1979; Boleij *et al.* 1986; Hangartner *et al.* 1989; Moschandres *et al.* 1990) and are summarised in Table 3.3.

3.2.4 CHOICE OF SAMPLER

In considering the variety of techniques and designs of air pollution monitors, it is clear that a compromise is needed between the accuracy of the data and the spatial density of the sampling network. In order to fulfil the aims of this project, the main requirement of the sampling technique was clearly for a method which provided good geographical resolution at an acceptable level of accuracy. Detailed temporal data were of less concern. As previously stated, active fixed-site monitors, and in particular chemiluminescent monitors, clearly provide the greatest accuracy but are inhibited by the cost and difficulties of locating the

Table 3.3 Assessment of the suitability of passive diffusion monitors

Advantages	Disadvantages
- the sensitivity of the device can be altered by changing the dimensions of the sampler	- results are not immediately available as there may be a delay between the end of sampling and the analysis
- Diffusion samplers are considered reliable and comparable with the well established chemiluminescent monitors	- samplers provide only an integrated reading of pollution for the exposure period
- total cost of the samplers is low, allowing a large number of samplers to used in a survey thus providing good spatial resolution	- the small size and numerous locations of the samplers incur problems of vandalism and theft
- diffusion samplers are simple to analyse and can be recycled	- samplers are subject to possible contamination during storage and transit
- the samplers can be left unattended throughout the exposure period	
- the samplers contain no moving parts and do not need a power supply	
- the samplers are weatherproof, small and therefore suitable for fixing to street furniture	
- the use of a dense network of samplers reduces the significance of individual sampler failure	

samplers. They were therefore rejected as the dominant sampling method, though they were used as a reference method in order to provide calibration and validation for the final choice of monitor. Active portable monitors were also rejected on the basis of cost and the problems of using them at unattended sites for long periods of time. Permeation monitors were rejected on the grounds of expense, difficulties in calibration and the time consuming process of sampler construction. Diffusion monitors were, therefore, chosen as the primary method of sampling for this project.

3.3 COMPARISON AND SELECTION OF PASSIVE DIFFUSION MONITORS

Most passive diffusion monitors are based on the principle of diffusion of a pollutant onto an absorption or reactive medium. Sampling occurs when air passes into the sampler by molecular diffusion and the specified pollutant is absorbed by the absorbent medium. Different media are used to sample specific pollutants. The rate of diffusion can be controlled by varying the dimensions of the sampler and is based on Fick's First Law of Diffusion (Atkins *et al.* 1986, Palmes 1978; Bocken *et al.* 1992):

$$F = \frac{D*A*(C-C_0)}{Z}$$

Where: F = mass flux (μg/s)
D = Diffusion coefficient (m^2/s)
A = surface diffusion opening (m^2)
C = external gas concentration ($\mu g/m^3$)
C_0 = gas concentration at the surface of the reaction filter (μg/m3)
Z = Diffusion length (m)

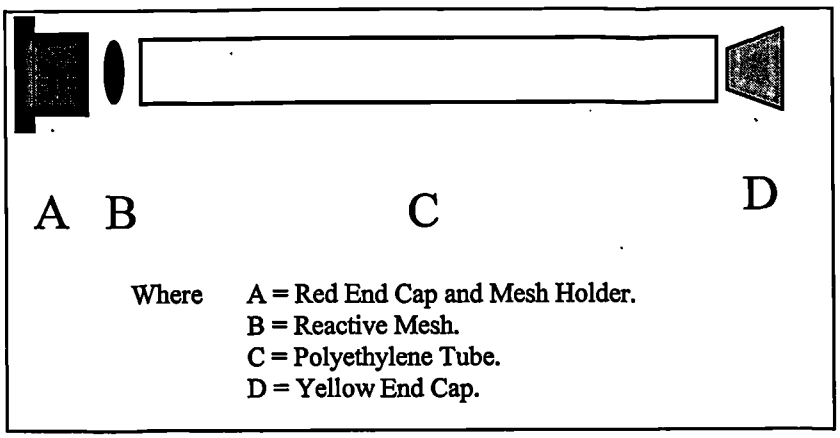
A number of diffusion samplers have been developed. Most are designed as either a badge or tube. Examples include the Yanagisawa badge (Yanagisawa & Niskimura 1982), Willems badge (Willems 1990), PRO-TEK badge (Kring 1981), Walden badge (Tompkins and Goldsmith 1977), the SVO tube (Bocken *et al.* 1992) and the Palmes tube (Palmes 1976, Atkins *et al.* 1986). Palmes tubes were the first passive diffusion sampler to be widely used. Originally designed for measuring occupational exposure to SO_2, they were later modified to measure NO_2 in ambient conditions (Palmes *et al.* 1976). Badge type samplers were developed in response to a number of limitations inherent in tube type

samplers. Both the Palmes tube and the Willems badge were evaluated for this study.

3.3.1 PALMES TUBES

The structure of the Palmes tube is shown in Figure 3.3. It consists of a tube with a mesh holder (A) which forms the cap of one end of the tube. The reactive grid (B) comprises a stainless steel mesh with a 0.21mm grid width and a 0.15mm wire thickness. The grid is inert and the spacing of the wire is small enough to allow a film of the absorbent reagent to be formed. The tube (C) is made of polyacryl and acts as the diffusive chamber through which the air passes. Both ends of the tube are machined to ensure that a good seal is formed with the caps. The end cap (D) is removed on sampling and replaced after exposure. Both caps A and D are made from inert polyethylene. Each of the caps is colour coded to facilitate identification in the field.

Figure 3.3 Components of a passive diffusion tube.



Triethanolaime (TEA) is used as the absorbent reagent for nitrogen dioxide. It is considered an effective absorbent, having near-perfect absorption (absorbent

efficiency of more than 95%) and unity of analysis (Palmes *et al.* 1976; Apling *et al.* 1979; Blacker 1973; Levaggi *et al.* 1973; Atkins *et al.* 1978).

For sampling, the diffusion tubes are mounted vertically with the large cap (A) containing the absorbent uppermost. In order to prevent deposition from the surrounding surface, a fixture (or bracket) should be used, as recommended in Brown *et al.* (1981). Sampling is started by the removal of the lower end cap (D) which is replaced at the end of sampling. The caps are colour coded to allow ease of identification. Details of the location, start and end time, and date should be recorded for purposes of analysis.

The accuracy and precision of passive diffusion tubes and their optimal operating conditions have been examined by a number of studies (e.g. Palmes *et al.* 1976; Apling *et al.* 1979; Blacker 1973; Levaggi *et al.* 1973). Comparison of diffusion tubes with standard chemiluminescent NO_2 monitors have been carried out by Apling *et al.* (1979), Atkins *et al.* (1986), Hollowell (1979), Cadoff *et al.* (1979), Heon *et al.* (1984), Boleij *et al.* (1986), Hangartner and Burri (1987) and Gair *et al.* (1991). Accuracy of the tubes relative to chemiluminescent monitors was generally found to be better than ±10%. Replication of the samplers was also reported to indicate an absolute difference of no more than 10%. Atkins *et al.* (1986), however, stated that although precision was "*generally very satisfactory*" for NO_2 concentrations greater than 5ppb, below 5ppb precision declined rapidly. Better results can be achieved by longer exposure periods at very low concentrations.

The effects of meteorology on diffusion tubes has also been investigated. A number of researchers (Brown *et al.* 1991; Boleij *et al.* 1986; Atkins *et al.* 1986) have reported that ambient air movements may create a turbulent mixing zone around the mouth of the diffusion tube, thus creating a resistance to diffusion. The turbulence generally causes the tubes to overestimate concentrations

(Bocken 1992; Girman *et al.* 1983; Heal and Cape 1997). Further research has indicated that, at low wind speeds (0.05-0.1cm/s), air within the tube stagnates, adversely affecting sampler performance (Boleij *et al.* 1986; Scheeren *et al.* 1991). Atkins *et al.* (1986), however, stated that although the diffusion tube samplers show a wind speed dependence, it is too small to be detectable. The effects of temperature on the performance of the tubes are also important. Girman (1983) observed a 15% fall in collection efficiency of the absorbent medium TEA, between 27 -15°C. He attributed this to the liquid-solid transition of TEA at 21°C. From the comparison between chemiluminescent monitor and the diffusion tubes, however, Atkins *et al.* (1986) concluded that no temperature bias could been seen in their data.

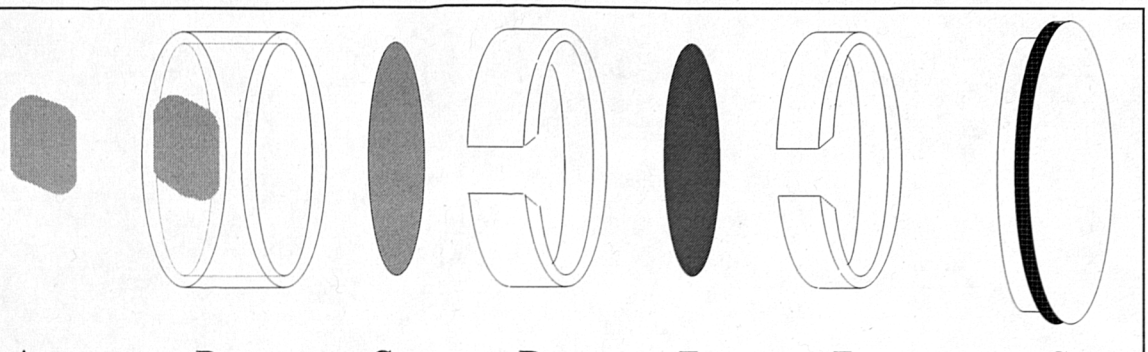
A further consideration in using passive diffusion tubes is the potential of the thermal and photochemical reaction of NO, NO_2 and O_3 in the air inside the diffusion tube to be modified, thus affecting the results. According to Atkins *et al.* (1986), this effect is only of importance during daylight hours and would not affect the precision of the tubes. Also of importance is potential interference on the absorption rate by peroxy acetyl nitrate (PAN) which gives rise to nitrate ions on hydrolysis. In most cases, however, neither PAN nor nitrate ions are likely to be present in sufficient concentrations, or over sufficiently long periods, to cause serious problems (Atkins *et al.* 1986, Gair 1991, Hisham and Grosjean 1990).

As mentioned previously, problems of contamination during preparation, storage and analysis of the diffusion tube also exist. These problems are not normally serious, however, and can be overcome by careful and meticulous laboratory procedures and by proper storage facilities (Miller 1988; Bocken *et al.* 1992).

3.3.2 WILLEMS BADGES

Passive diffusion badges have been developed to measure a range of pollutants (e.g. Yanagisawa and Nishimura 1982; Mulik *et al.* 1989; Kring 19** and Scheeren 1991). Most badges have been based on a similar design principle. The Willems badge, chosen for use in this study, is one of the more widely used and extensively tested versions (Bocken *et al.* 1992; Willems 1993; van Reeuwijk and Lebret, 1993). It was developed by J.J.H. Willems in 1987 at Wageningen Agricultural University (Willems 1990). Originally developed for measuring NH_3, it was later adapted for monitoring O_3 (Scheeren 1991) and NO_2 (van Reeuwijk 1991). The body of the badge (Figure 3.4) consists of a circular vessel made of perspex (B), into which is placed a Whatman GF-A glass fibre filter (C). The filter is coated in Triethanolamine (TEA), an absorbent reagent for NO_2. A spacer ring (D) is then inserted, followed by a hydrophobic Teflon membrane (Schleicher and Schuell TE-38, 5μm) (E). The membrane is re-enforced with polyester fibres to ensure sufficient stiffness, while the 5μm pores allow air to penetrate into the inner chamber and circulate. The Teflon membrane is used to reduce the effects of turbulence. The inclusion of polyester fibres in the membrane ensures that the membrane will not vibrate during exposure, as this would create a pump-like situation resulting in an over-estimation of the measured concentration. Finally, a fixation ring (F) is placed in the badge to ensure that the Teflon membrane remains fixed in place and to that no movement occurs when removing the lid (G). The lid is made of inert polyethylene. The badge is attached to its fixture or bracket using Velcro to allow easy installation/removal. The bracket is designed to act as a rain shield for the badge.

Figure 3.4. Components of Willems Badge



Where A = Velcro
B = Outer casing
C = Reaction filter
D = Spacer ring
E = Teflon membrane
F = Fixation ring
G = Lid

Analysis of the badges is based on the established Saltzman colorimetric method (Saltzman 1954). The exposed reaction filter (C) is placed in contact with a modified Saltzman reagent (Palmes *et al.* 1976) which causes a colour alteration in the solution. The degree of colour change is measured with a photometer (λ = 540nm) and is proportional to the amount of captured NO_2. The actual amount of NO_2 captured by the badges is calculated using Fick's First Law of Diffusion, allowing for the transport resistance.

Although NO_2 badges are still subject to a number of problems common to most diffusion samplers, such as interference from PAN and the effect of temperature on sampling rates, the badge is designed to eliminate many of the other limitations found with diffusion tube samplers. The most obvious is exposure time. As already stated, by reducing or increasing the diffusion length, the rate of sampling can be altered (Atkins *et al.* 1986; Hangartner 1987). The geometry of the badge, with its large surface area and short diffusion pathway, allows

greatly reduced exposure times compared to the Palmes tubes. Exposure times of 1-2 days may be used. The shorter diffusion path also reduces the effect of turbulence on the sampler.

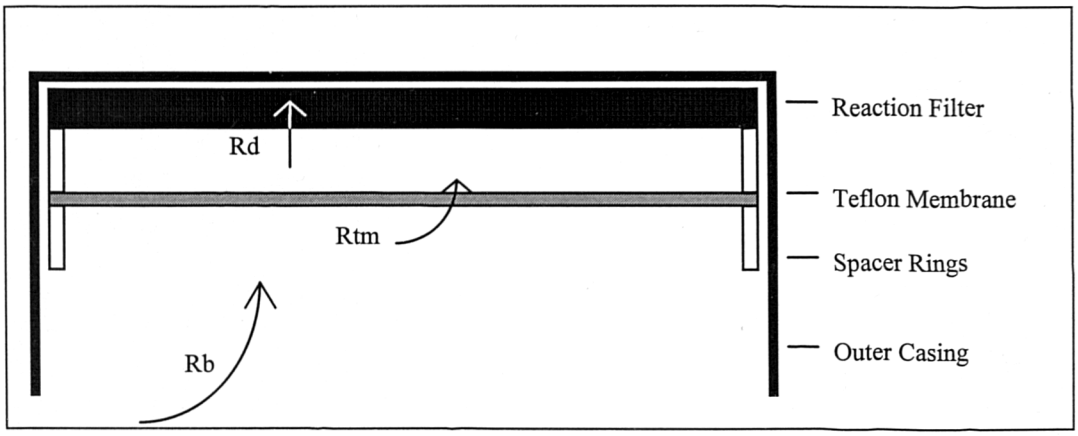
The Teflon membrane (E), however, adds a new problem to the sampler - that of resistance (Figure 3.5). The membrane and the shape of the badge affects the flux of NO_2 molecules. In reaching the reaction filter (C), the molecules experience three transport resistances: the boundary layer resistance at the mouth of the badge (Rb), the Teflon membrane resistance (Rtm) and the diffusion resistance (Rd). The boundary layer resistance (Rb) is due to the short distance between the rim of the badge and the Teflon membrane. This resistance would be removed if the Teflon filter were placed over the end of the badge. The rim, however, is needed to create space for the cap to be fixed in place. The shape and resistance of the boundary layer is dependent on the turbulence around the mouth of the badge. As wind speed and therefore turbulence increases, the effect of the boundary layer resistance decreases. The Teflon membrane, used to prevent undesirable absorption reactions and to reduce turbulence in the badge, forms the second resistance barrier (Rtm). The resistance from this barrier is assumed to be constant (Willems 1990; van Reeuwijk *et al.* 1993). The third resistance is the diffusion resistance (Rd). This is a function of free moving molecules in the area between the Teflon membrane and the reaction filter. The diffusion resistance is expressed as a measure of the diffusion length (z) and the diffusion coefficient of NO_2 (D):

$$Rd = \frac{z}{D}$$

The diffusion coefficient (D) is dependent on temperature and pressure. van Reeuwijk (1991) stated that a fourth "chemical" resistivity factor could be assumed due to the influence of humidity on the absorbance rate of NO_2 on

TEA. As the factors needed to calculate the resistivity factor of the badges, namely meteorological factors, cannot be measured at every site due to lack of monitoring equipment, certain assumptions must be made by the analysing laboratory based on reference devices and meteorological data, thus creating an additional source of error.

Figure 3.5 Cross-section of a badge, indicating paths of resistivity.



3.3.3 Comparison of Passive Samplers - A Pilot Study

In order to make a selection between badges and tubes for this project, a pilot study was undertaken, in which both devices were used in combination at a number of sample sites. The study was conducted in all four participating SAVIAH centres (i.e. Poznan in Poland, Amsterdam in Netherlands, Prague in the Czech Republic and Huddersfield in the UK). The Polish study, however, primarily concentrated on measuring levels of SO_2 and is therefore excluded from these discussions. All other centres monitored NO_2 levels. The planning and preparation for the Huddersfield study were conducted as part of the project

reported here. Eighty sites within the study area were selected in accordance with the standard protocol for air pollution sampling (Section 4.5). The sites were distributed to provide both a wide range of pollution levels and a good geographical coverage (Figure 3.6). Sites were chosen as either regional background sites or kerbside sites in accordance with the Department of Environment's regulations for the siting of air pollution monitoring sites (QUARG 1993). Each site was first visited to check its suitability and to obtain permission where necessary. Metal brackets, designed to hold both tubes and badges (Figure 3.7), were then affixed to suitable street or garden furniture. Information on the site character (appendix 1) was also recorded in order to help interpret any variations in performance.

From previous studies conducted in the Netherlands (Bocken *et al.* 1992) and a review of published literature concerning both badges and tubes (Harssema 1992), it was initially expected that the pilot survey results would favour the use of badges over tubes. It was this expectation that resulted in the decision to use the Willems badge at all eighty sites for the pilot survey. Palmes tubes were placed at only twenty of these eighty sites, due to financial restrictions, as a basis for comparison of the monitoring techniques to be undertaken.

For the pilot survey, duplication of both types of sampler occurred at each site to allow at-site variations to be examined. In addition, a number of sites were located at fixed-site monitoring stations in order to allow calibration of the samplers (Ladybower (rural) and Dewsbury (urban)). Although both the Ladybower and Dewsbury sites were outside the confines of the study area, they were included in the surveys as they were the locations of the nearest available chemiluminescent monitors. In Huddersfield, further reference sites were used: two urban and two rural were used to test the absorption rates on unexposed samplers (i.e. field blanks). Duplicate field blank samplers were placed at the

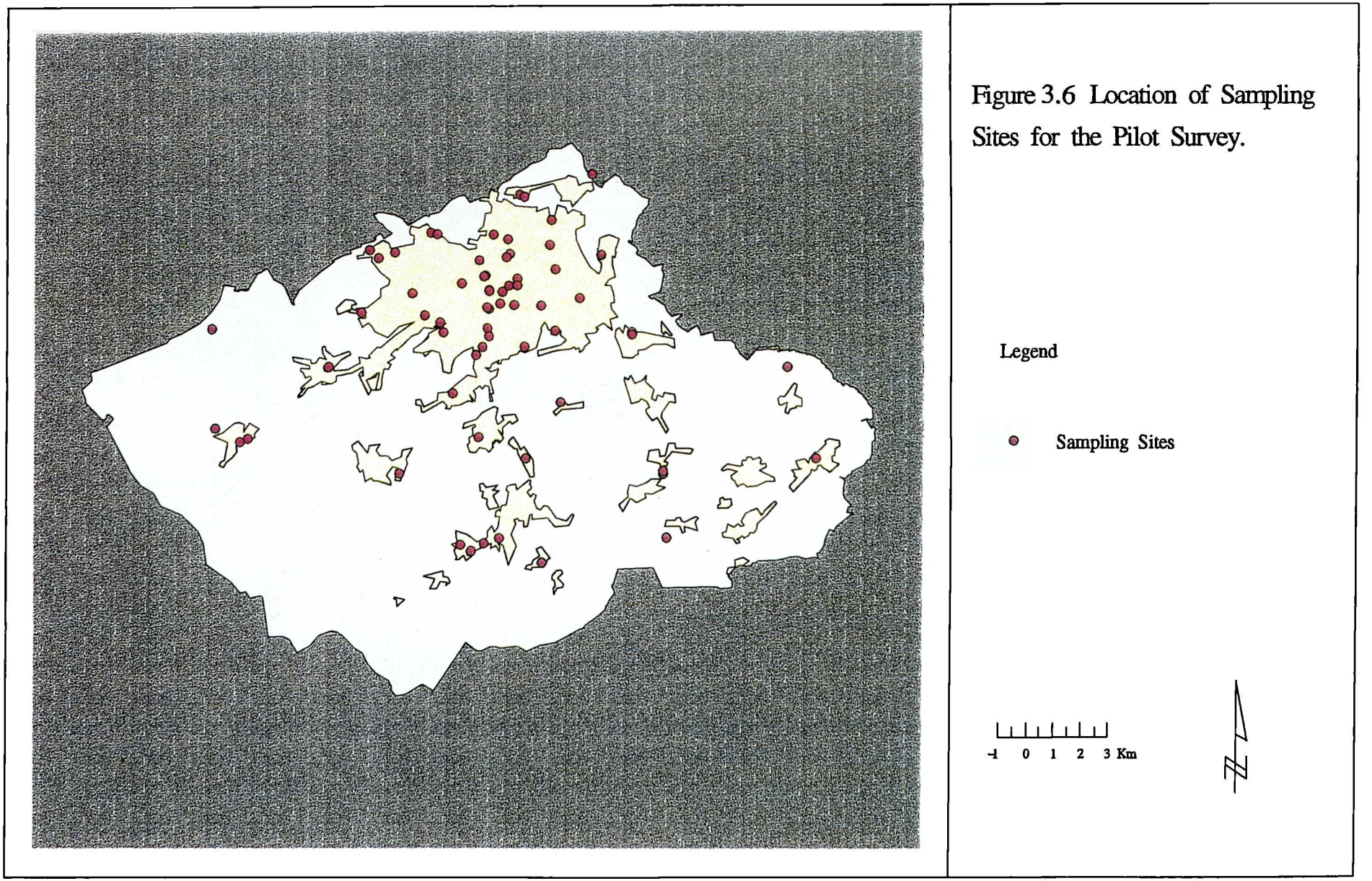
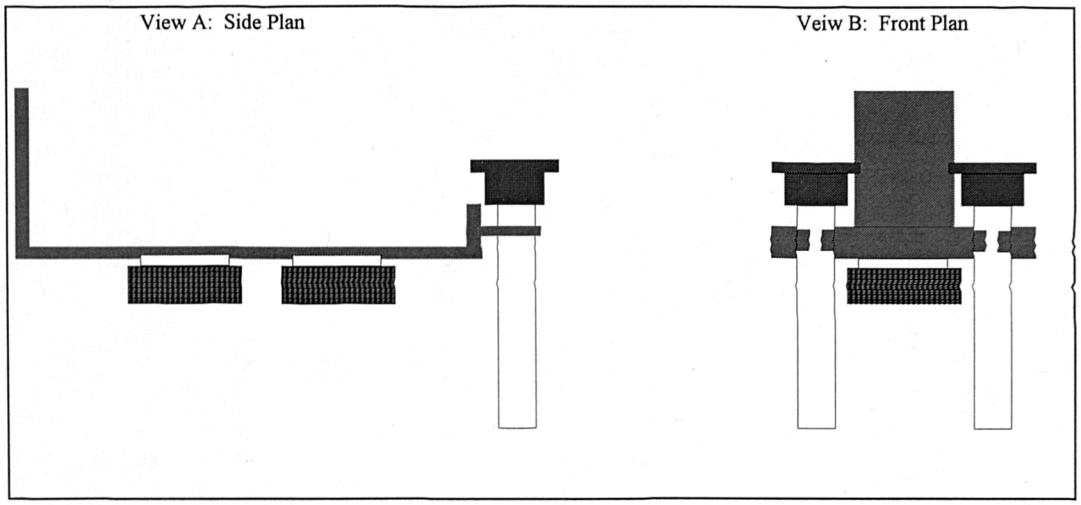


Figure 3.6 Location of Sampling Sites for the Pilot Survey.

Figure 3.7 Position of the badge and tube samplers on the bracket.



above locations next to their exposed counterparts during the survey. In each case the seals on the blanks were deliberately broken and then immediately replaced. Four laboratory blank samplers were also used. These were stored in a refrigerator (Girman 1983) for the duration of the sampling period and used to assess sampler contamination and TEA breakdown during storage and transportation. When not in use, all samplers were stored in a refrigerator at 4°C (Girman 1983; Atkins *et al.* 1986) and were transported in insulated packaging by courier post between the laboratories.

Four teams of two field workers were used to place the samplers in the field, thus reducing the time-lag between exposure of the first and last sampler. Samplers were exposed for a two week period during June 1993. On collection, it was noted that a number of the badge samplers had suffered damage through the collapse of the Teflon membrane onto the reactive filter. Although the damaged badges were returned to the laboratory for inspection, analysis was not undertaken as in all cases the filter was thought to have been contaminated. At one site, the samplers (both the badges and tubes) had been stolen, thus further reducing the number of sites for which data were available. Similar sampling

protocols were used in the other study centres. A summary of the survey structure is given in Table 3.4.

Table 3.4 Summary of the pilot survey structure.

Centre Name	No of Samplers (inc blanks)		No of Missing / Damaged Samplers		No of Blanks	
	Badges	Tubes	Badges	Tubes	Badges	Tubes
Huddersfield, UK	170	45	13	2	8	8
Amsterdam, NL	152	36	14	4	8	9
Poznan, PL	16	70	-	-	8	6
Prague, CZ	168	34	20	8	6	8

3.3.3.1 ACCURACY OF SAMPLERS

Although both the badge and tube samplers have been assessed for systematic error in laboratory conditions (Boleij *et al.* 1986), performance under such conditions does not necessarily give a true indication of performance in the field. Unfortunately, under field conditions, the true pollution concentrations are rarely known. Assessments of sampler accuracy are therefore normally made by comparing results from the samplers with a reference method, normally a chemiluminescent monitor. In this case, it was hoped that results from both badge and tubes could be compared with chemiluminescent monitors at two sites: the rural site at Ladybower and the urban site at Dewsbury. Unfortunately, comparison of the diffusion badge samplers with the results from the chemiluminescent monitor, were not possible, owing to the factor of resistivity. As noted, the resistivity factor affects the measured concentrations of NO_2 and therefore must be considered. No standard resistivity factor exists, however, so it must be determined individually for each badge. This is ideally accomplished by comparing the concentrations of NO_2 with independent measurements of pressure, temperature and wind velocity etc. As these cannot be measured at

each sample site, it is usual to compare the sampling results with an independent reference method, i.e. the chemiluminescent monitors. Thus the badge samplers are actually calibrated to the very device which would be used to assess their accuracy. This process effectively eliminates the possibility of calculating the accuracy of the badges. The calibration process for the badges is explained in more detail by van Reeuwijk *et al.* (*in press*).

Results from the pilot survey (Table 3.5) indicate that the diffusion tubes recorded higher levels of NO_2 than the chemiluminescent monitor at the Ladybower site (rural) but not at the Dewsbury site (urban) (Table 3.5). Differences between readings at the Ladybower site may be because the diffusion tubes were not immediately adjacent to the sniffer pipe inlet of the chemiluminescent monitor; this was rectified in later surveys

Analysis of the samplers (4 at each site) placed adjacent to the continuous monitors indicated that, overall, tubes at the Ladybower site did not provide a close resemblance to pollution levels obtained from the reference method (see Table 3.5). Diffusion tubes as the urban Dewsbury site did, however, record much closer resemblance to the continuous monitor (reference method). There may be a number of explanations for this result. In field trials conducted by Tromp *et al.* (1987), it was found that, on average, the accuracy of the Palmes diffusion tubes was worse in a street location than in a rural location. This may be due to the increase in very localised turbulence associated with vehicle wakes. Similarly, a study by Hem and Tulleken in 1990, reported an overestimation of the diffusion tubes of 12% in rural sites, compared to an overestimation of 0-36% for urban sites. A number of researchers have stated that the diffusion tubes tend to overestimate at low concentrations (Atkins 1986; Atkins *et al.* 1995; Heal and Cape 1997). The chemiluminescent monitors may also be a subject of error. Bailey *et al.* (1992) stated that measurements from a calibrated

chemiluminescent monitor may be inaccurate due to interference present in the field. It is also noteworthy that, unlike the Ladybower chemiluminescent monitor, the Dewsbury monitor was not calibrated to the Warren Spring Laboratory national monitoring network, and thus the accuracy of the monitor is uncertain.

Table 3.5 Comparison of accuracy in the NO_2 monitoring methods.

Site Name	Diffusion Tube Concentrations (ug/m^3)	Chemiluminescent Monitor Concentrations (ug/m^3)
Ladybower	15.2	12.11
Dewsbury	38.8	40.57

3.3.3.2 PRECISION OF SAMPLERS

The ability of both the tubes and badges to provide consistent readings under uniform conditions was investigated. This was accomplished by replicating measurements at all sites. The results from the Huddersfield pilot survey were analysed using the SPSS statistical package using Oneway Analysis of Variance, to assess within-site and between-site variation. In the case of the tubes, within-site variation accounted for only 3.1% of the total variation. For the badges, however, within-site variation was 15.6% of the total. Similar analysis was undertaken at the remaining three centres and all indicated similar results (Table 3.6). These results show that both the badge and tube samplers gave high levels of precision although, overall, the tubes performed better than the badges.

Table 3.6 Comparison of within site variation (precision).

Centre Name	Within Site Variation (Badges) as a %	Within Site Variation (Tubes) as a %
Huddersfield, UK	7.4	3.1
Amsterdam, NL	15.6	4.9
Prague, CZ	7.4	2.0

3.3.3.3 CHOICE OF SAMPLERS

Based on the relative performance of the badge and tube samplers in the pilot survey, it was decided to use the diffusion tubes for subsequent surveys. Crucial factors in this decision were the slightly better precision of the tubes and the tendency of the badges to suffer damage by membrane collapse. Initially, tubes were obtained from Warren Spring Laboratory and from Rotherham Environmental Laboratory. Comparison under field conditions showed no obvious differences in the performance of the tubes from different sources, so the decision was taken to adopt samplers from Rotherham Environmental Laboratory as standard, since these were already being used in the Kirklees MC surveys and were also cheaper.

Subsequently however, further comparisons, as part of the SAVIAH study (sections 3.3.2 and 3.3.3) resulted in the decision to adopt tubes supplied and analysed by Wageningen Agricultural University, as standard throughout the SAVIAH study. For those surveys in Huddersfield conducted as part of the SAVIAH project, therefore, tubes were supplied and analysed by Wageningen Agricultural University. For other surveys, outside the scope of the SAVIAH project, tubes supplied and analysed by Rotherham Environmental Laboratory were used, to ensure consistency with Kirklees MC (Table 3.7).

Table 3.7 Type of sampling device for each survey.

Survey Used For	Date	Monitoring Device	Tubes Obtained From:
General Survey	June 1992	Tube	Warren Spring
General Survey	Mar 1992	Tube	Rotherham Lab
General Survey	June 1993	Tube / Badge	Wageningen & Rotherham Lab
General Survey	Oct 1993	Tube	Wageningen & Rotherham Lab
General Survey	Mar 1994	Tube	Wageningen & Rotherham Lab
General Survey	May 1994	Tube	Wageningen & Rotherham Lab
General Survey	July 1994	Tube	Wageningen & Rotherham Lab
Linear Surveys	July - Dec 1993	Tube	Rotherham Lab

3.4 SUMMARY

This chapter has investigated the range of air pollution sampling techniques available to this study. After careful consideration of the aims and objectives of this study, it was apparent that a compromise would have to be reached between data accuracy and the spatial coverage of the surveys. On reflection, therefore, it was decided that passive diffusion samplers would enable the maximum spatial coverage to be achieved whilst retaining an acceptable level of accuracy. Field trials of both diffusion tube and badge samplers were conducted. On the basis of these results, it was decided to use passive diffusion tubes as the primary sampling device. Two chemiluminescent monitors would be used as reference monitors for validation purposes. The following chapter details the survey design and formulates the sampling structure for this project.

4. *SURVEY DESIGN*

Considerable variation in levels of air pollution occurs within urban areas which leads to marked differences in both levels of human exposure and in the potential for environmental damage, as noted in chapter 2. In order to investigate the sources and patterns of this local variation in air pollution, this study required detailed data on pollution levels, across a range of environments and conditions.

A series of air pollution surveys were undertaken for this purpose. Three different types of survey can be distinguished, as described below:

Routine Surveys: These were designed to provide a basis for mapping air pollution in the study area. They also provided data for the validation and testing of the final air pollution maps.

Consecutive Surveys: Consecutive surveys were designed to provide a long-term description of temporal variations throughout the year and to assess whether the routine surveys provided a valid estimate of the annual mean concentrations

Special Surveys: These surveys examined specific aspects of spatial variation in air pollution at the micro scale.

The three types of surveys are discussed in detail in the following section.

4.1 ROUTINE SURVEYS

The routine surveys, as stated above, were designed to fulfil two distinct purposes. First, they provided information on the spatial variation in pollution at the local and microscale within the study area, as a basis for air pollution mapping. Second, they provided data which could be used for the validation and testing of the final pollution maps. In addition, the pilot surveys were used to help compare and select the sampling methods and develop a general understanding of spatial patterns of pollution in the study area.

The large degree of variation in levels of urban air pollution observed in previous studies (e.g. Hewitt 1991; Loxen and Noordally 1987) implies that a relatively large number of data points are required to describe pollution patterns. Consideration of cost and logistics, however, limited the number of sites and surveys which were practicable within this study. Nevertheless a total number of seven surveys were conducted between June 1991 and July 1994. In each case, between 80 and 120 sample sites were used in any one survey and each survey period lasted for two weeks. The nature and purpose of each of the surveys is summarised in Table 4.1.

As indicated in Table 4.1, surveys S_A and S_B were used to assess the use of passive sampling techniques and surveying methodology, as discussed in chapter 3. These surveys also provided pollution data for validation of the air pollution maps in the *pre* (before June 1993) study period. Survey S_5 was similarly used to provide data for validation of the air pollution maps in the *post* survey period (after June 1994). No data from any of these surveys were used in the construction of the air pollution maps.

Table 4.1. Summary of the routine surveys

Survey No	Date	No of Samplers	Core Data	Validation	Purpose
S_A	Jun 1992	80	0	80	Pilot survey. To test the sampling devices. To test sampling methods and examine general levels of variation within the study area. To provide validation and test data for the pre-study period.
S_B	Mar 1993	120	0	120	Pilot survey. To test sampling methods and examine general levels of variation within the study area. To provide validation and test data for the pre-study period.
S_1	Jun 1993	80	20	60	Core Data. Incorporated field trials to assess the performance and suitability of the badge and tube samplers for use in the EU-SAVIAH study.
S_2	Oct 1993	120	80	40	Core Data. To provide the basis for mapping air pollution and for the testing and validation of the maps.
S_3	Feb 1994	120	80	40	Core Data. To provide the basis for mapping air pollution and for the testing and validation of the maps.
S_4	May 1994	120	80	40	Core Data. To provide the basis for mapping air pollution and for the testing and validation of the maps.
S_5	Jul 1994	60	0	60	To provide validation and test data for the post-study period.

Surveys S_1, S_2, S_3 and S_4 provided the core data used in the creation of the air pollution maps. Survey S_2, S_3 and S_4 also provided data for the validation and testing of the air pollution maps during the same time period. Two types of sample sites can be defined in these surveys: core sites and variable sites.

- *Core sites.* Eighty core sites were selected to represent and describe the variation in pollution levels across the study area while providing a good

spatial distribution of sites (Figure 4.1). These sites remained constant throughout the sampling period and provided the data which formed the basis of the air pollution mapping. The core sites were not used for any validation purposes.

- *Variable sites.* Variable sites were used in survey S_2, S_3 and S_4 to provide information for the testing and validation of the air pollution maps during the survey period. These sites were not at any stage used in the creation of the pollution maps. Forty variable sites were used in each survey, sites being relocated on each occasion to provide a different network of test sites. In the latter surveys (S_3 and S_4), the variable sites focused on assessing variation in pollution concentrations at urban background sites, i.e. at sites which did not appear to be influenced by any nearby pollution source (e.g. main road, industrial factory). The distribution of the variable sites is shown in Figure 4.1.

Survey S_1 was also used to help select the sampling devices for the routine surveys. As noted in chapter 3, it was initially expected that Willems badges would be selected as the dominant sampling device, and these were therefore installed at the majority of sites. In practice, however, the Palmes tubes proved to be more reliable and were chosen for subsequent surveys. Only 20 sites from survey S_1 were thus used to examine the patterns of, and methods of mapping, traffic-related air pollution. As explained later (section 4.3), the imbalance in the number of core sites in the various surveys was allowed for through the use of multi-level modelling techniques.

The results of the routine surveys are summarised in Table 4.2. As can be seen, a number of samplers were lost due to vandalism and theft. Survey S_2 suffered most from this problem, as sites in surveys S_A, S_B and S_1 tended to be on private

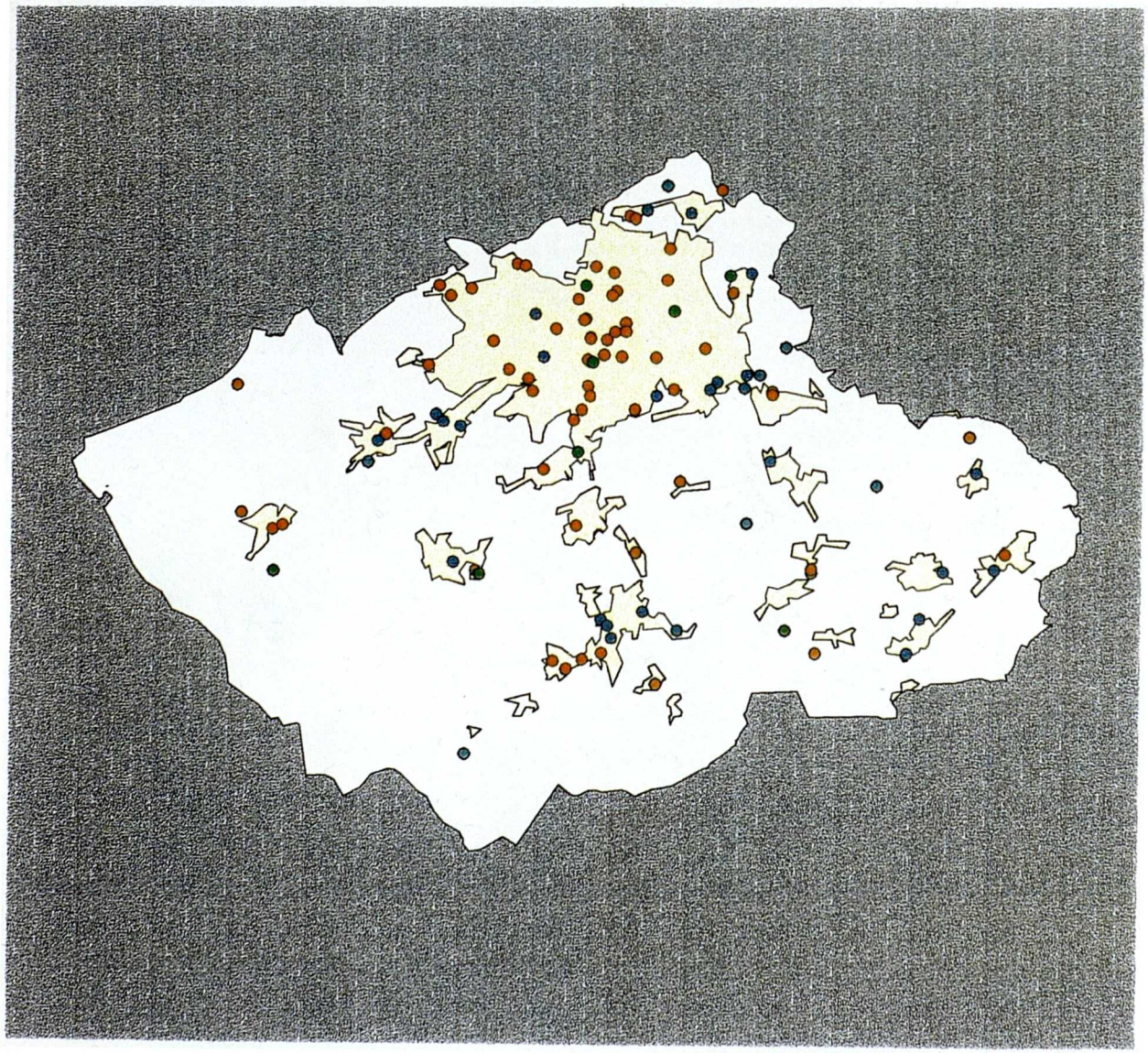


Figure 4.1 Location of Sampling Sites for the Routine & Consecutive Surveys.

land (e.g. in gardens) or in rural areas. Due to the nature of the remaining surveys(i.e. to monitor variation across the study area), however, it was necessary to place the samplers in more public and exposed areas. At sites which proved prone to vandalism in survey S_2, samplers were raised to a height of 3m, thus reducing this threat in succeeding surveys (Table 4.2).

Table 4.2 Results of the routine surveys ($\mu g/m^3$)

Survey No	Date	No of Samplers	Type of Sampler	No of Missing Samplers	Min NO_2 Conc	Max NO_2 Conc	Mean	S. D.
S_A	June 1992	80	Tube	3	15.2	58.9	31.50	10.59
S_B	Mar 1993	140	Tube	7	22.0	66.0	33.00	7.29
S_1	June 1993	80	Badge/ Tube	6	10.5	88.4	29.06	14.50
S_2	Oct 1993	120	Tube	15	27.7	79.5	46.45	10.30
S_3	Feb 1994	120	Tube	6	8.8	51.5	24.50	9.77
S_4	May 1994	120	Tube	*0*	*14.4*	*69.4*	*31.29*	*12.79*
S_5	Jul 1994	80	Tube	2	11.8	48.2	22.25	8.46

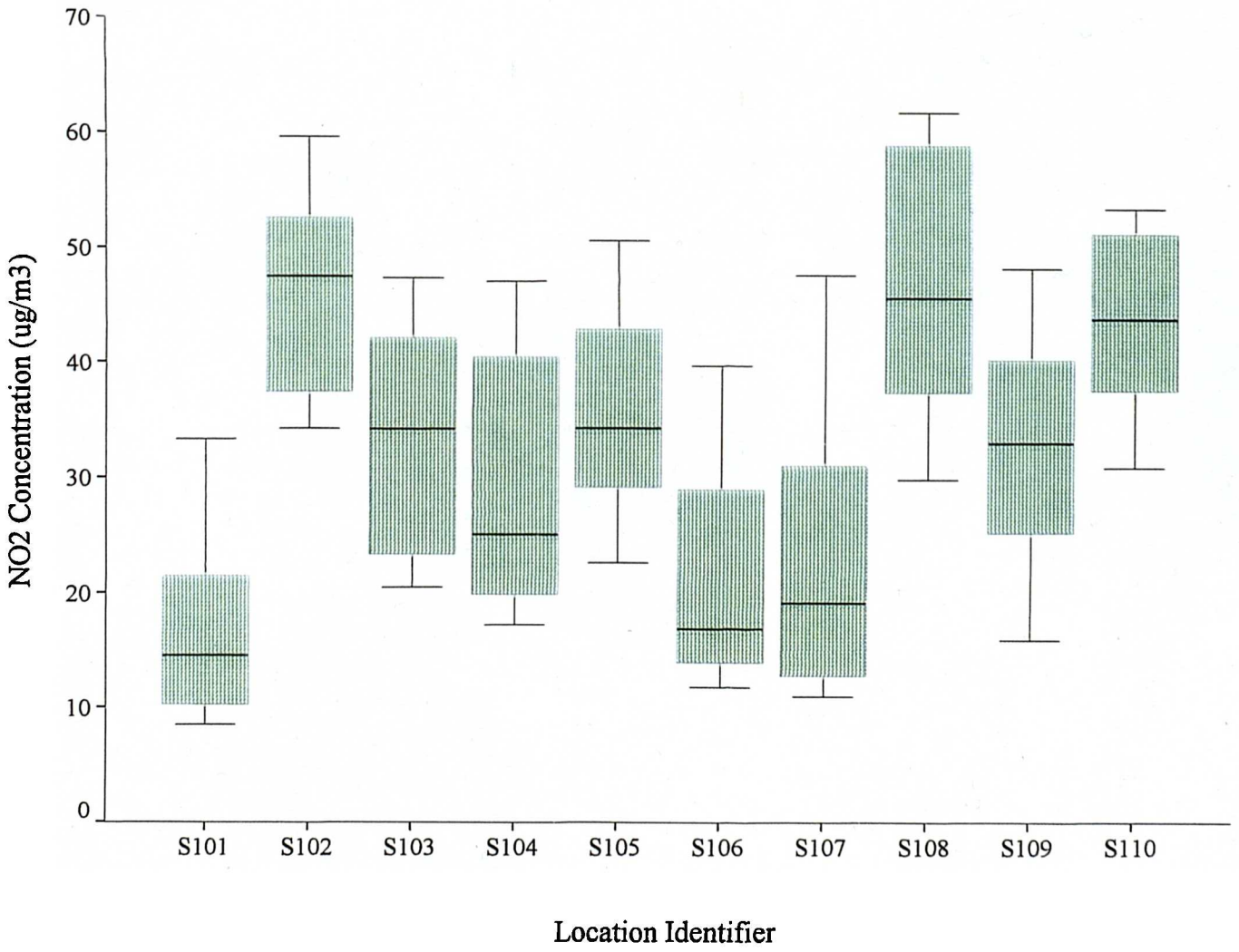
As can be observed from Table 4.2, all the surveys recorded a wide range of pollution concentrations, indicating that considerable spatial variation in pollution levels existed in the study area. A three- to eight-fold variation was seen between minimum and maximum concentrations, with standard deviations of between 7.29 and 14.5 ug/m^3 (20-50% variation around the mean). Survey S_2 - the winter survey - had the highest mean concentration (46.5 ug/m^3); survey S_4 - in July 1994 - had the lowest mean concentration (22.3 ug/m^3). No obvious seasonal pattern in the results is, however, apparent.

4.2 CONSECUTIVE SURVEYS

In order to understand temporal variation in air pollution levels in the study area, it was necessary to undertake continuous monitoring at a number of sites. No fixed-site chemiluminescent monitors existed within the study area. Consequently, for calibration purposes, data from chemiluminescent monitors were obtained from the nearest sites - a rural site at Ladybower Reservoir (part of the national network run by AEA Technology) and an urban site at Dewsbury (run by Kirklees Council MC). Consecutive monitoring using diffusion tubes identical to those used in the routine and special surveys was also undertaken at the Ladybower and Dewsbury sites, in order to provide calibration against the fixed-site monitors. In addition, a series of eight sites was defined within the study area at which passive samplers were again operated on a continuous basis throughout the period October 1993 to September 1994. These sites were selected to provide both a geographic coverage of the study area and to represent different types of land use. At each site (the 8 consecutive and 2 chemiluminescent locations), diffusion tubes were exposed consecutively for four-week periods. In order to provide data which coincides with, and is therefore comparable to, the routine surveys, however, and thus to provide additional opportunities for validation of the maps, the samplers were exposed only for a two-week time period during the routine surveys. The locations of all ten consecutive sites are shown on Figure 4.1. The results from the consecutive surveys are shown in Table 4.3.

From the results of the consecutive surveys, it is clear that a number of sites are consistently low (e.g. 101, 106) while others remain consistently high (e.g. 102, 108) (Figure 4.2). This indicates that the sites are reasonably consistent over time, but do describe spatial variations in air pollution. The ten sites also show patterns of seasonal variation, with most sites recording higher concentrations in

Figure 4.2 Box plot of NO2 Concentrations at Consecutive sites



NB. The box represents 50% of the data values, the thick black line represents the median value and the whiskers represent the highest and lowest values (excluding outliers).

the winter months and lower concentrations in the summer months (Table 4.3). Further discussion and analysis of these results is undertaken in the following chapter.

Table 4.3 Summary of consecutive survey NO_2 results ($\mu g/m^3$).

Date	101	102	103	104	105	106	107	108	109	110
18/10/93	23.0	50.7	43.3	40.6	50.6	31.9	33.7	59.3	48.2	49.4
01/11/93	33.3	59.6	47.4	47.1	46.6	33.5	34.2	59.3	46.7	53.0
01/12/93	12.5	46.8	30.5	27.1	37.0	25.7	24.1	46.2	26.4	43.0
31/12/93	16.5	51.8	39.8	39.9	39.3	39.7	28.3	49.4	32.9	42.5
28/01/94	22.0	34.2	45.3	40.6	23.8	17.3	47.6	29.8	40.5	45.5
16/03/94	10.5	37.7	20.5	21.3	22.6	14.1	11.3	33.6	15.9	30.8
13/04/94	11.6	43.0	18.5	15.5	299	12.6	12.9	38.8	-	34.9
13/05/94	18.0	53.4	26.8	18.5	39.0	16.4	14.1	58.4	34.9	53.4
27/05/94	8.5	35.0	20.8	17.5	28.6	11.8	12.2	33.4	19.5	32.9
24/06/94	8.6	37.1	21.3	17.2	31.5	12.7	11.0	42.3	29.1	40.4
26/07/94	12.0	48.2	37.8	22.9	29.7	13.8	13.4	45.2	32.9	44.6
09/08/94	10.0	38.5	25.3	21.2	31.1	14.8	13.4	41.0	23.9	34.9
08/09/94	20.9	58.5	41.0	40.3	48.5	26.0	26.9	61.7	39.9	53.5
Min Conc	8.5	34.2	18.5	15.5	22.6	11.8	11.0	29.8	15.9	30.8
Max Conc	33.3	59.6	47.4	47.1	50.6	39.7	47.6	61.7	48.2	53.5
Mean	15.9	45.7	32.2	28.4	35.3	20.8	21.8	46.0	32.6	42.9
S.D.	7.3	8.8	10.6	11.4	9.1	9.4	11.7	10.9	10.2	7.9

4.3 ANNUAL MEAN CONCENTRATIONS

The ability of the four core surveys to predict annual mean pollution concentrations was assessed using data from the 8 consecutive sites. Simple averaging of the data for each site was not used due to the effects of vandalism and damaged samplers which resulted in an incomplete data set. In order to consider the effects of the missing pollution values, multi-level modelling was therefore undertaken. A mixed effect model was applied, using terms for site, survey and sampler effects, plus interactions. Analysis was carried out by RIVM,

Bilthoven (The Netherlands), as part of the SAVIAH project. A comparison was subsequently conducted between the modelled mean values and the arithmetic mean of the diffusion tube data obtained from the 8 consecutive sites. Results shown in Table 4.4.

Table 4.4 Regression analysis of the multilevel modeling (MLM) concentrations

	Annual Mean
Degrees of Freedom	1/7
Multiple R	0.939
R^2	0.883
Adjusted R^2	0.863
Standard Error	2.554
Slope Value	0.727
Constant	8.568
F value	152.803
Significance F	0.000

The results clearly show a high degree of correlation between the modelled mean for the four surveys and the actual mean from the eight consecutive monitoring sites (r^2=0.86, SEE=2.55 ug/m^3, $p<0.0001$). Similarly high levels of correlation were also found in other centres in the SAVIAH study (Briggs *et al.* 1997). Thus the four core surveys may be assumed to provide a reliable estimate of mean annual concentrations across the study area.

4.4 SPECIAL SURVEYS

A number of special surveys were designed to assess the micro scale variation in pollution levels within the study area. The surveys were conducted to examine two main sources of variation:

Roadside Surveys: Roadside surveys were designed to examine variation in air pollution in relation to traffic flow and distance from road.

Vertical Surveys: These surveys were designed to assess variation in pollution concentrations with sampling height.

The number of sample sites used in each of the above surveys varied depending on local characteristics. Each sample site was chosen in accordance with the sampling protocol described in Section 4.3 (below) and each survey period lasted for two-weeks. The following sections describe each of the two types of special survey in turn and examines their specific aims, requirements and initial survey outcomes.

4.4.1 Roadside Surveys

Roadside surveys were conducted at a number of roads within and adjacent to Kirklees (Figure 4.4). A variety of roads were chosen. These ranged from dual carriageways (e.g. site N422 - A638 near Cleckheaton) to minor country roads (e.g. site U101 - Hopton Lane). All roadside surveys were undertaken simultaneously with surveys of road traffic volume conducted by HETS (West Yorkshire Highways, Engineering and Technical Services). Hence it was possible to gain detailed information on the traffic volume at the time of sampling. This information allowed the effect of traffic volume on pollution concentrations to be examined.

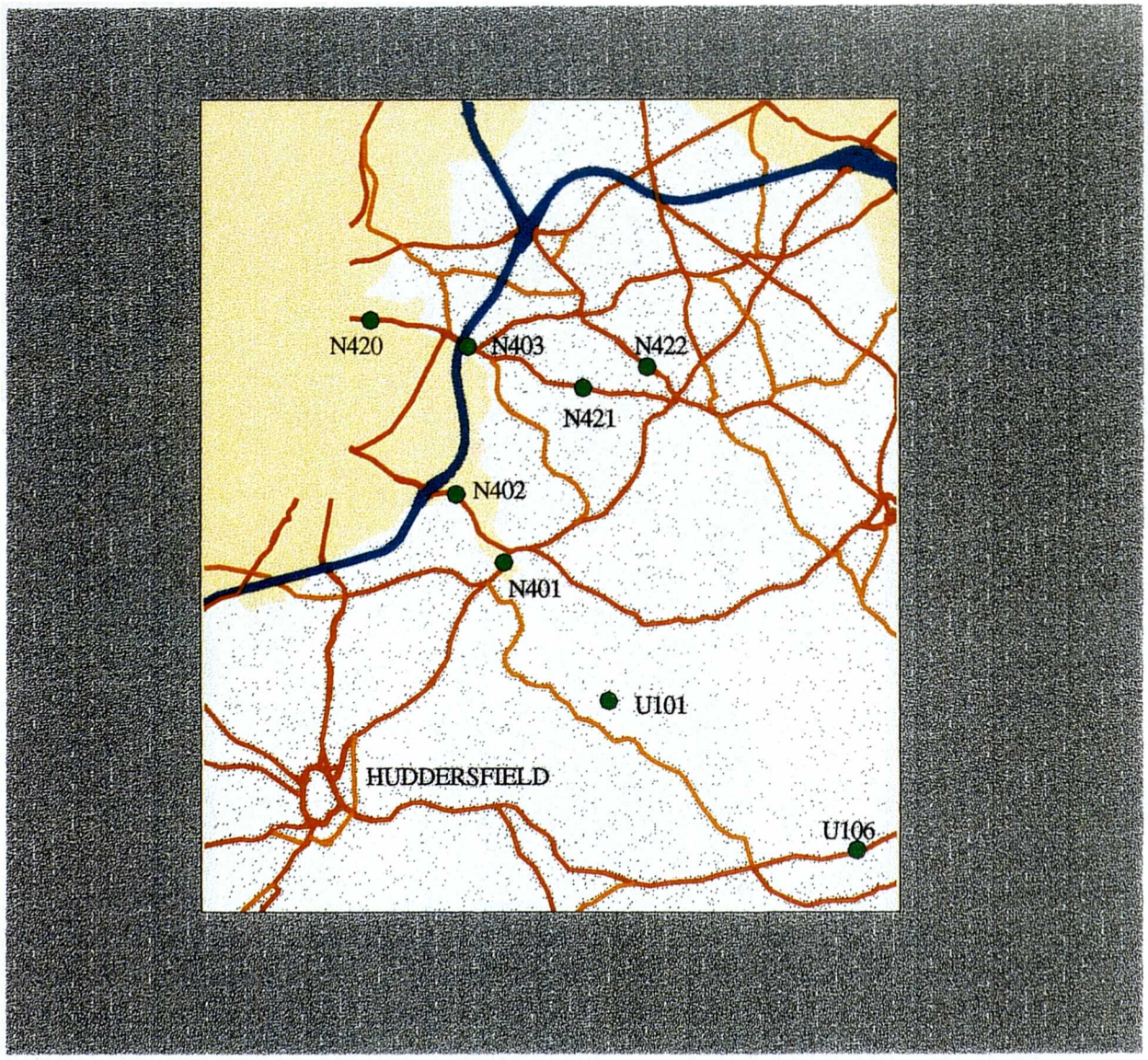


Figure 4.3 Location of Sampling Sites for Near–Source Survey

Legend

Sample Sites

Calderdale

Kirklees

Motorway

Trunk Road

Main Road

Secondary Road

-1 0 1 2 3 Km

Sample sites were chosen in accordance with the siting protocol (Section 4.3), at points perpendicular to the road (Figure 4.5). At every site, information was collected on the site characteristics and recorded on site description forms (appendix 1). The number of sites at each survey location was dependent on access to the site and the availability of suitable street or garden furniture (Table 4.5). Thus the number of sample sites varied from a maximum of nine sites at location N401 to a minimum of two sites at N420. As far as possible, samplers were located on both sides of the road with at least one sampler placed on the kerbside, and others located in transects ranging up to 200m from the road-axis. In a number of cases, however, it was only possible to place samplers on one side of the road. This was especially true in town centre areas (e.g. site N420 - A649, at Hartshead Moor), where access was restricted.

Weather data was also collected during the sampling period at the weather stations closest to the sample site (either Huddersfield University station or Leeds Meteorological station). The data was used to examine dispersion conditions throughout the sampling period and as input data for dispersion modelling (see Chapter 6).

Figure 4.5 Example of sampler locations at a roadside site.

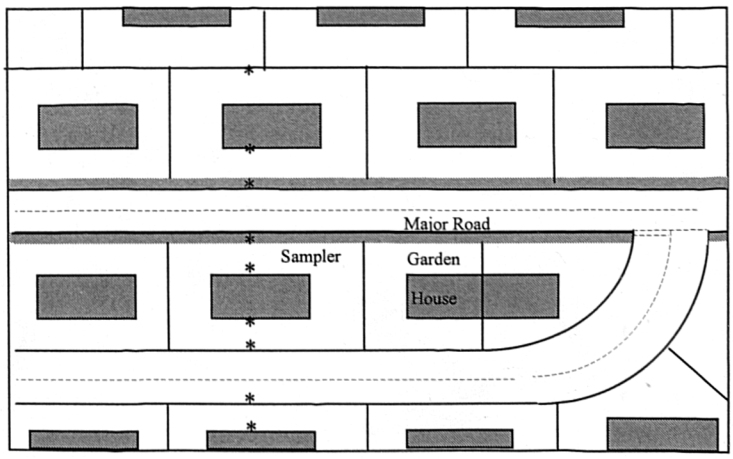


Table 4.6 Summary of information collected for each site during roadside surveys (NO_2 concentrations in $\mu g/m^3$)

Site-ID	Road Name	Road Width (m)	Start Date	No of Tubes	No of Missing tubes	Min NO_2 Conc.	Max. NO_2 Conc.	Mean	S.D.
N401	A62 Leeds Rd	9.3	19/07/93	9	-	16	37	22.33	5.93
N402	A644 Kirklees Hall	7.5	19/07/93	4	-	34	60	49.75	10.11
N403	A649 Hartshead Moor Side	7.5	19/07/93	4	-	28	37	32.50	3.20
N420	A649 Hartshead Moor	10.0	26/07/93	2	-	20	22	21.00	1.00
N421	A649 Liversedge	7.0	26/07/93	6	-	16	29	23.17	4.80
N422	A638 Littletown	14.0	26/07/93	6	2	21	30	24.25	3.69
U101	Hopton Lane	7.0	26/07/93	4	-	16	31	23.75	6.38
U106	A642 Stanley	6.0	26/07/93	4	2	21	23	22.00	1.00

4.4.2 VERTICAL SURVEYS

Vertical surveys were conducted to examine the variation in pollution levels with sampling height. A number of surveys have been conducted by various researchers to study the effects of NO_2 variation with height (Loxen *et al.* 1988; Loxen and Noordally 1987; den Tonkelaar *et al.* 1987). While indicating that such variation could be identified, the studies were mostly conducted in major urban conurbations to a height of 3-4 storeys (9 - 12 metres). No published studies, however, have been identified in which the NO_2 variation has been examined to heights of greater than about 5 storeys in a relatively small urban centre.

A number of buildings of between 18 and 23 metres were identified within the town centre and permission for access obtained (Figure 4.6). A number of buildings outside the town centre were also considered for this study, but

Figure 4.5 Location Map of Sample Sites used in Vertical Surveys

Legend

Sample Sites

Trunk Road

Main Road

Secondary Road

Road > 4m wide

Other Road

-1 0 1 2 3 Km

subsequently rejected, for a number of reasons: either permission for sampling was denied, or a suitable emission source near the building was not identified, or the buildings were working industrial premises which would influence the results. Where possible a diffusion tube was placed on the outside of the building at every floor, in accordance with the sampling protocol. In some cases, however, access was either restricted (i.e. windows would not open) or the conditions of the sampling protocol were not met. On a number of floors, therefore, sampling could not be conducted. Again, concurrent meteorological data was collected from the University of Huddersfield weather station. Survey format and preliminary results are shown in Table 4.6.

Table 4.6 A summary of information collected for the vertical surveys (NO_2 concentrations in $\mu g/m^3$)

Building	No of Floors	Start Date	No of Tubes	No of Missing Tubes	Min NO_2 Conc.	Max NO_2 Conc.	Mean	S.D.
Oldgate House	9	20/07/93	9	-	22	31	25.22	2.57
Tech. College	8	15/08/94	8	-	24	45	31.630	7.01
University	10	15/08/94	10	-	21	41	30.50	5.50
St Peters	10	15/08/94	10	-	22	33	25.00	3.19

4.5 SAMPLING PROTOCOL

In order to ensure representativness and replication of results, it was essential that the choice of site locations was carefully controlled. A number of studies have indicated that choice of site location is very important, and have consequently suggested several factors which should be taken into account in siting the diffusion tubes (Brown 1981; Hargartner 1989; Munn 1981; Noll and Miller 1977; Bower 1991). Based on these recommendations, the following protocol was developed:

Siting Protocol.

1. Sampler locations should be chosen to be representative of their surroundings.
2. Care should be taken to avoid areas of uneven terrain (where the height of the sampler cannot be accurately ascertained) and sites which may be prone to vandalism.
3. Urban background sites should be between 50-100m from a major road.
4. Where possible, the presence of buildings or large obstacles which may distort the air flow should be avoided.
5. In order to retain as much similarity as possible, samplers should be located perpendicular to buildings or walls etc. In the case of major roads, samplers should be placed with their brackets parallel to the road.
6. Samplers should not be sited in areas of *exposed or stagnant air.*
7. Samplers should not be sited near emission sources, e.g. extractor fans, gas flues etc.
8. Samplers should be placed in an upright position (a variation of 10-15^{o} is considered acceptable).
9. Samplers should be set between 2 and 3m from ground level (3m is acceptable in areas prone to vandalism).
10. Samplers should be attached via 'Velcro' or a 'terry clip' to a bracket to prevent deposition from the immediate surroundings.
11. The brackets should be attached by waterproof PVC tape or self amalgamating rubber tape to suitable fixtures (e.g. drain pipe, clothes post, garden furniture, free standing post).
12. At all sites, specific measurements and site plans should be taken during the field visit (see appendix 1).

Once suitable sites had been identified with respect to the above siting protocol and necessary permission obtained, the following siting procedure was undertaken. Prior to each survey, each site was visited 1-2 weeks in advance, in order to attach the sampling bracket in the selected position. In order to obtain information which might help explain the variation in pollution concentrations, details of the site characteristics were recorded at each site (appendix 1). On returning from the field, this information was transferred to a database for ease of analysis. A site and area plan were drawn for each site to aid the field-workers in locating the sites during the surveys. This site plan would also allow the exact position of the samplers to be found for future surveys (appendix 2). At the end of the sampling period, each bracket was removed to prevent vandalism and theft.

On each occasion, samplers were exposed for either a two week or, in the case of the consecutive surveys, a four week period. As noted in Chapter 3, different samplers were used on various occasions and replicates were used at most sites. For all core and consecutive surveys, except survey S_2, all site measurements were duplicated. In addition both field and laboratory blanks were used to assess the accuracy of the tubes. Laboratory blanks remained in a refrigerator at the required temperature for the entirety of the sampling period. This allowed tube contamination during storage and long distance transit to be investigated. Field blanks were installed adjacent to operational diffusion tubes and the seals broken to allow comparison of contamination during sampling and local transit to be examined.

Installation of the tubes was conducted by four teams of two field-workers. Each sampling team was allocated a number of colour coded sites and briefed fully on how to place the tubes in the field, how to deal with the blank samplers, what to do in an emergency (e.g. transportation failure, inability to locate a site, lack of

time, etc) and what to record in the field log. A fifth team attended all briefing sessions, but remained on standby in case of emergencies. Each of the sampling teams was given a field-worker protocol which reinforced the briefing requirements and could be consulted in the field (appendix 3). The field logs were designed to be simple to use in the field. They contained information on site-ID, address, start/end time, date and tube number. After the samplers had been placed in the field, the field logs were cross-referenced with the laboratory check list which contained all the tube numbers. Any errors (e.g. duplicate tube numbers in the field logs) could then be queried on sampler collection. This process was repeated with the 'end of sampling' field logs. Each tube number consisted of a four digit number which included a code for survey number (see appendix 4).

To reduce further the possibility of human error, a laboratory check list which recorded the unique identification code of each tube was provided with each shipment of tubes (appendix 4). On arrival in Huddersfield, each tube was rechecked against the laboratory check list to ensure that the required number of tubes had arrived and to prevent the possibility of duplicated tube numbers. It also allowed each sampler to be examined for damage during shipment. Each tube number was then allocated to a sampling team. Cross-referencing of this check list against the field logs occurred during and after sampling as noted above. Missing or damaged samplers were also recorded on the list. All samplers recovered, including the blank samplers, were returned to the laboratory blind, along with a list of tube numbers. Field logs were sent separately to the co-ordinating centre in the Agricultural University of Wageningen, Netherlands.

Laboratory analysis of the samplers were conducted blind and the results sent to the co-ordinating centre in the Netherlands for matching against the field logs in order to obtain exposure times and therefore allow the calculation of

concentrations of NO_2. The site-id and tube number remained constant throughout this process to allow each tube to be traced through the system.

4.6 SUMMARY

This chapter has described in detail the survey methodology used in this research. A range of surveys was undertaken, with different objectives. The sampling methodology used in each survey, and the selection of sample sites, was kept as rigorous and consistent as possible in order to reduce the number of confounding factors and effects of human error. The next chapter examines the data collected in these surveys.

5. *SOURCES, PATTERNS AND MAGNITUDE OF VARIATION*

A sound understanding of the magnitude, source and patterns of air pollution variation at the small area level is essential as a basis for air quality management. Without this, it remains difficult to predict or interpret patterns of variation in air quality, and thus to generate reliable pollution maps. Nor is it possible accurately to assess either human exposure to air pollution or potential health effects.

Research in this area has been limited, spasmodic and piecemeal. Most studies have focused on small areas (e.g. a single street canyon) or a particular aspect of variation (e.g. distance from roads). Few studies have attempted to quantify or compare the effect of different factors on air pollution across an entire area.

This chapter, therefore, examines the sources of variation in air pollution in the study area. It considers both spatial and temporal components of variation and assesses the extent to which each of these, first individually and then collectively, can explain patterns of variation in the study area.

5.1 SOURCES OF VARIATION

In general terms, three main components of variation in air pollution may be identified: spatial variation, temporal variation and measurement error. Each of these, however, derives from a number of sources , as explained below.

5.1.1 SOURCES OF SPATIAL VARIATION.

Spatial variation, defined as the variation over space in one time period, is exceedingly complex and can be considered to occur on both the horizontal and vertical plane. Horizontal or geographic variation normally dominates spatial variation. Hewitt (1991) stated that variation in NO_2 concentrations could be related to traffic volume and land cover. In addition, within urban environments, complex patterns of variation can also be perceived on the vertical plane. Loxen and Noordally (1987), for example, noted that traffic-related NO_2 concentrations varied between 54 and 90 $\mu g/m^3$ with height from ground level in a canyon street in London. Spatial variation can therefore be considered to be three-dimensional. The amount of spatial variation in pollution concentrations is dependent on two factors: that of emission patterns and dispersion patterns. The factors which determine the dispersion and emission patterns are discussed below.

5.1.1.1 FACTORS INFLUENCING SPATIAL EMISSION PATTERNS

Emission patterns and characteristics, whether they be from line, point or area sources (e.g. roads, chimneys or residential housing estates), will greatly influence the three dimensional patterns of spatial variation. The land cover type will influence the magnitude of pollution levels. The distribution of the road network, for example, will affect emission patterns in an area (Williams *et al.* 1988; Harrop *et al.* 1990; Eggleston *et al.* 1992; Hewitt 1991; Davison and Hewitt 1996; Green and Gebhart 1997). Additionally, central and local government structure plans, by actively encouraging or restricting the location of industry and housing development, will also influence the age of developments and thus the distribution of emission sources. For example, the type of heating fitted, age (affects the amount of building insulation), and type of property (detached, semi-detached, terraced house, flat, warehouse)

and nature of use (i.e. residential, commercial, industrial usage) will all affect the magnitude of emissions contributing to ambient air pollution.

Variation within those land cover types will also influence emissions. For example, variation in the emission characteristics of a particular source type (i.e. linear, point or area) such as road traffic will be affected by traffic volume and composition, speed, fuel type, the age of the vehicle and the driving habits of the user (i.e. heavy acceleration and deceleration).

The presence of abatement technology such as catalytic converters in the case of road transport and scrubbers (cyclones, electrostatic precipitators, etc) in the case of industrial point sources, contribute to a reduction in emissions and therefore affect the magnitude of spatial emission patterns. The presence of abatement technology is expected to improve in light of recent changes in air pollution legislation and this will affect the magnitude of pollution in the future.

Meteorological factors such as external temperature will affect the efficiency of control technology (e.g. in cold weather emissions from vehicles fitted with catalytic converters will be higher owing to the inefficiency of the technology at low temperatures).

5.1.1.2 FACTORS INFLUENCING SPATIAL DISPERSION PATTERNS

The dispersion of pollutants on both a horizontal and vertical plane is also important in understanding patterns of pollution in the urban environment. The spatial patterns of dispersion as with emission patterns, however, can be influenced by a number of factors. Emission characteristics such as exit temperature, emission rate and emission height will initially influence the dispersion of a gas or particulate. For example, hot gases with a high fast release rate will have greater initial buoyancy and therefore the potential for greater dispersion. Meteorology is also an important consideration. Wind

speed, wind direction, ambient temperature, the amount of sunshine/cloud cover and therefore the stability of the air will affect the amount of turbulence, buoyancy of the emission 'parcel', likelihood of temperature inversions, development of photochemical smog and the level of scavenging (removal of pollutants from ambient air by a range of processes including chemical conversions and wet and dry deposition etc). These, in turn, influence both the rate and direction of dispersion. A further influence on the spatial dispersion of pollution is topography. At a regional scale the presence of valleys may help to concentrate pollution and prevent dispersion. At a more localized scale, building characteristics and land cover type may influence dispersion patterns. For example, canyon streets concentrate pollution while open ground such as playing fields allows the wider dispersion of the pollutant (Colls 1997).

5.1.2 Sources of Temporal Variation

Temporal variation, like spatial variation, is a complex issue. Pollution can vary with an amplitude of a few microseconds to an amplitude of months and years. The level of temporal variation identified is dependent to a great extent on the type of monitoring devices (e.g. continuous monitors can identify variation by minutes while passive diffusion tubes provide average pollution concentrations over the full exposure period). The following discussion, however, will be focused on temporal variation relevant to this study. Like spatial variation, therefore, there are two main factors affecting patterns of temporal variation: emission patterns and dispersion patterns.

5.1.2.1 Factors influencing temporal patterns of emissions

Temporal variation in emissions, whether line source or area, will influence concentrations in air pollution in a number of ways. For example, variations

in emission from a line source (i.e. from vehicles) will vary minute by minute due to driving conditions. Similarly, industrial emissions may vary depending on whether the source is a continuous process or batch process which may therefore produce intermittent emissions.

The amplitude of these variations is dependent on both external environmental and sociological factors. Emissions from road transport, for example, vary over time with changes in traffic volume, reflecting the influence of factors such as traffic-control devices (e.g. traffic lights -minute variation), rush hours (hourly variation) or seasonal traffic (e.g. work days versus holidays). Similar temporal patterns will also be seen in industrial or point emissions as many factories reduce or halt emissions at nights, weekends or over seasonal holiday periods (e.g. Christmas).

The influence of meteorology is also important. In cold weather, emissions from residential areas, for example, will increase due to the increased use of space heating. Similarly poor driving conditions due to inclement weather will increase transport emissions. In cold temperatures, catalytic converters, the most common form of vehicle abatement technology, do not function effectively. In addition, reduced visibility due to precipitation, will slow vehicle speeds, therefore increasing emissions.

5.1.2.2 FACTORS INFLUENCING TEMPORAL PATTERNS OF DISPERSION

As with emissions, the pattern and magnitude of the dispersion of pollutants will also vary over time due to the influence of a number of factors. Any variation in emission conditions will, by its very nature, lead to changes in dispersion rates. Meteorological variations in wind speed, wind direction, temperature, humidity and the effects of scavenging will all vary over time from a few seconds to weekly and seasonal changes. Equally, changes in environmental conditions (e.g. installation of temporary traffic-lights, construction of new buildings, creation of pedestrian areas and alterations to

road layouts) - however short term - will all affect the distribution of pollution over time.

Finally the influence of the emission characteristics will themselves influence the temporal patterns of dispersion. The exit temperature and emission release rate will vary over time (especially from vehicle exhausts) and the influence of building or vehicle (vehicle wake) induced turbulence will all influence the dispersion of pollutants.

5.1.3 SOURCES OF ERROR

As well as the sources of spatial and temporal variation mentioned above, variation at a site at one point in time and space (i.e. between adjacent samples at one site exposed for identical time periods) may occur. This error-induced variation can be decomposed into two main sources - measurement error and sampling error - each of which will now be examined in turn.

5.1.3.1 MEASUREMENT ERROR

Measurement error may occur due to a wide range of effects including inaccuracies in laboratory procedure, differential effects of storage and transportation, calculation errors (e.g. conversion of results from $\mu g/m^3$ to ppb) and reporting and transcription errors. Much of this error can be controlled or eliminated by careful, rigorous methods of cross-checking of data, laboratory procedures and by the use of analytical field and laboratory blank samplers. These procedures are explained in more detail in section 3.3.1 and 3.3.2.

5.1.3.2 SAMPLING ERROR

Sampling error relates, in part, to the ability of the monitoring device (i.e. the diffusion tube) to provide consistent readings under uniform conditions. Error may occur due to the influence of meteorological conditions such as low temperatures, humidity and turbulence, all of which may adversely affect the ability of the monitoring device to measure accurately the concentration of a pollutant. Error may also occur due to variations in the diffusive rate of the individual tubes or differences in absorption rates (receptivity) of the absorption medium (see Section 3.3.1). Investigations into the NO/NO_2 ratio, for example, have indicated that passive diffusion tubes will over-predict by between 8 and 14 per cent in winter months. Heal and Cape (1997) stated that this over-estimation may be attributed to high wind speeds and independent within-tube chemistry – but that there is no simple method for retrospectively correcting the NO_2 measurements, especially in urban areas.

5.2 COMPONENTS OF VARIATION

In order to assess the contribution of these various sources of variation to measured patterns of air pollution in the study area, a series of special surveys were conducted, as outlined in Section 4.3. These examined the effects of:

- traffic volume
- distance from emission source
- land cover
- altitude
- sampling height
- measurement and sampling error
- temporal variation

Based on these results, the contribution of spatial, temporal and error effects to overall levels of variation were assessed. In addition, attempts were made to decompose variation in the study area into its spatial and temporal components, and to define 'affinity areas' (McGregor 1996)

5.2.1 Influence of Variation in Traffic Volume

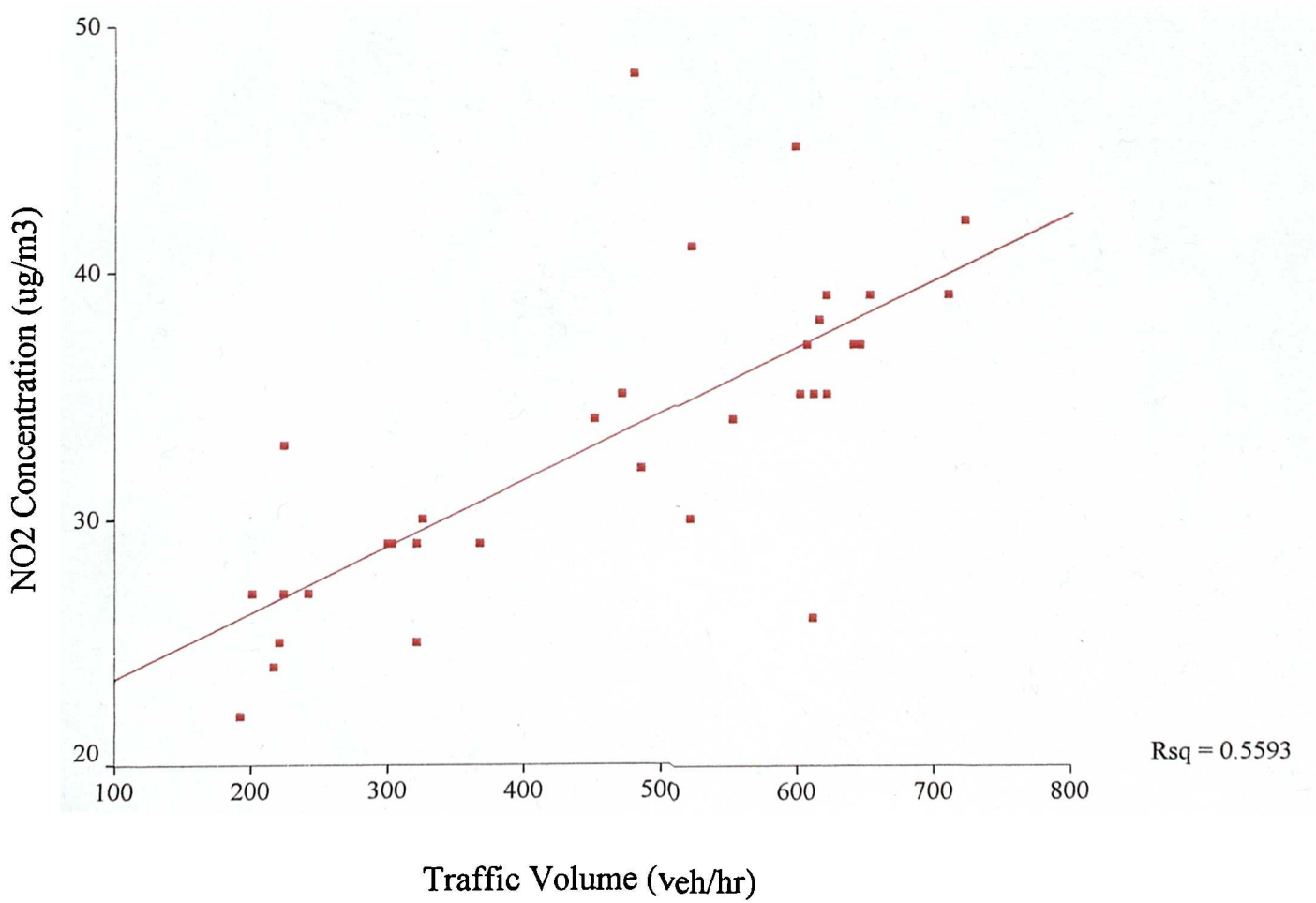
Most NO_2 pollution in urban areas is attributed to emissions from road traffic (Farber *et al.* 1997; Green and Gebhart 1997; DoE 1996). Variation in traffic volume may thus be expected to account for much of the variation in pollution levels within an urban environment. In order to analyse the relationship between NO_2 and road traffic volume, a number of surveys were undertaken at kerbside locations with varying traffic volumes in and around the study area in conjunction with HETS (West Yorkshire Highway engineers and Transport Consultants) (see Section 4.2). A total of 20 surveys were undertaken and in each case passive diffusion samplers were placed on either side of the road to allow for the influence of wind direction. A number of samplers were lost or damaged due to vandalism.

Data on traffic flows and pollution concentrations obtained from the surveys were entered into the SPSS statistical package and regression analysis conducted in order to analysis relationships between traffic volume and NO_2 concentrations. The results are shown in Table 5.1 and in Figure 5.1.

Table 5.1 Regression analysis of variation with traffic volume

	All Roads
Degrees of Freedom	32/1
Multiple R	0.7479
R^2	0.5593
Adjusted R^2	0.5455
Standard Error	4.2620
Slope Value	0.0268
Constant	20.8345
F value	40.6095
Significance F	0.0000

Figure 5.1 Relationship Between Kerbside NO2 Concentrations and Traffic Volume



The results of the analysis indicate that traffic volume explains 54.6 per cent of the recorded variation in pollution concentrations and that this relationship is significant at the 0.001 per cent level. Graphically the data indicates that the relationship, while broadly linear, does have a number of outliers. These can be attributed to local conditions or the open aspect of some sites, which may increase turbulence. The constant value of 20.83 $\mu g/m^3$ is consistent with the background concentrations measured at a number of locations in and around the study area.

This study confirms that traffic volume is an important determinant of variation in NO_2 concentrations in the study area. This implies that NO_2 concentrations can, indeed, be considered as a reliable marker for traffic-related pollution. Nevertheless, 45 per cent of the variation in NO_2 concentrations at these sites remains unexplained. A proportion of this may be attributable to emissions from non-road sources. Part may also reflect changing weather conditions between the different surveys. Much, however, is probably a result of differences in unmeasured characteristics of road traffic at the various sites, for example, traffic composition, vehicle speed, waiting time, cold starts, and local factors such as terrain, building height and the presence of trees. The results thus serve as a useful reminder that traffic volume alone is not a perfect indicator of exposure to traffic-related pollution. This undoubtedly has implications for those epidemiological studies that have used traffic volume as an exposure indicator.

5.2.2 Variation with Distance to Road

Pollution concentrations naturally tend to decline with distance from their source, as a result of dispersion and atmospheric chemical processes (Colls 1997; Green and Gebhart 1997). The degree of variation in pollution levels with distance from traffic-related emission sources is therefore important for the quantification and subsequent understanding of the spatial patterns of

NO_2. As noted in Chapter 2, a number of epidemiological studies have also used distance from road as an indicator of exposure. How well this relates to actual pollution levels is nevertheless uncertain. Consequently, a number of surveys were undertaken using diffusion tube samplers placed perpendicular to a number of roads and exposed for a two-week period in order to examine the relationship between distance from road and NO_2 concentrations. A total of 7 transects were studied, comprising between two and nine sites, according to the availability of suitable street furniture or garden furniture. Where possible, tubes were placed on both sides of the road to assess the effects of meteorological factors (e.g. wind direction). A number of samplers were lost or damaged due to vandalism. Data on traffic volume at the time of the survey was available from automatic traffic counts conducted by HETS. The location of these sites and more detail on the surveys, is given in Section 4.2.1.

Table 5.2 Regression Analysis of variation with distance to road

	All Roads
Degrees of Freedom	1/20
Multiple R	0.562
R^2	0.316
Adjusted R^2	0.218
Standard Error	5.255
Slope Value	-0.087
Constant	28.123
F value	9.225
Significance F	0.007

Results were analysed in two ways. Table 5.2 and Figure 5.2 show relationships between raw NO_2 concentrations and distance from road for the 22 sample sites. As can be seen, the adjusted R^2 value explains 21.8 per cent of the recorded variation, significant at the 1 per cent level. The data nevertheless shows considerable scatter (Figure 5.2), partly no doubt because traffic volume varied between the various sites. A second analysis was therefore conducted, after first standardizing NO_2 values relative to the kerbside concentrations for each transect. Results are shown in Table 5.3 and

Figure 5.2 Relationship Between NO2 Concentrations And Receptor Distance to Road

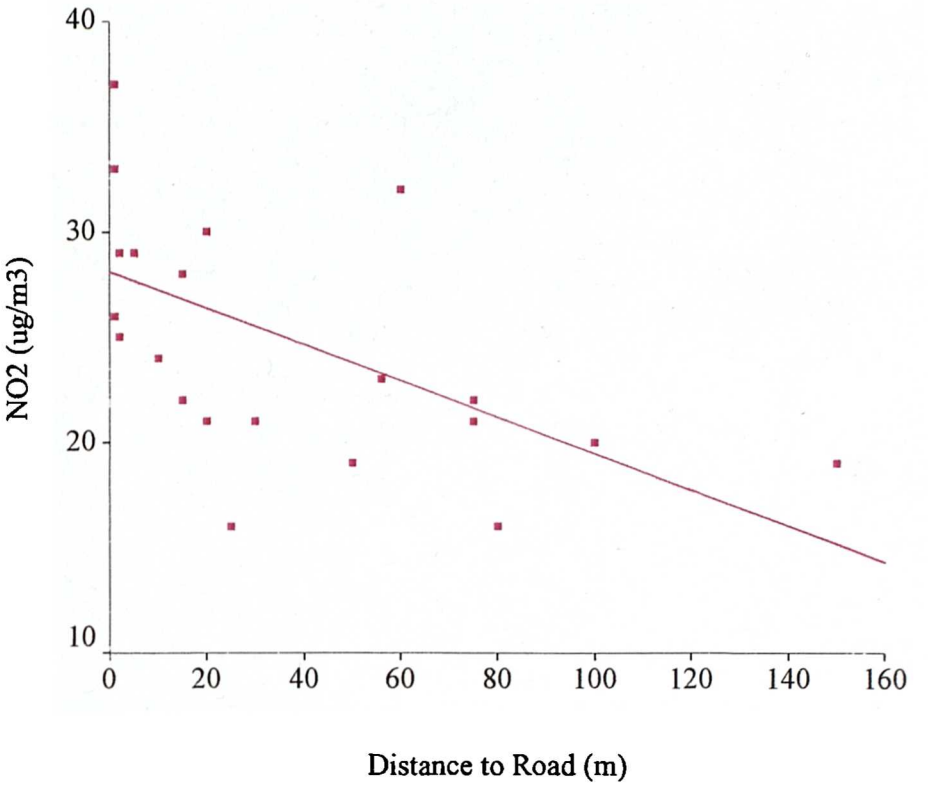


Figure 5.3 Regression analysis of Standardised NO2 Concentrations and Receptor Distance from Road

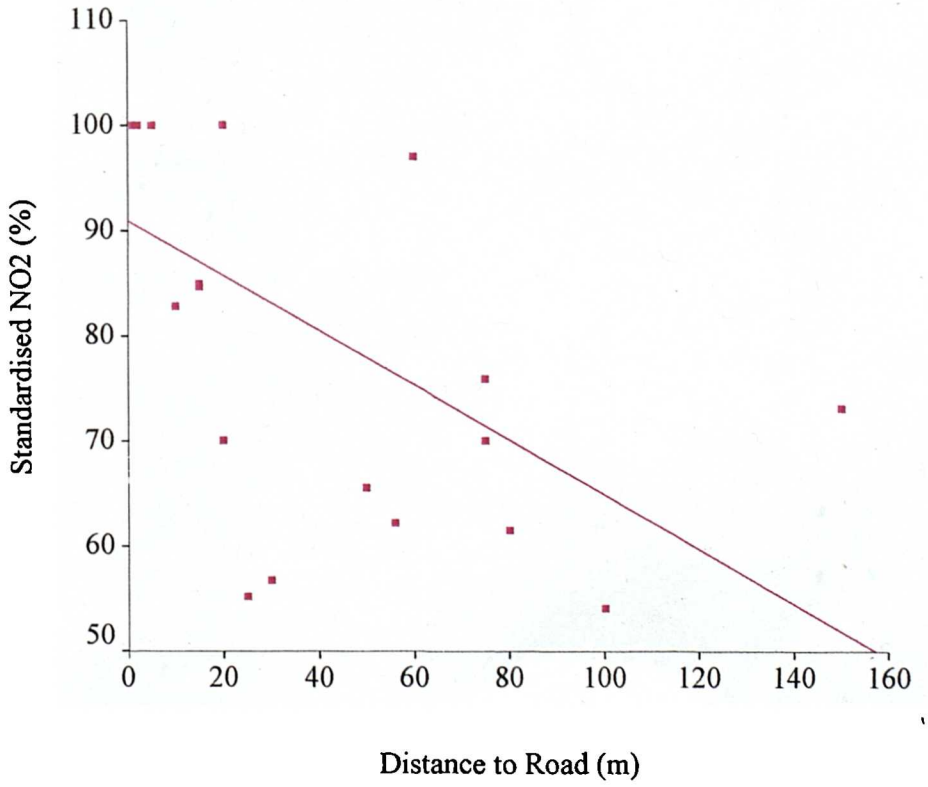


Figure 5.3. The linear model gave a slight improvement in the adjusted R^2 value (R^2 = 32.2 per cent, significant at the 1 per cent level). Further analysis of the data indicated that a better fit was obtained using a logarithmic model (adjusted R^2 value = 56.0 per cent, significant at the 0.001 level). Results are shown in Table 5.3 and Figure 5.4.

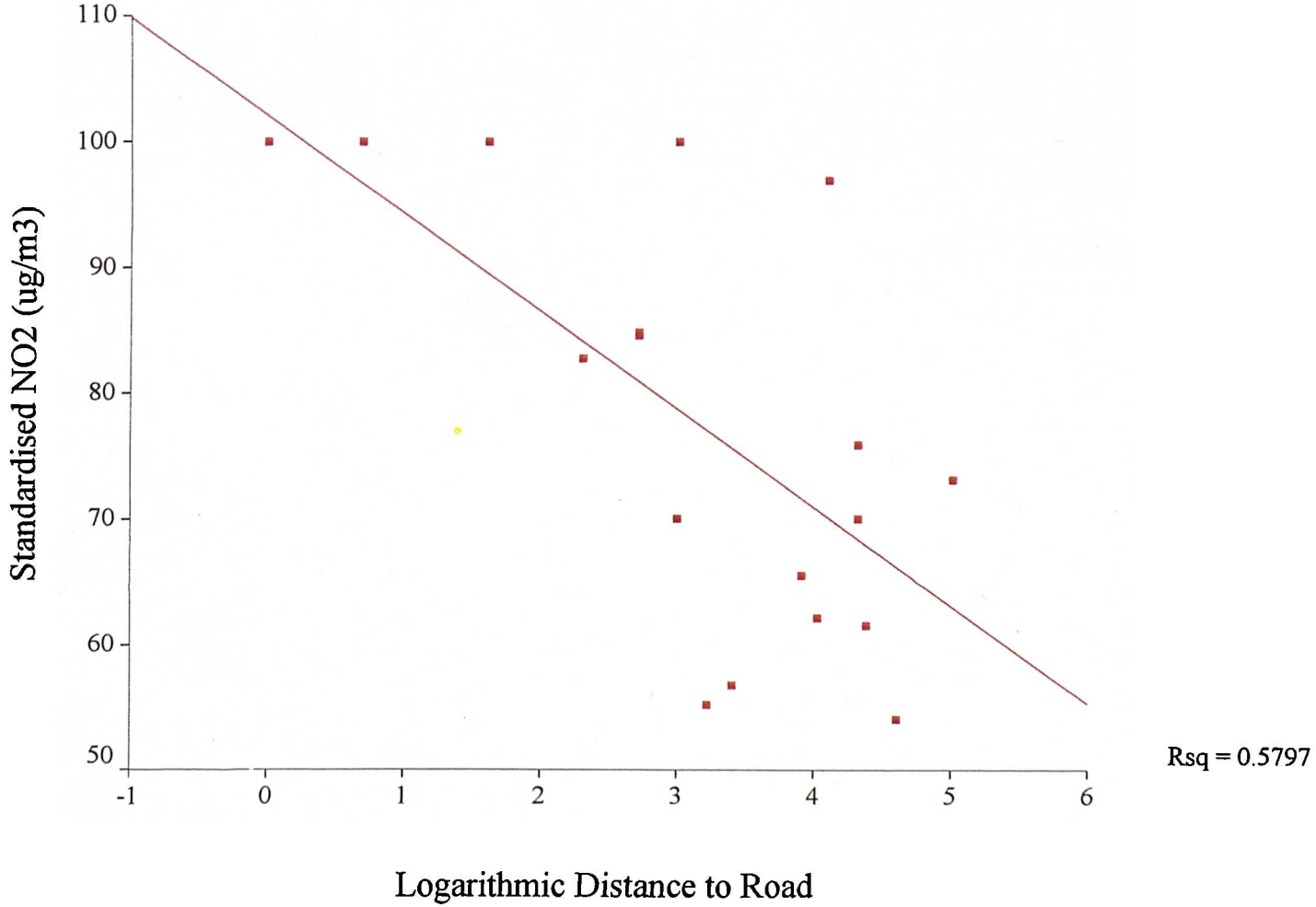
From the results it is clear that NO_2 concentrations decrease rapidly within the first 40 metres from the road. Concentrations then appear to tail off at approximately 60 metres from the road, at which point it may be assumed that background concentrations have been achieved and therefore the influence of road traffic on pollution levels is minimal (see Figure 5.2). The remaining 44.1 per cent unexplained variation may again reflect the influence of non-road source emissions, topographical factors and meteorological conditions as explained in the previous section.

Table 5.3 Standardized regression analysis of variation with distance to road

	Linear	Log
Degrees of Freedom	1/20	1/20
Multiple R	0.595	0.761
R^2	0.354	0.580
Adjusted R^2	0.322	0.559
Standard Error	14.437	11.645
Slope Value	-0.261	-7.793
Constant	90.920	102.056
F value	10.961	27.590
Significance F	0.004	0.000

The results were presented in both the raw and standardized format as it was felt important to examine the effect that standardization has on the data, as most epidemiological studies use unstandardised distance to road / NO_2 as a proxy variable for air pollution and therefore may not be presenting a true picture of the relationship between air pollution and respiratory health. Overall, the results indicate that, despite the effects of variation in site characteristics and traffic volume, physical distance to vehicular emission sources is a meaningful predictor of NO_2 concentrations.

Figure 5.4 Relationship Between Standardised NO2 Concentrations and the Logarithmic Receptor Distance to Road



5.2.3 VARIATION ATTRIBUTABLE TO LAND COVER

Whilst factors such as road traffic volume and distance from road clearly account for much of the spatial variation in air pollution, they are unlikely to provide a complete explanation of pollution patterns at the small-area scale. Important variation may also occur as a result of the effects of emissions from non-rural sources, and due to the effects of buildings and vegetation and dispersion processes. Both these effects may be expected to relate to patterns of land cover and usage. In order to investigate these effects a land cover map (1:10,000) was created from the interpretation of detailed (1:5,000) aerial photographs. Originally, 20 classes of land cover were used ranging from high density commercial land cover to moorland (See Appendix 5 for full classification). The number of categories was later reduced owing to the fact that some groupings did not have enough sample sites to make them statistically significant, nor did they contribute to explaining pollution levels (e.g. there was felt to be very little difference between heathland and grassland).

Once the classifications had been determined, pollution data from the 80 core sites in the routine surveys (S_2, S_3 and S_4) and the annual average were used (as four separate data sets) to examine the effects of land cover on patterns of NO_2 variation. Land classification for each site was obtained in the field and cross-checked with the land classification map. A more detailed explanation of this procedure and the sampling regime is explained in Section 4.1. Analysis of the data was conducted in SPSS statistical package. Data were analyzed at three different levels of classification as follows:

- Degree of urbanization
- DETR site type classification
- Land cover

a) Degree of urbanization. Data from the routine pollution surveys was initially classified into 3 broad categories, reflecting the level of urbanization:

- *Urban* More than 70 per cent of land surrounding the sample site is occupied by buildings.
- *Suburban* Between 20-69 per cent of land surrounding the sample site is occupied by buildings.
- *Rural* Less than 20 per cent of land surrounding the sample site is occupied by buildings.

The extent to which NO_2 levels varied in relation to these land cover categories was then investigated for the three surveys (S_2, S_3 and S_4) and the annual average (see Table 5.4). Further investigation was undertaken using Analysis of Variance in SPSS and the results are shown in Table 5.5 and Figure 5.5.

Table 5.4 Summary statistics for NO_2 ($\mu g/m^3$) variation by the degree of urbanisation

Group	Survey Number	No of Cases	Minimum	Maximum	Mean	S.D.
Urban						
	S_2	23	37.06	78.5	55.4	8.6
	S_3	23	18.7	51.5	32.9	8.5
	S_4	23	27.1	69.4	44.7	10.9
	A_m	23	25.6	57.6	41.5	7.7
Suburban						
	S_2	50	27.7	66.6	45.0	9.1
	S_3	50	9.5	42.7	22.8	7.8
	S_4	50	15.7	52.3	28.7	9.8
	A_m	50	17.8	46.9	29.8	7.6
Rural						
	S_2	7	31.3	50.0	39.3	6.5
	S_3	7	12.2	49.0	23.0	12.2
	S_4	7	15.6	54.7	25.9	13.4
	A_m	7	20.3	52.9	28.2	11.4

The results indicate that significant differences in pollution levels do occur between the three groups, with mean concentrations consistently being highest in the urban areas, intermediate levels in the suburban areas and

Figure 5.5 Mean and Standard Deviation of the

Degree of Urbanisation

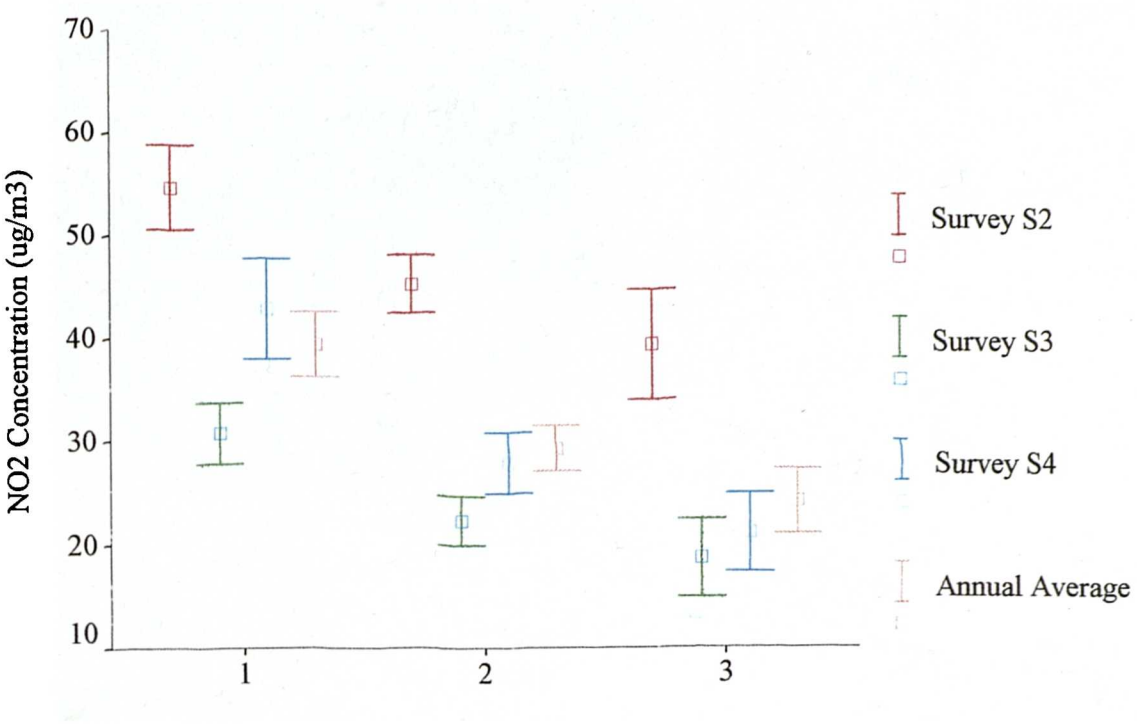
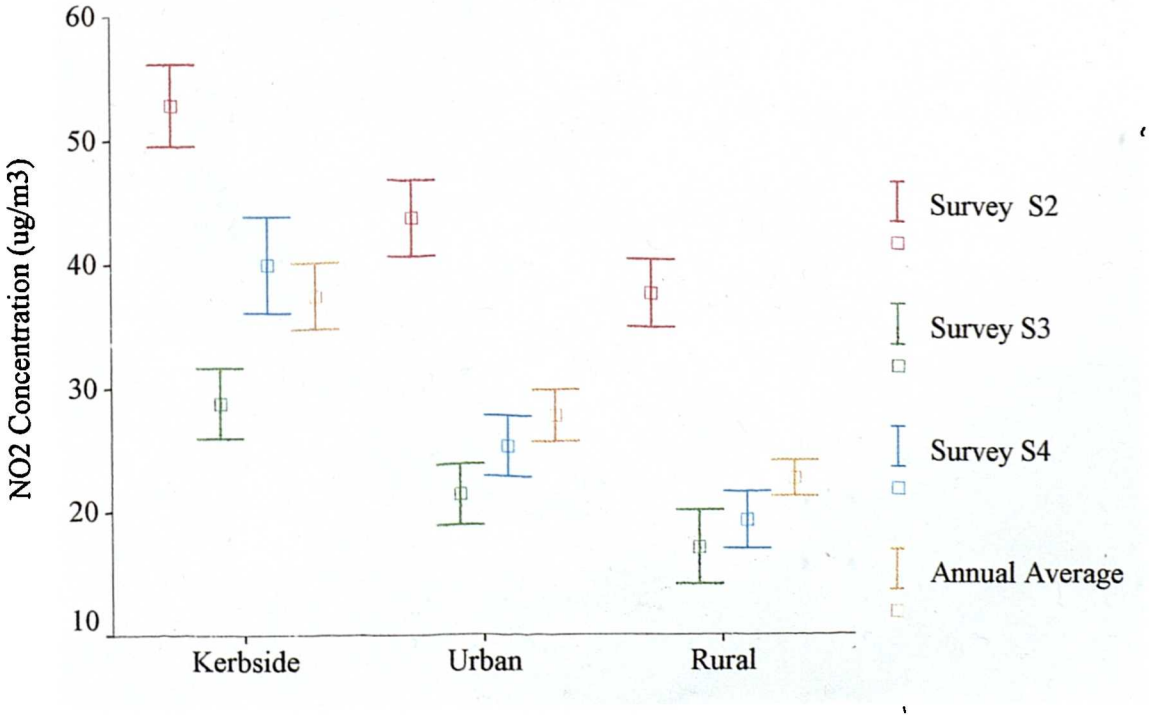


Figure 5.6 Mean and Standard Deviation of the

DETR classification



lowest in the rural areas (see Figure 5.5). This clearly matches expectations, and largely reflects the distribution of road sources and traffic emissions in these three zones. What is perhaps more surprising is that within group variation still accounts for the large majority of variation in the measured data - from 65.5 per cent in S_4 to 77 per cent in survey S_3. The implication is that considerable small area variation occurs within each of these land cover zones.

Table 5.5 Analysis of variance for degree of urbanization.

		D.F.	Sum of Square	Mean of Square	F	Sig. of F	%
Survey S_2	Between Group	2	1925.033	962.517	12.349	0.000	27.23
	Within Group	66	5144.423	77.946			72.77
	Total	68	7069.457				
Survey S_3	Between Group	2	1564.569	782.285	10.941	0.000	23.06
	Within Group	73	5219.409	71.499			76.94
	Total	75	6783.978				
Survey S_4	Between Group	2	4431.102	2215.551	20.286	0.000	34.51
	Within Group	77	8409.625	109.216			65.49
	Total	79	12840.728				
Annual Average	Between Group	2	2327.761	1163.881	18.329	0.000	22.30
	Within Group	77	4889.145	63.499			67.7
	Total	79	7217.145				

b) DETR site type classification. In order to further investigate the effects of broad-scale variation in land cover further, a second classification, based broadly on the Department of the Environment, Transport and the Regions' classification for the siting of NO_2 continuous monitors was devised as follows:

- *Kerbside* — Within 20m of an emission source, in either a rural or urban location.
- *Urban background* — Within an urban (built-up) conurbation, not less than 20m from the nearest emission source.

- *Rural background* Excluding urban conurbations and at a distance of more than 20m from the nearest emission source.

Once classified, the data for the 80 core sites was transferred into the SPSS statistical package and summary statistics calculated (see Table 5.6). Oneway Analysis of Variance was then conducted. The results are shown in Table 5.7 and Figure 5.6.

The results indicate that kerbside sites had the highest concentration in all three surveys, and for the annual average (ranging from 30.5 for S_3 to 53.4 $\mu g/m^3$ for S_2). The urban background sites for all surveys were consistently lower than the kerbside sites (21.2 to 43.3 $\mu g/m^3$) but higher than the rural background sites (19.1 to 37.4$\mu g/m^3$). This is expressed clearly in Figure 5.6. Examination of the results of the Oneway Analysis of Variance shows that these differences are statistically significant but that most of the variation occurring in the surveys was again within groups as opposed to between groups: between group variation accounts for between 26.8 and 46.8 per cent of the total recorded variation (Survey S_3 and S_4).

Table 5.6 Summary statistics for NO_2 ($\mu g/m^3$) variation by DETR classification

Group	Survey Number	No of Cases	Minimum	Maximum	Mean	S.D.
Kerbside						
	S_2	41	37.0	78.5	53.4	9.3
	S_3	41	10.1	51.5	30.5	9.6
	S_4	41	19.6	69.4	41.5	11.5
	A_m	41	22.4	57.6	39.0	8.6
Urban background						
	S_2	31	27.7	56.8	43.3	8.2
	S_3	31	9.5	33.3	21.2	6.4
	S_4	31	15.7	46.6	25.0	6.3
	A_m	31	17.8	41.0	27.4	5.5
Rural background						
	S_2	8	31.3	42.0	37.4	3.6
	S_3	8	12.2	33.8	19.1	7.0
	S_4	8	15.6	37.6	21.5	7.1
	A_m	8	20.3	38.6	24.5	6.0

Table 5.7 Oneway Analysis of Variance for distance to emission source.

		D.F.	Sum of Square	Mean of Square	F Ratio	Sig. of F	%
Survey S_2	Between Group	2	2370.580	1185.290	16.648	0.000	33.53
	Within Group	66	4698.877	71.195			66.47
	Total	68	7069.457				
Survey S_3	Between Group	2	1816.319	908.160	13.345	0.000	26.77
	Within Group	73	4967.659	68.050			73.23
	Total	75	6783.978				
Survey S_4	Between Group	2	6003.491	3001.746	33.805	0.000	46.75
	Within Group	77	6837.236	88.765			53.25
	Total	79	12840.728				
Annual Average	Between Group	4	1207.156	301.789	3.767	0.007	16.7
	Within Group	75	6009.989	80.133			83.3
	Total	79	7217.145				

c) Local Area Land Cover. The preceding analysis indicated that broad-scale variation in pollution levels in the study reflects the underlying patterns of land cover and site types. Much of the variation inherent in the pollution data nevertheless remains unexplained. Much of this may be expected to be a result of local land cover effects, especially in urban areas. These were, therefore, further investigated using data from the three surveys and the annual average results. Sites were first selected and divided into five classes, reflecting differences in intensity of land cover (Table 5.8). Summary statistics were calculated for each survey and the results collated in Table 5.9. Differences in levels of NO_2 across these classes were then analysed using Oneway Analysis of Variance in SPSS. Results are shown in Table 5.10 and Figure 5.7.

Table 5.8 Land cover classifications

Land cover category	Code	Definition
1	IND	High density commercial land/industrial land
2	HD	>60 % of the area is housing or public institutions
3	LD	25 - 60 % of the area is housing
4	VLD	1-24 % of the area is housing
5	OPEN LAND	non-built up urban green space / sports ground. parks, rural areas

Table 5.9 Summary statistics of NO_2 ($\mu g/m^3$) variation with local land cover category

Group	Survey Number	No of Cases	Minimum	Maximum	Mean	S.D.
IND						
	S_2	10	46.4	62.3	56.4	5.6
	S_3	10	23.7	49.0	35.5	7.8
	S_4	10	29.2	54.7	41.7	8.2
	A_m	10	30.9	52.9	41.5	6.3
HD						
	S_2	28	33.0	78.5	48.8	10.6
	S_3	28	10.1	51.5	26.3	10.2
	S_4	28	16.9	69.4	36.7	13.7
	A_m	28	20.5	57.6	34.5	10.2
LD						
	S_2	25	28.2	66.6	44.2	9.6
	S_3	25	9.5	42.7	22.1	8.2
	S_4	25	15.7	48.9	27.5	10.3
	A_m	25	17.8	44.1	29.6	8.0
VLD						
	S_2	8	27.7	66.2	46.6	11.9
	S_3	8	12.2	38.1	26.0	10.0
	S_4	8	15.6	63.2	32.8	15.7
	A_m	8	20.3	54.5	32.7	12.1
OPEN LAND						
	S_2	9	31.3	52.8	44.6	8.5
	S_3	9	15.6	28.1	22.5	4.3
	S_4	9	17.9	47.0	27.8	10.0
	A_m	9	21.5	36.7	29.1	5.8

Figure 5.7 Mean and Standard Deviation of the

Local Area Land Cover

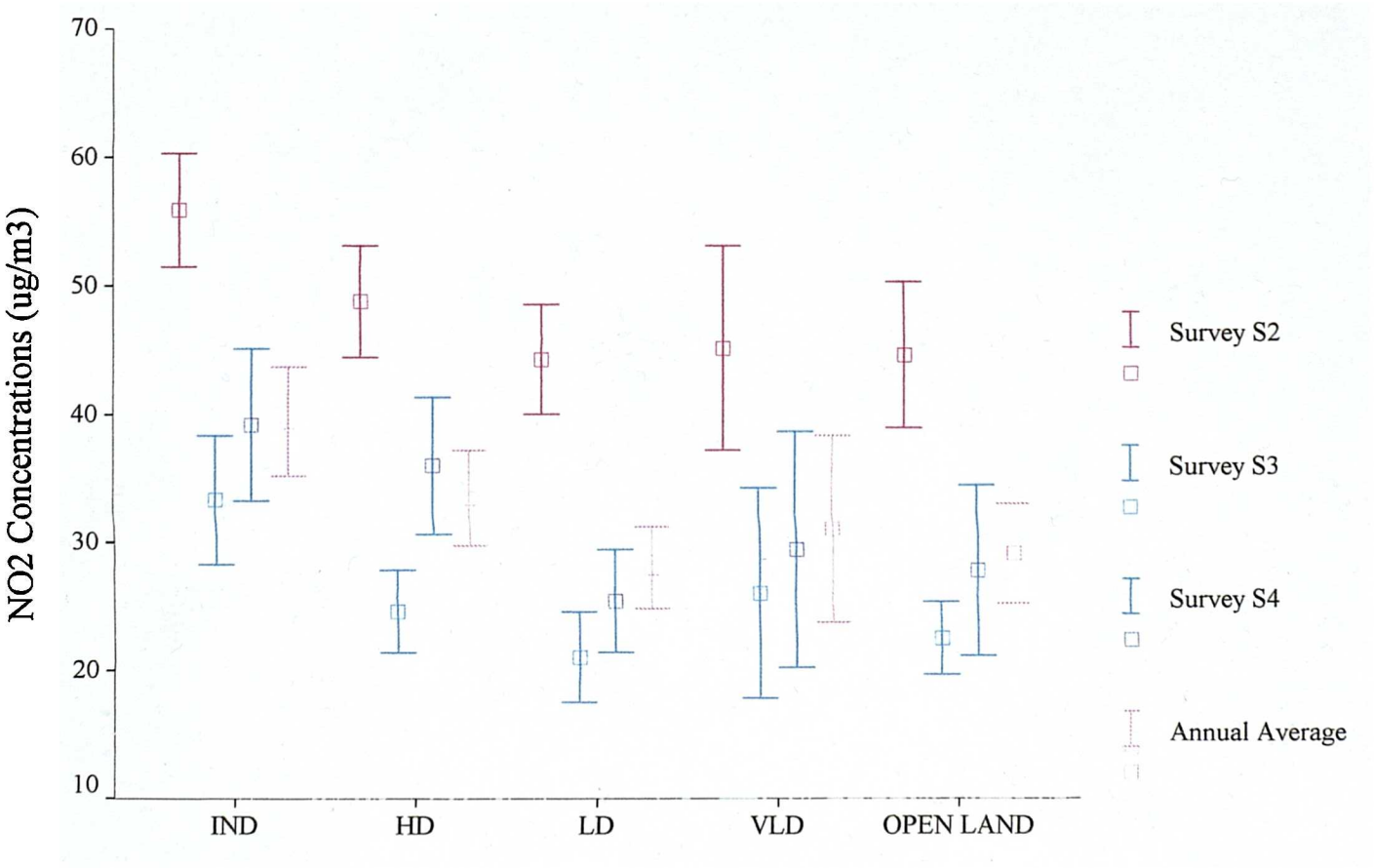


Table 5.10 Analysis of Variance attributed to land cover at the small scale

		D.F.	Sum of Square	Mean of Square	F Ratio	Sig. of F	%
Survey S_2	Between Group	4	855.281	213.820	2.245	0.076	13.82
	Within Group	56	5333.888	95.248			86.18
	Total	60	6189.169				
Survey S_3	Between Group	4	887.773	221.943	2.913	0.028	16.04
	Within Group	61	4647.098	76.182			83.96
	Total	65	5534.870				
Survey S_4	Between Group	2	6003.491	3001.746	33.805	0.000	46.75
	Within Group	77	6837.236	88.765			53.25
	Total	79	12840.728				
Annual Average	Between Group	2	3062.783	1531.392	28.384	0.000	42.40
	Within Group	77	4154.362	53.953			57.60
	Total	79	7217.145				

The summary statistics indicate that levels of NO_2 for all surveys decrease in the first three groups (see Figure 5.7). Mean concentrations are highest in the industrial zone for all surveys (33.5 to 56.2 $\mu g./m^3$). Levels then decrease with high density housing (26.3 to 48.8 $\mu g./m^3$) and a further fall is noted in the low density housing land cover group (22.1 to 44.2 $\mu g./m^3$). Concentrations recorded in the open land category are similar to those recorded in low density housing group although the standard deviation is smaller. Concentrations recorded in the very low density housing group are higher than those recorded within low density housing cover. This may be due to the historical land cover patterns of the study area, as many large houses were built to accommodate mill owners on roads which have now become busy dual carrageways.

Results of the Oneway Analysis of Variance indicate that, for all three surveys and the annual average data, the majority of the variation in NO_2 concentrations occurs within the land cover groups (ranging from 53 – 57 per cent in S_4 and the annual mean, to 84 - 86 per cent in surveys S_2 S_3). Nevertheless, differences between land cover classes are significant at the

0.001 per cent level for all surveys except survey S_2, and for the annual mean. More detailed comparisons between the five land cover classes using the annual average data (see Table 5.11) show that most of this variation occurs in land cover class 1 (Industry). This is significantly different (at the 0.05 per cent level) from all other land cover classes except 4 (very low density housing). Otherwise, none of the land cover groups differ from each other at the 0.05 significance level.

Table 5.11 Correlation analysis significance values for local area land cover

Groups	1	2	3	4	5
1		0.019	0.000	0.094	0.000
2	0.019		0.056	0.711	0.058
3	0.000	0.056		0.509	0.835
4	0.094	0.711	0.509		0.453
5	0.000	0.058	0.835	0.453	

In conclusion, the results of the analysis indicate that most of the variation in NO_2 concentrations occurs within land cover groups, whichever the system used. Relatively little variation occurs between the groups. The only exception to this are the results using the local area land cover results for surveys S_4 and A_m where between-group variation accounted for 46.8 and 42.4 per cent of the total variation respectively. Overall, therefore, the influence of land cover on patterns and magnitude of pollutant dispersion is small, most of the variation occurring at scales below that of the land cover class. This may be the result of factors such as traffic volume and local topographic conditions, which cannot entirely be controlled. These results are again a reminder that the use of land cover as a proxy for air pollution levels, as used in some epidemiological studies (see Table 2.2), is of only limited validity.

5.2.4 VARIATION ATTRIBUTABLE TO ALTITUDE

As noted in Chapter 3, the study area comprises a complex terrain, with a series of relatively deep valleys dissecting the plateau margins of the Pennines. These variations in altitude may be expected to affect pollution patterns in a number of ways. Historically, they have acted to influence the distribution of settlements, industry and infrastructure in the area and thus have exerted a major control on the patterns of emission sources. The pattern of relief also affects local weather conditions, with sheltered areas, characterized by frequent inversions, in the valley floors, and with exposed areas with high average wind speeds in the hilltops. At the same time, it is likely that the higher areas in the west of the region are more affected by long-range transport from the Manchester Metropolitan area. Together, therefore, these effects are expected to be reflected in the pattern of pollution across the area.

These effects were investigated using concentration data from the 80 core sites used in the routine surveys (S_2 S_3 and S_4) and from the annual mean adjusted for missing values (A_m). Initially all core data sites were examined. Subsequent analyses were conducted on sites classed as rural or urban background only, in order to remove the confounding effects of nearby emission sources. Corresponding heights in metres above OD for each sample site were calculated using a Digital Terrain Model (DTM) and cross-checked against data from 1:10,000 OS maps of the area. The information was entered into the SPSS statistical package and descriptive statistical techniques conducted (Table 5.12).

Table 5.12 Altitudinal survey statistics (mAOD)

Altitude	No of Cases	Min	Max	Mean	S.D.
S_2	80	45	455	153.49	68.32
S_3	80	45	475	155.23	74.54
S_4	80	45	475	158.11	78.81
A_m	80	45	475	158.11	78.81

The summary statistics indicated that sampling in all surveys had been conducted across a similar range of altitudes, but that there was significant variation with height within each survey. After examination of the data in graphical format (see Figure 5.8), curvilinear regression analysis was conducted. The results are shown in Table 5.13 and Figure 5.9.

Table 5.13 Regression analysis (r^2 values) of the effects of altitude on NO_2 concentrations (All sites)

	S_2	S_3	S_4	A_m
Degrees of Freedom	1/67	1/74	1/78	1/78
Linear	0.227	0.207	0.136	0.205
Logarithmic	0.244	0.276	0.169	0.257
Inverse	0.209	0.293	0.170	0.261
Quadratic	0.247	0.274	0.168	0.251
Cubic	0.251	0.302	0.180	0.278
Compound	0.244	0.197	0.146	0.215
Power	0.254	0.254	0.177	0.259
S	0.215	0.259	0.172	0.253
Growth	0.244	0.197	0.146	0.215
Exponential	0.244	0.197	0.146	0.215
Logistic	0.244	0.197	0.146	0.215

Results of the analysis indicate that the relationship between NO_2 concentrations and altitude is not linear and can best be explained by using either a cubic or power equation. The power equation explains 25.4 and 17.7 per cent of the variation in NO_2 concentrations for surveys S_2 and S_4 respectively. Surveys S_2 and A_m are best explained using a cubic equation (30.2 and 27.8 per cent respectively). The influence of factors such as the distance of the sample site to a road, vehicle volume and land cover, however, may distort the relationship between NO_2 concentrations and altitude. Consequently the analysis was rerun using only sites not classed as urban sites according to the DETR classification used in the previous section (See Figure 5.10). Non-urban results for the curvilinear analysis are shown in Table 5.14 and Figure 5.11. The subsequent analysis indicates that inverse, cubic and compound equations provide the most accurate explanation of NO_2 concentrations in this case (explaining between 8.4 and 13.4 per cent of the

Figure 5.8 Relationship Between NO2 Concentrations and Altitude

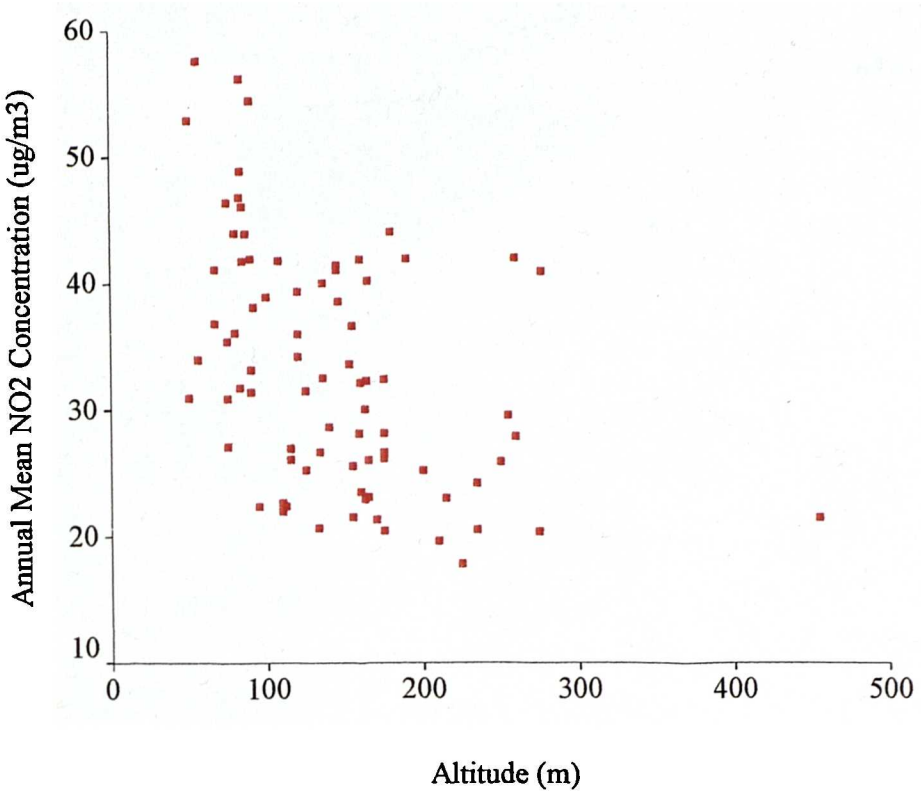


Figure 5.9 Selected Curvilinear Relationships Between NO2 Concentrations and Altitude

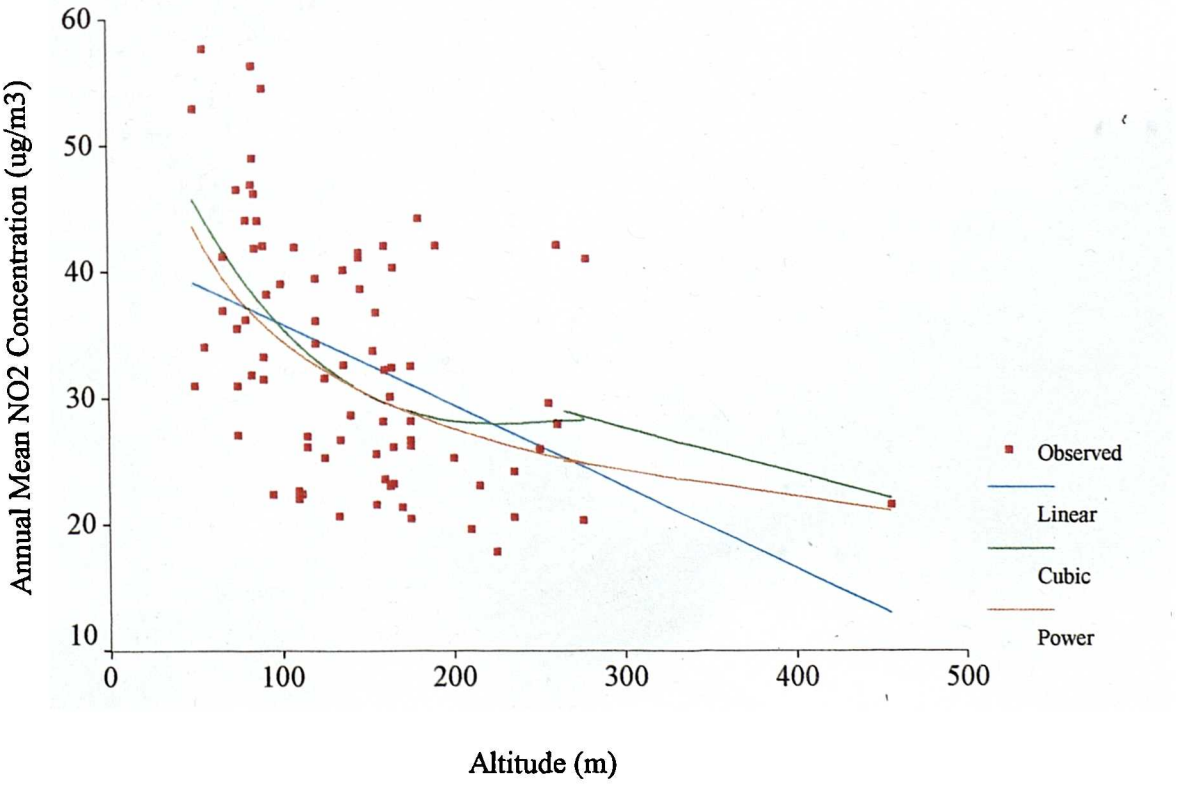


Figure 5.10 Relationship Between NO2 Concentrations and Altitude by DETR Landclass

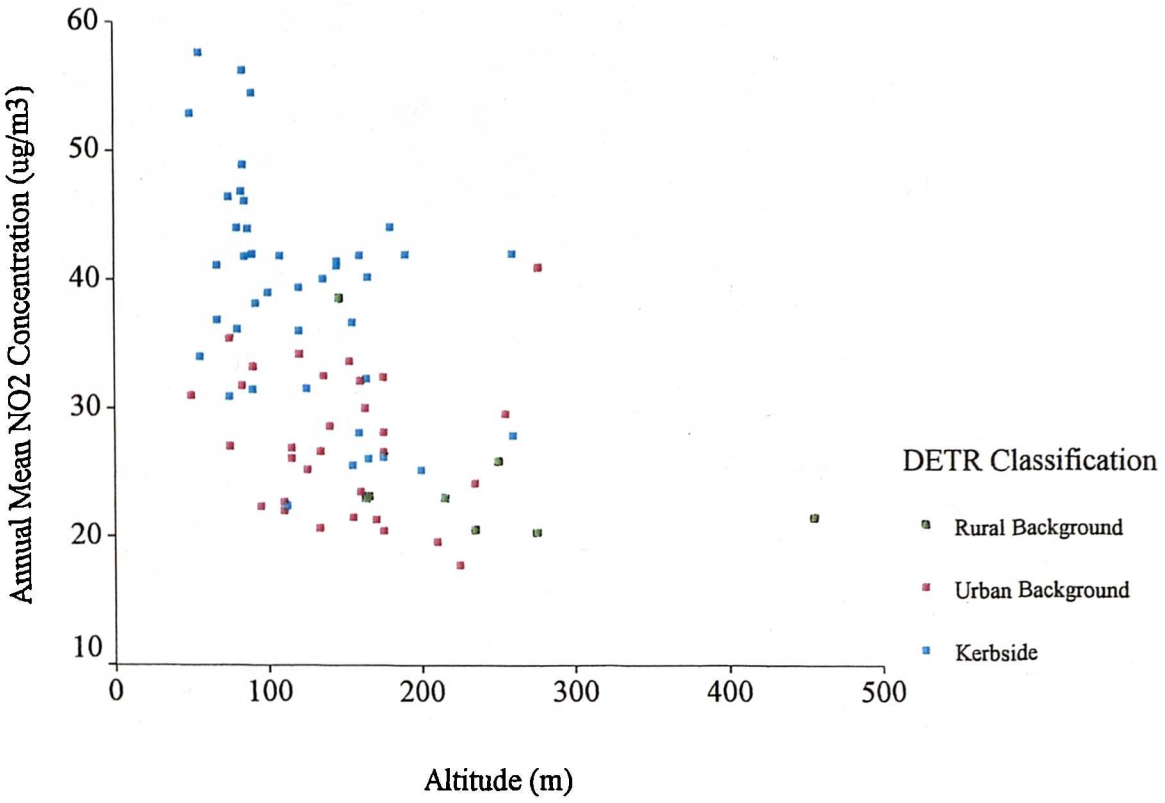
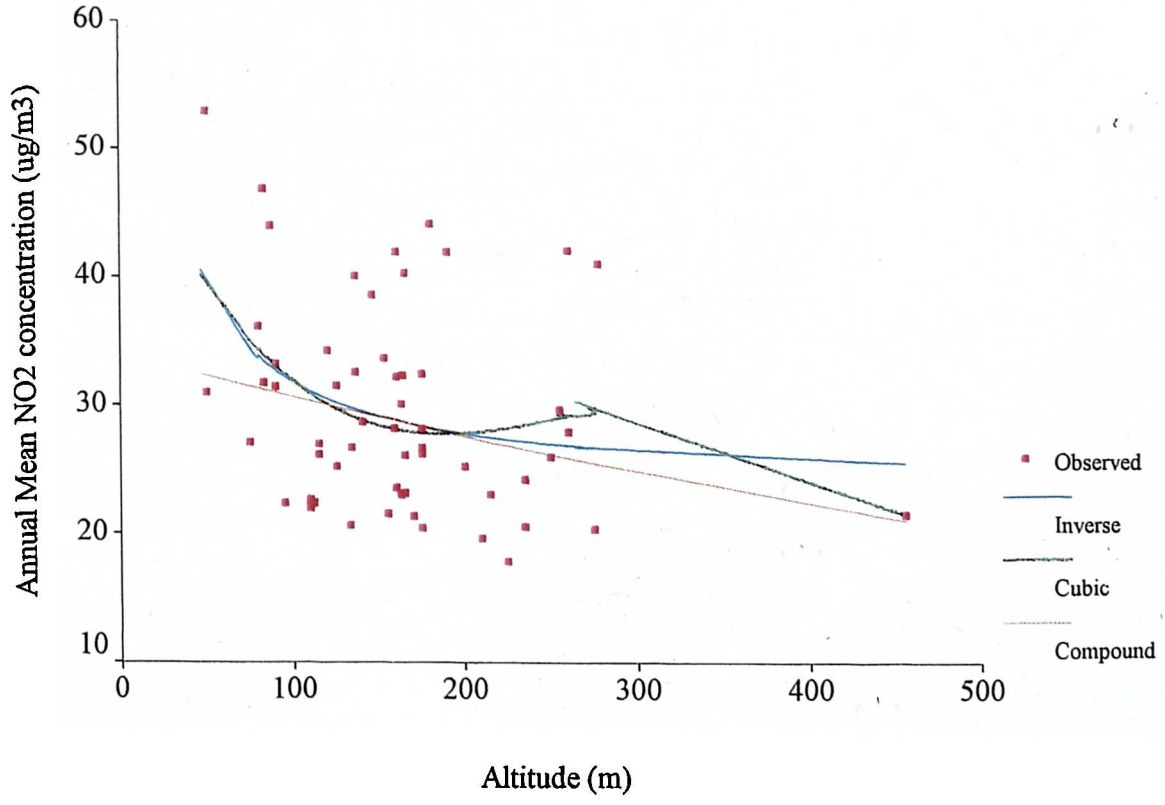


Figure 5.11 Selected Curvilinear Relationships Between NO2 Concentrations and Altitude - Non Kerbside Sites Only



variation for surveys S_4 and A_m respectively). The outcome of the analysis indicates that the removal of the urban locations does not improve the overall explanation of the relationship between NO_2 concentrations and altitude. By using all sites between 17.7 and 30.2 per cent of the variation in NO_2 can be explained by altitude. This suggests that, although altitude does explain a significant amount of variation in NO_2, this relationship is not straightforward. Indeed, it seems likely that much of the apparent altitudinal effect on levels of air pollution is indirect, through the influence of altitude on land cover and the distribution of emission sources.

Table 5.14 Regression analysis(r^2 values) of the effects of altitude on NO_2 concentrations (Non urban sites)

	S_2	S_3	S_4	A_m
Degrees of Freedom	1/47	1/53	1/55	1/55
Linear	0.103	0.080	0.032	0.072
Logarithmic	0.103	0.115	0.053	0.102
Inverse	0.087	0.138	0.074	0.125
Quadratic	0.104	0.106	0.044	0.085
Cubic	0.112	0.131	0.084	0.134
Compound	0.118	0.073	0.037	0.080
Power	0.115	0.102	0.054	0.104
S	0.095	0.114	0.069	0.118
Growth	0.118	0.073	0.037	0.080
Exponential	0.118	0.073	0.037	0.080
Logistic	0.118	0.073	0.037	0.080

5.2.5 POLLUTANT VARIATION WITH VERTICAL DISTANCE

Several previous studies (e.g. Loxen and Noordally 1987; Loxen *et al.* 1988; den Tonkelaar *et al.* 1987) have shown that NO_2 concentrations typically decline with height above ground, as a result of the effects of dispersion, deposition and atmospheric chemical reactions. Nevertheless, the importance of sampling height as a component of urban air pollution variation has not been extensively studied. This source of variation was examined here by conducting a number of surveys, during which diffusion tubes were placed at

regular vertical intervals on the outside of tall buildings within the study area. Buildings over five stories were chosen to maximize the possible number of sites at each location. Four buildings within the study area were considered suitable, and between 7 and 9 samplers were used at each site. At each site, tubes were exposed for a two-week period. Details are given in section 4.2.2. Data were entered into SPSS, and relationships between sampler height and concentrations analyzed using curvilinear regression analysis. The results are shown in Table 5.15 and Figures 5.12 to 5.15.

Table 5.15 Curvilinear Regression Analysis of Variation with Vertical Distance (R^2 values)

	Oldgate House	University of Huddersfield	Technical College	St Peters House
Number of Floors	8	9	7	9
Degrees of Freedom	1/7	1/8	1/6	1/8
Linear	0.335	0.744	0.886	0.565
Logarithmic	0.467	0.821	0.979	0.784
Inverse	0.600	0.771	0.924	0.910
Quadratic	0.393	0.763	0.955	0.731
Cubic	0.563	0.971	0.977	0.894
Compound	0.335	0.741	0.934	0.594
Power	0.455	0.760	0.976	0.794
S	0.572	0.670	0.871	0.890
Growth	0.335	0.741	0.934	0.594
Exponential	0.335	0.741	0.934	0.594
Logistic	0.335	0.741	0.934	0.594

As can be seen, trends with height are generally curvilinear, and are variously described by cubic, inverse or logarithmic models (with R^2 values of between 0.910 and 0.979 for three of the four buildings). The exception is Oldgate House for which the R^2 value is relatively low (R^2 value of 0.600): concentrations around the building may have been affected by the emissions from vehicles on the nearby inner ringroad and the associated traffic-generated turbulence.

In order to analyse the data collectively, concentrations for each of the buildings were first standardised relative to the ground level value. The results of this analysis can be seen in Table 5.16 and Figure 5.16.

Figure 5.12 Relationship Between NO2 Concentrations and Height

(Oldgate House)

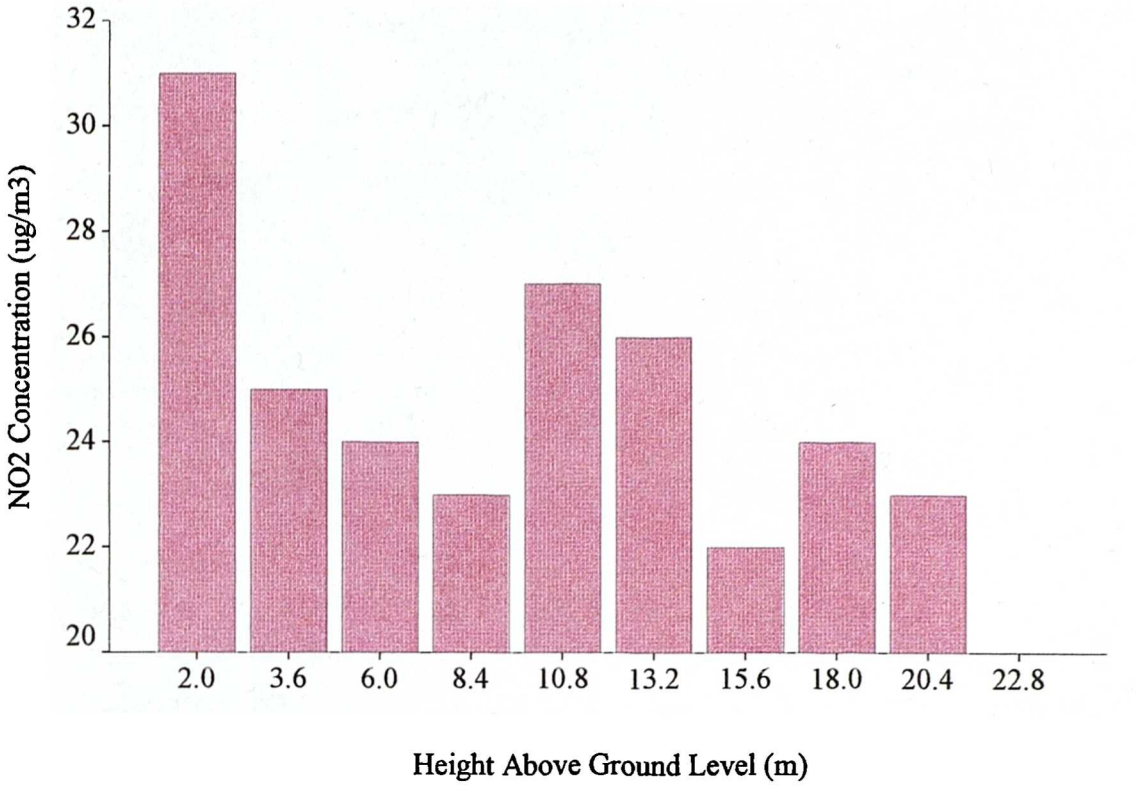


Figure 5.13 Relationship Between NO2 Concentrations and Height

(The University of Huddersfield)

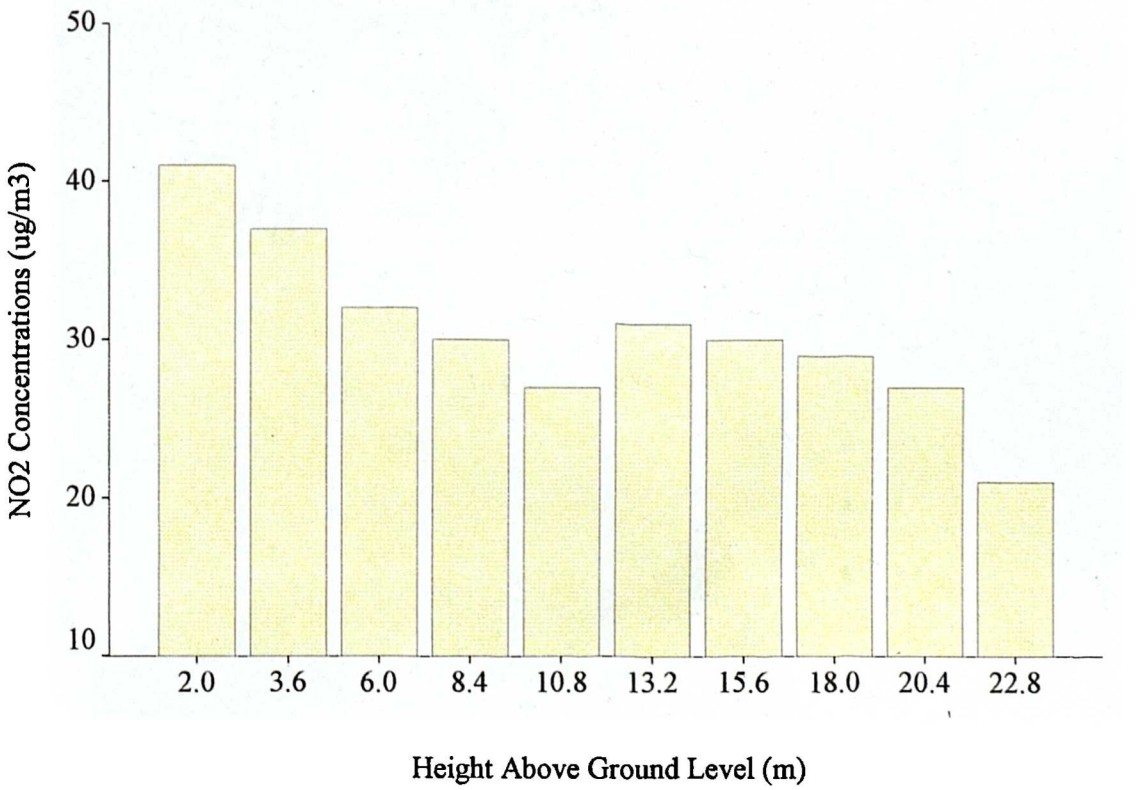


Figure 5.14 Relationship Between NO2 Concentrations and Height

(Technical College)

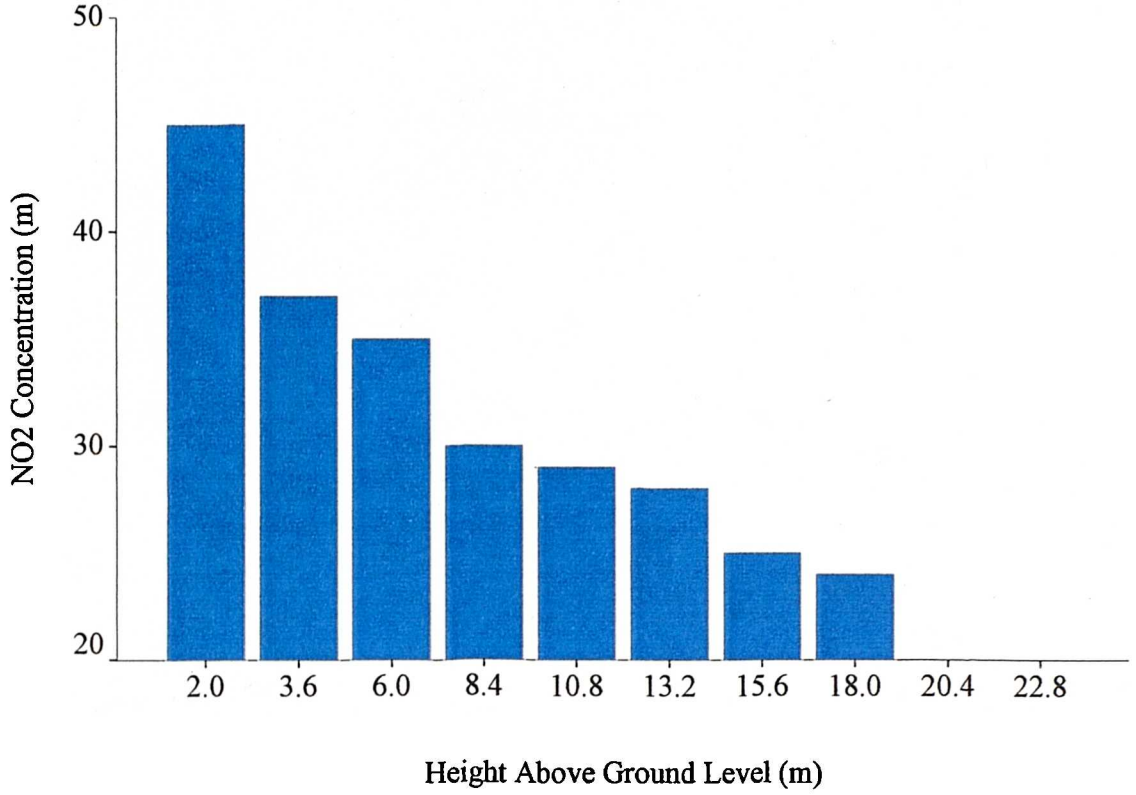


Figure 5.15 Relationship Between NO2 Concentrations and Height

(St Peters House)

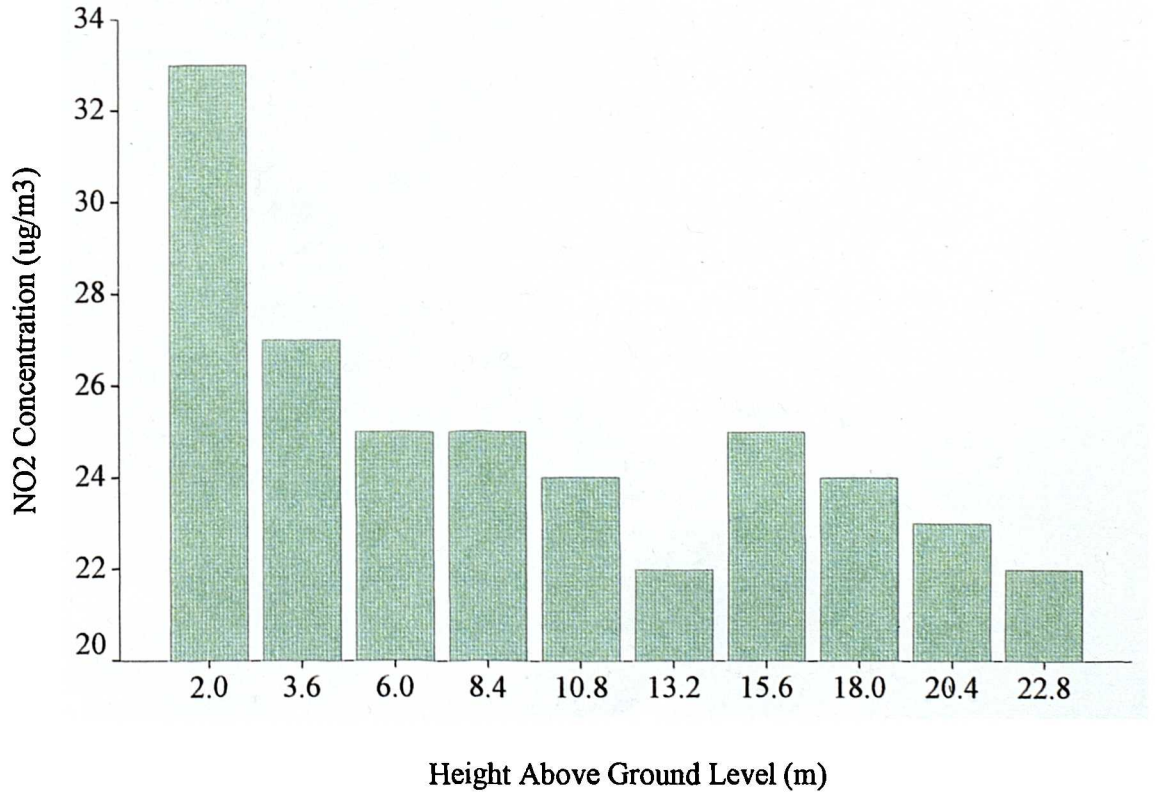


Figure 5.16 Relationship Between Standardised NO2 Concentrations And Height above Ground (m) - For All Sites

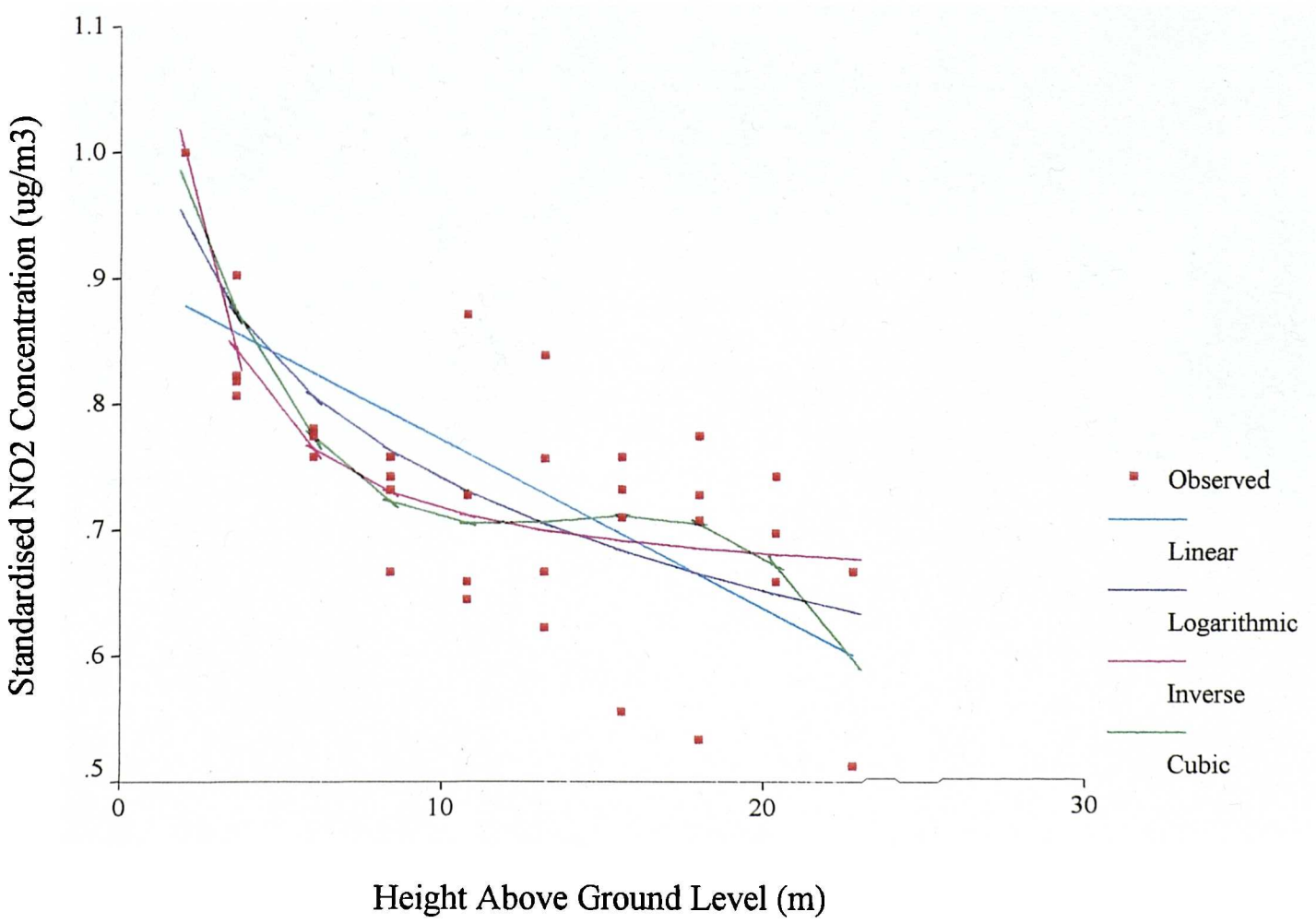


Table 5.16 Standardised Curvilinear Regression Analysis of Variation with Vertical Distance (R^2 values)

	All vertical height data
Degrees of Freedom	1/35
Linear	0.426
Logarithmic	0.388
Inverse	0.343
Quadratic	0.481
Cubic	0.483
Compound	0.416
Power	0.384
S	0.344
Growth	0.416
Exponential	0.416
Logistic	0.416

Various regression models were then used on all the data, and interestingly, linear, cubic and quadratic models provided the best fit, accounting for ca. 42 to 48 per cent of the variation in NO2 concentrations. Overall, although it tends to provide a slightly lower concentration in some cases, the linear model may be considered an adequate fit, given its simpler form. Model parameters for this are as follows:

NO2 (as a percentage of ground level concentrations) = 5.333 + (Height above ground Level * 0.426)

5.2.6 Variation in Measurement and Sampling Error

In order to examine the effect of possible errors from laboratory and field procedures, the amount of nitrogen dioxide recorded in the blank tubes was assessed. Measurements from the blanks tubes for the three centres in the SAVIAH study using diffusion tubes were analyzed and tested for deviation from zero. Results are shown in Table 5.17.

Table 5.17 Comparison of laboratory and field blank accuracy

Centre	Lab Blank ($\mu g/m^3$)		Field Blank ($\mu g/m^3$)		p Value
	Mean	**S.D.**	**Mean**	**S.D.**	
Huddersfield, UK	0.472	0.254	0.297	0.042	0.264
Amsterdam, NL	0.355	0.042	0.399	0.149	0.430
Prague, CZ	0.287	0.069	0.615	0.306	0.028

These results indicate that, for all centres, the amount of measured nitrogen dioxide was very small (i.e. below $1\mu g/m^3$) in both field and laboratory blanks. The standard deviation of the tubes was also very small. Contamination of the tubes, and thus errors induced by either laboratory or field procedures, can be consequently considered to be negligible.

A second way of examining the error effect is by comparing results for tubes at each site in the routine surveys. For two surveys (S_3 and S_4) duplicate tubes were placed at each of the routine and variable sample sites (see section 4.1). Comparability between the duplicates was assessed for these surveys by examining the correlation between each of pair of tubes. Results are shown graphically in Figure 5.17 to 5.18. These graphs show that there is very good correlation between the data at a site with the slope values almost at unity (R^2 values of 83 and 93 per cent for surveys S_3 and S_4 respectively), thus indicating that the error effect is small. Further investigation was conducted using Oneway analysis of variance. Results of this analysis is shown in Table 5.18.

Results of the Oneway analysis of variance indicated that approximately 96 and 98 per cent of the variation (recorded in surveys S_3 and S_4 respectively) occurred between the sites with only 4.2 and 1.7 per cent variation at a site (i.e. between two tubes at a site). These results indicate that less than 5 per

Figure 5.17 Comparison of NO2 concentrations at a site (Survey S3)

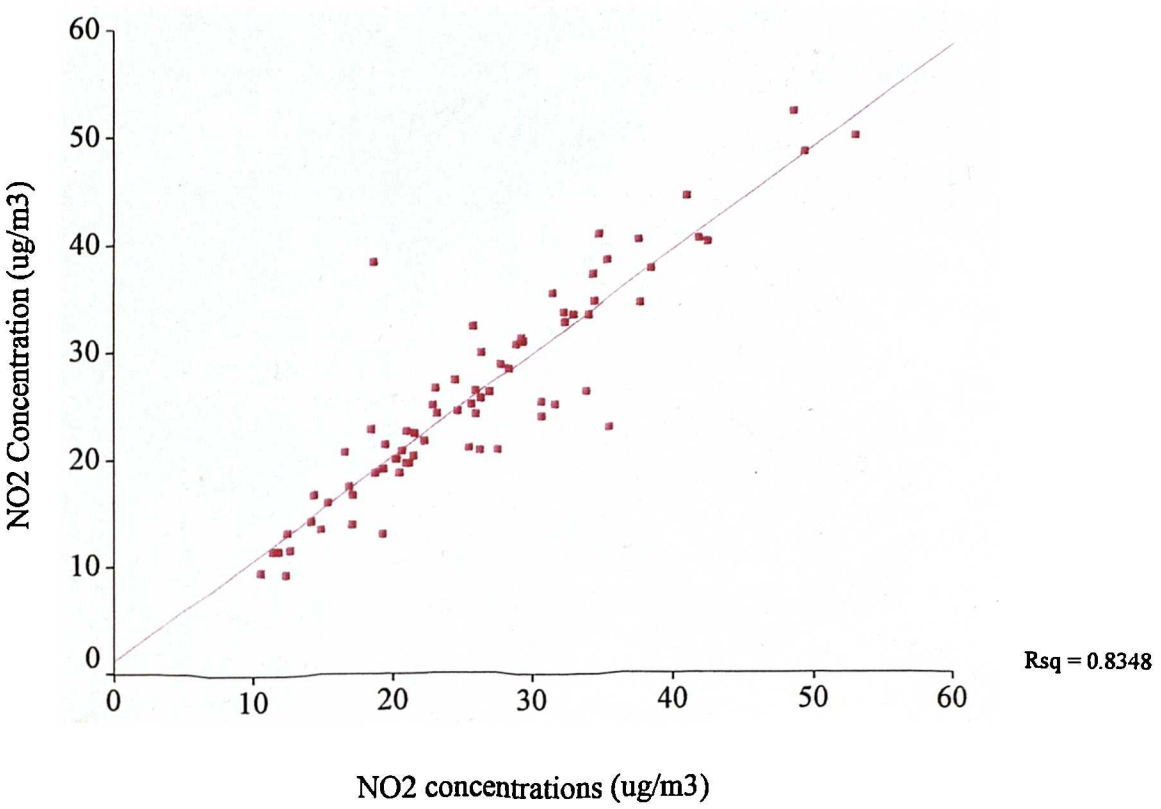
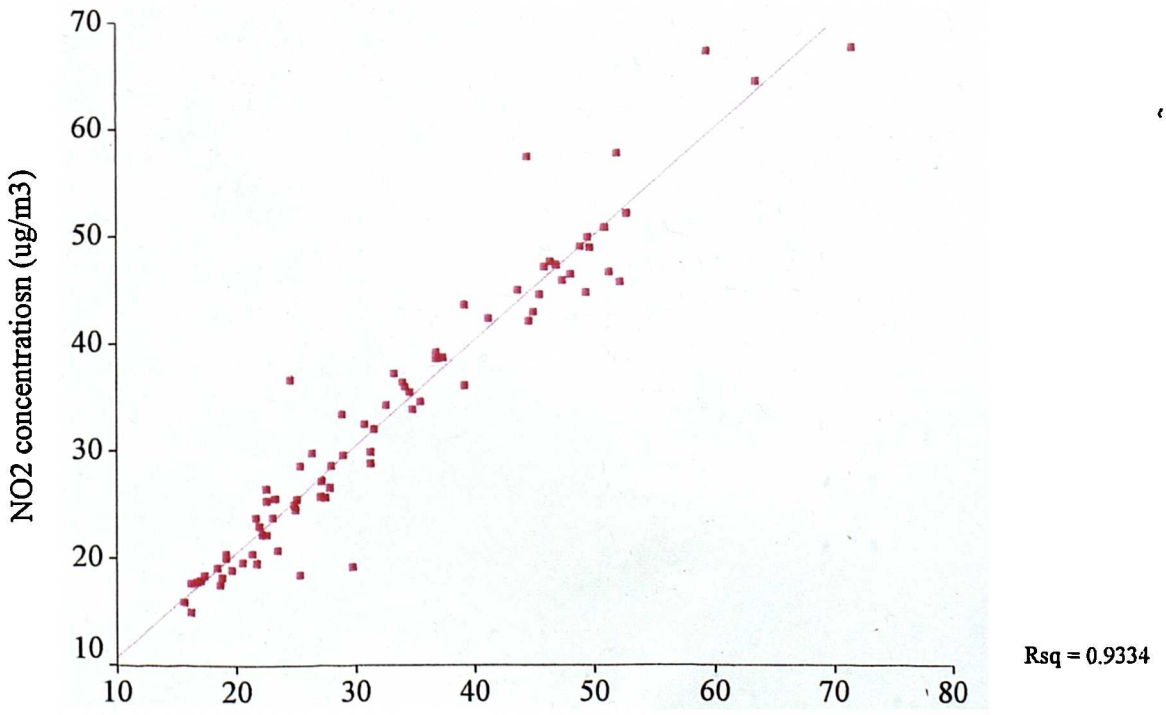


Figure 5.18 Comparison of NO2 concentrations at a site (Survey S4)



cent of the recorded variation can be attributed to the error effect – i.e. sampling and measurement error. Further decomposition of this source of variation is not possible in this analysis due to the sampling techniques used. For the purposes of this study, however, such variation can be considered negligible.

Table 5.18 One-way Analysis of Variance of the error effect

		Sum of Square	D.F.	Mean of Square	F	Sig. of F	%
Survey S_3	Between-site variation	13181.213	75	175.750	21.979	0.0000	95.8
	At-Site variation	583.715	73	7.996			4.2
	Total	13764.928	148				
Survey S_4	Between-site variation	25513.105	79	322.951	56.497	0.0000	98.3
	At-site variation	445.870	78	5.716			1.7
	Total	25958.975	157				

5.2.7 Spatial and Temporal variation

The preliminary analysis of the sources of variation in NO_2 concentrations in the study area, reported in the previous sections of this chapter, indicated that a large proportion (ca. 40 per cent) of the total variation in pollution levels could be attributed to temporal effects. These temporal effects suggested that further investigation was necessary for a number of reasons. Firstly, there was the question of whether the temporal variation discerned in the data can be explained in terms of seasonal or meteorological factors. Secondly, there was the question of the spatial character of the temporal variations. For example, is the spatial variation spread evenly across the area or concentrated in a few sites: in other words, do some sites vary over time while others

remain constant? Alternatively, do different types of site show distinctive patterns of temporal variation, as implied by the recognition of so-called 'air pollution affinity areas' (McGregor 1996). The following investigations attempt to address these questions.

5.2.8 TEMPORAL VARIATION

The analysis of spatial patterns of variation in NO_2 concentrations in the study area, reported in the previous section, has shown that considerable small area variation occurs in pollution levels, related to factors such as traffic volume, landcover and altitude. As noted earlier, however, this is not the only source of variation. Significant temporal variation may also be expected, as a result of meteorological and seasonal effects.

With the available data, it is not possible to examine short-term variations in the study area. Results for the routine surveys can, however, be used to examine variation at the seasonal scale (between-surveys).

Temporal patterns in the data were analysied by comparing measured concentrations at each of the 80 core sites, between surveys, using regression analysis. In this way it was possible to determine to what extent patterns of pollution remain broadly the same over time - i.e. whether concentrations at that site at one time help to predict concentrations at that site at a later time (temporal auto-correlation). Survey S_5 was not used in this analysis as S_5 was not a routine survey and did not contain the core sites and therefore was not directly comparable. Results are shown in Table 5.19 and Figures 5.19 to 5.21.

The results demonstrate that patterns of pollution are broadly stable. Adjusted R_2 values between surveys are between 58.1 and 69.4 per cent, with standard errors of 5.4 to 8.3 $\mu g/m^3$. Slope coefficients between surveys S_2

Figure 5.19 Comparison of NO2 Concentrations Between Surveys - (S2 and S3)

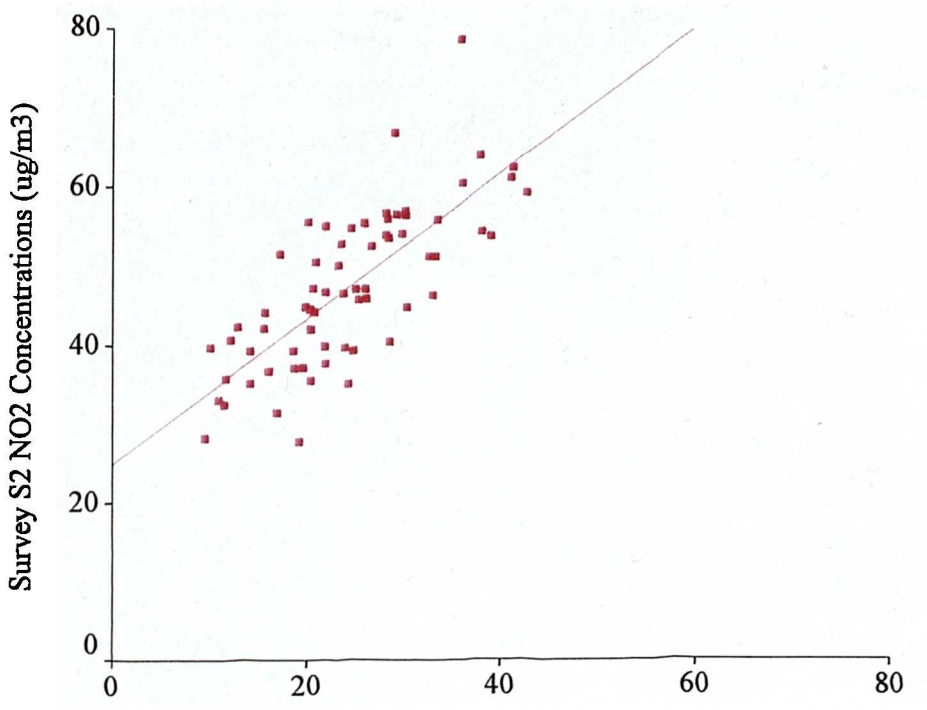


Figure 5.20 Comparison of NO2 Concentrations Between Surveys - (S3 and S4)

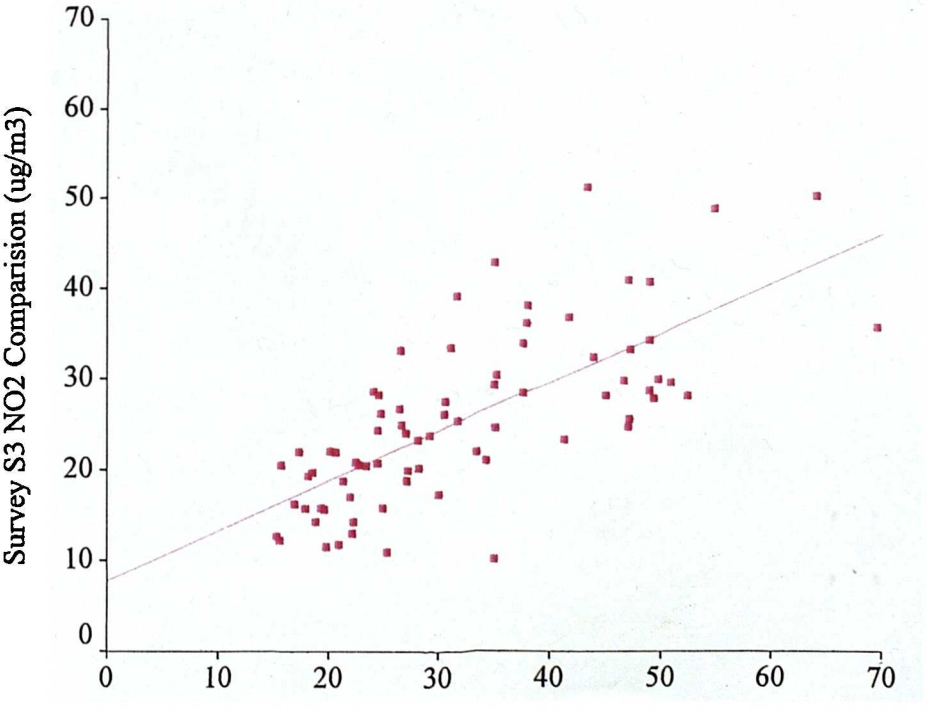
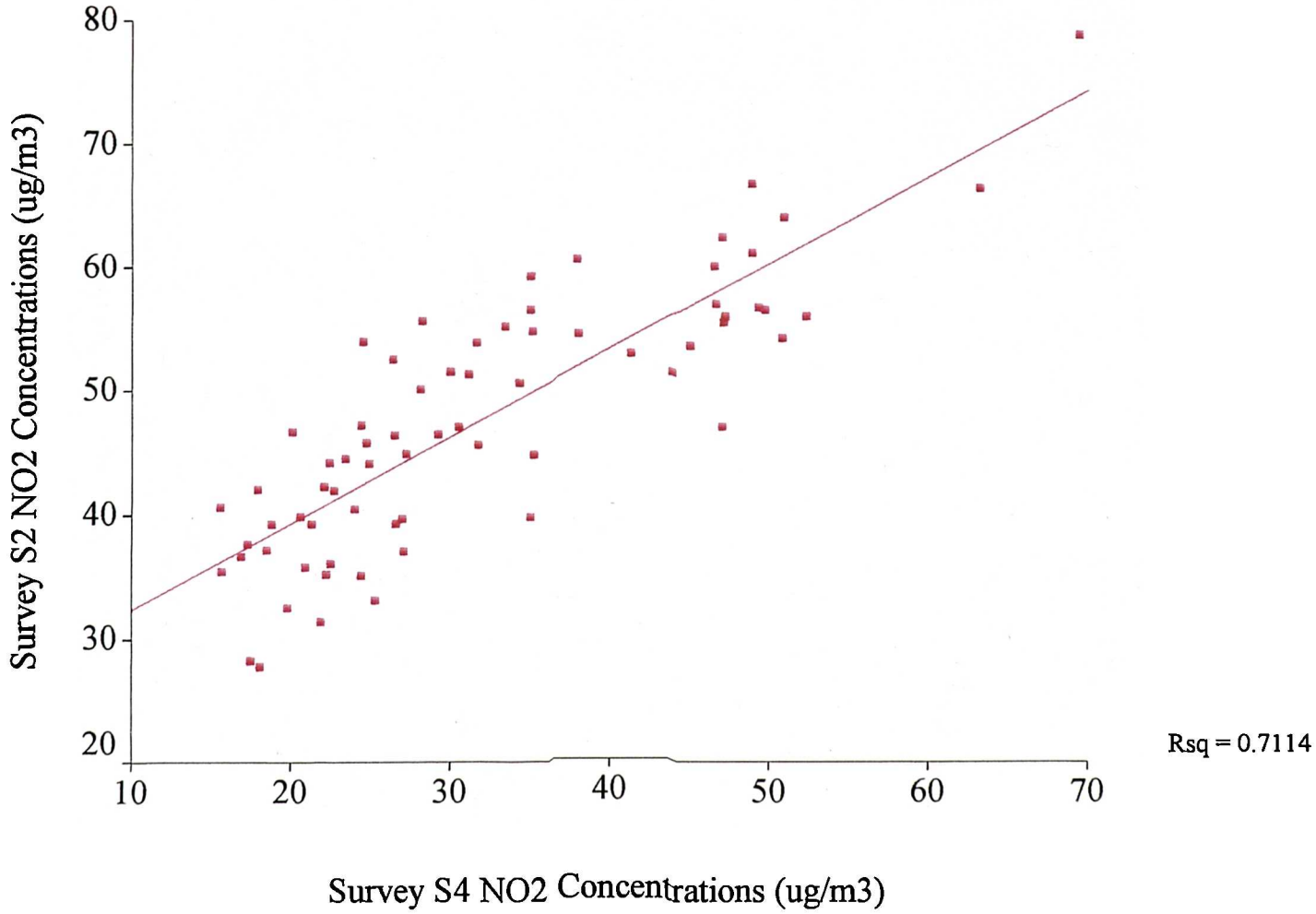


Figure 5.21 Comparison of NO2 Concentrations

Between Surveys - (S2 and S4)



and S_4, and surveys S_3 and S_4 are close to unity, though the constants vary, indicating that while absolute levels of pollution may vary from one survey to another, the inter-site differences remains broadly the same. For survey S_2 versus survey S_3, the slope coefficient is flatter, reflecting the relatively lower concentrations in the latter survey.

Table 5.19 Regression analysis of data stability

	S_2 V S_3	S_3 V S_4	S_4 V S_2
Degrees of Freedom	1/74	1/79	1/77
Multiple R	0.7621	0.7659	0.8329
R^2	0.5808	0.5866	0.6937
Adjusted R^2	0.5751	0.5832	0.6898
Standard Error	5.3788	8.3019	7.1904
Slope Value	0.6217	1.0061	1.0400
Constant	-4.8179	-6.6718	-16.7806
F Value	102.5295	171.6903	174.4068
Significance F	0.0000	0.0000	0.0000

5.2.9 SPATIO-TEMPORAL VARIATION

The previous section has shown that many factors contribute to variation in air pollution levels in the study area, including spatial, temporal and error components. In order to estimate the relative contribution of all these components to variation in NO_2 concentrations, oneway analysis of variation was conducted on the 80 core sample sites. Data for surveys S_2, S_3 and S_4 only were used in this analysis. The outcome of the analysis is show in tabular format in Table 5.20.

Table 5.20 Spatio-temporal Oneway Analysis of Variance

	Sum of Square	D.F.	Mean of Square	F	Sig. of F	%
Main effect	37459.843	81	462.467	16.248	0.000	85.40
Spatial effect	33319.183	79	429.480	14.817	0.000	88.95
Temporal effect	3529.538	1	3529.538	124.001	0.000	9.42
Error effect	3.864	1	3.864	0.136	0.713	0.01
Explained	37459.843	81	462.467	16.248	0.000	85.40
Interaction effect	6404.368	225	28.464			14.60
Total	43864.211	306	143.347			100.0

As these results show, 85.4 per cent of the variation can be explained by spatial, temporal and error effect acting independently. Only a small percentage, 0.01 per cent is attributable to variation between duplicates, reinforcing the view that this in an unimportant source of variation in the data (as stated in section 5.1.3). Temporal variation accounts for 9.42 per cent of the explained variation, while spatial (between-site) variation accounts for 88.9 per cent of the total explained variation. From these results, it is apparent that the most significant component of variation is the spatial effect. Temporal variation represents only a relatively small contribution to the total (<10%), while the effects of measurement and sampling error is negligible. As stated in section 5.1, however, the dispersion and emission patterns of air pollution vary over time and space in a complex, three dimensional way. The interaction between spatial and temporal variation and the effects of measurement error were thus found to explain 14.6 per cent of the recorded variation.

5.2.10 TEMPORAL 'AFFINITY AREAS'

The concept of air pollution 'affinity areas' was evolved recently by McGregor (1996). Using data from 15 fixed site monitoring stations in Birmingham, he showed that groups of sites could be discerned which showed similar temporal patterns of air pollution, yet differed from other groups. These groups were defined as affinity areas. Recognition of affinity areas in this way has considerable implications, for it provides a basis on which to judge the representativeness of fixed-site monitoring stations, to plan monitoring campaigns and to extrapolate from monitoring sites to wider areas. The monitoring carried out as part of the current study was insufficient for identifying affinity areas: data at core sites were available for too few locations. Monitoring carried out by Kirklees M.C., however, are appropriate for this purpose. Kirklees Scientific Services have been conducting surveys since 1992 at 20-30 sites, using passive diffusion tubes deployed on a

monthly basis. A number of sites have been relocated on several occasions, and problems of vandalism have resulted in some gaps in the coverage so a full set of data for the whole period was not available. More or less complete data do exist, however, for 25 sites, covering the period from 1992 to 1995. These were kindly made available by Andrew Sheard of the Scientific Services.

In order to investigate whether there was a quantifiable pattern in the behaviour of the sites (i.e. whether pollution levels at the sites vary concordantly), factor analysis was conducted on the data. Factor analysis assumes that variation within the data set can be represented as a linear combination of a smaller number of index variables, plus the residuals, which reflect the extent to which they are independent of the other variables (Chapman and Collins 1995; Manly 1994). By representing cases (i.e. sites) as variables and measurement events (i.e. survey periods) as cases, Q mode Factor Analysis allows the 25 sites included in the Kirklees data to be grouped into a smaller number of 'site types'. Factor analysis was therefore undertaken in SPSS. Results of the analysis are shown in Tables 5.21 to 5.23.

As Table 5.21 indicates, three main factors were identified, the first of which explained 67.1 per cent of the communal variation in pollution concentrations in the data. The second and third factors explained 15.5 and 9.8 per cent of the communal variation respectively. Factor analysis using only three factors thus explained 92.4 per cent of the communal variation in pollution patterns in the data, leaving only 7.6 per cent of the variation to be explained by the remaining 22 factors. Following the procedures recommended by Chatfield and Collins (1995), these additional factors were rejected, since all had eigenvalues of less than 1. The importance, or weighting of each factor for each site, was tested in Table 5.22 and is summarised in Table 5.23.

Table 5.21 Final Statistics of Factor Analysis

Factor	Eigenvalue	Pct of Variance	Cumulative Percentage
1	16.783	67.1	67.1
2	3.885	15.5	82.7
3	2.442	9.8	92.4
4	0.944	3.8	96.2
5	0.849	3.4	99.6
6	0.553	2.2	100.0
7	0.426	1.7	100.0
8	0.328	1.3	100.0
9	0.206	0.8	100.0
10	0.114	0.5	100.0
11	0.100	0.4	100.0
12	0.069	0.3	100.0
13	0.049	0.2	100.0
14	0.028	0.1	100.0
15	0.021	0.1	100.0
16	0.008	0.0	100.0
17	0.004	0.0	100.0
18	-0.002	-0.0	100.0
19	-0.003	-0.0	100.0
20	-0.033	-0.1	99.8
21	-0.058	-0.2	99.6
22	-0.134	-0.5	99.1
23	-0.193	-0.8	98.3
24	-0.300	-1.2	97.1
25	-1.080	-4.3	100.0

From the tables (Table 5.22 and 5.23) it is apparent that the majority of the sites are heavily loaded on factor 1; only two sites loaded heavily on factor 2 and three sites loaded on factor 3. Further investigation of the data indicates that there is some degree of coherence within these groups in terms of site characteristics. Group 3 contains only residential sites in out of town or pedestrian areas. Group 2, although accounting for only 2 sites, depicted sites within suburban town centers. Sites within group 1 were less homogeneous. Core members of this group, with the highest loading on factor 1, comprised busy town centre sites (sites 11,8, 13, 12, 23 and 14). As loadings on factor 1 fall, however, the sites become progressively more residential in character, and sites 10, 19 and 16 all of which are relative marginal members of the group, relate to less busy, residential locations.

Table 5.22 Factor Matrix

Grouping	Site No	Factor 1	Factor 2	Factor 3
One	11	0.983	-0.179	-0.026
	08	0.977	-0.217	0.087
	13	0.967	-0.064	0.015
	12	0.965	0.163	0.040
	23	0.963	-0.190	-0.659
	14	0.962	-0.020	-0.085
	28	0.942	0.148	-0.296
	27	0.885	0.175	-0.009
	09	0.879	-0.293	0.116
	02	0.870	0.231	-0.269
	07	0.864	0.261	0.248
	26	0.860	0.152	0.055
	17	0.841	0.113	0.293
	21	0.829	0.312	0.101
	24	0.770	-0.624	0.071
	03	0.723	0.364	0.499
	05	0.714	0.492	-0.262
	10	0.694	0.186	0.384
	19	0.616	-0.198	0.584
	16	0.601	-0.387	0.548
Two	18	0.111	0.987	0.075
	20	0.272	0.977	0.053
Three	06	-0.817	0.302	0.901
	15	0.018	-0.297	0.883
	22	0.536	0.051	0.608

5.23 Summary of Factor Loadings by Group

Grouping	Factor 1	Factor 2	Factor 3
One	1	2	3
Two	2	1	3
Three	2	3	1

In addition, concentrations between the three groups vary by approximately 10μg/m^3 in each case. Group 2, consisting of suburban town centre sites, recorded the highest mean pollution concentration over the sampling period of 64.0 μg/m^3. Groups 1 (urban) and 3 (residential) recorded mean concentrations of 56.8 μg/m^3 and 43.7μg/m^3 respectively.

This analysis is inevitably limited for several reasons: the number of sites is small, and the averaging period (one month) relatively long and the survey

period (ca. 12 months) short. Little information is available (e.g. on changes in traffic conditions, meteorology or site characteristics) on which to build explanations of the patterns identified. Nevertheless, the analysis does suggest that, while most sites follow a broadly similar pattern of variation over time, some show a distinctively different pattern. With more data it may thus be possible to define 'affinity areas', as proposed by McGregor (1996), and thereby establish a framework for analysing spatio-temporal variation in air pollution. In the meantime, the strong grouping of most sites in the study area again show that patterns of pollution are, for the main part, stable over time. This is a crucial finding, for it implies that data from a monitoring campaign or period may indeed be used to predict patterns of pollution at other times. It thus helps to explain the high degree of correlation found between the core surveys conducted in Huddersfield and the annual mean mentioned at the consecutive sites (Section 4.1 and 4.2) . It also means that pollution maps generated from the available data may have relatively long lasting relevance, and that patterns of human exposure to air pollution are likely to be geographically consistent from season to season and perhaps from year to year.

5.3 CONCLUSION

This chapter has examined the temporal and spatial influence of both emission and dispersion patterns and the influence of measurement error. The effects of measurement error on NO_2 variation have been examined and considered negligible. The influence of spatial emission and dispersion patterns is one of great complexity. Relationships have been identified, however, between NO_2 concentrations and vehicle volume, distance to road and altitude. The influence of land cover on the spatial patterns of variation is more complex although some relationship does appear to exist. Temporal

patterns of emission and dispersion characteristics were also investigated. Investigation of inter-survey relationships indicated that the patterns of pollution are broadly stable over time. The concept of air pollution 'affinity areas' (i.e. the definition of areas showing broadly similar temporal patterns of pollution) was applied to the study area and three 'pollution groupings' identified. The data thus suggests that patterns of pollution remain stable over time within the 'groupings'.

The results of this analysis have provided some interesting finding which will be of great use in the development of methods for mapping air pollution at the small area scale. The following chapters attempt to examine a variety of methods for mapping air pollution.

6. *DISPERSION MODELLING*

The marked levels of local variation in urban air pollution, illustrated in the previous chapter, indicate the problems which face attempts to map and predict air pollution concentrations, and to assess levels of human exposure at the small area scale. An approach which may nevertheless appear to offer an effective means of pollution mapping is the use of dispersion models. Dispersion modelling may be defined as a process by which an understanding of the processes of emission and dispersion is used to estimate atmospheric pollutant concentrations in the ambient environment (Seinfield 1986). This approach has a long history with a wide variety of dispersion models being developed in recent years. Nevertheless, the application of these models for pollution mapping and exposure assessment has so far been surprisingly limited, and the extent to which they can provide valid estimates of pollution levels, in the context of this high degree of local variation, remains uncertain. This chapter will thus examine a number of dispersion models in order to assess their capability for predicting and mapping urban air pollution at the small area level.

6.1 PRINCIPLES AND DEVELOPMENT OF DISPERSION MODELLING

The development of dispersion modelling paralleled the introduction of air quality legislation in the western world. Such models offered an efficient and

relatively simple method of allowing the relevant regulatory bodies to assess compliance with specific government standards. Dispersion models also acted as a guide for governments, in implementing emission control strategies to improve air quality, to assess planning applications for new emission sources and for devising responses to air pollution events (McCrae and Hickman 1988; 1990; Calvert *et al.* 1993; Simpson *et al.* 1993; Szpesi and Fekete 1987; Eskridge and Hunt 1979; Elsom 1995; DOE 1996). Russell (1988), for example, stated that:

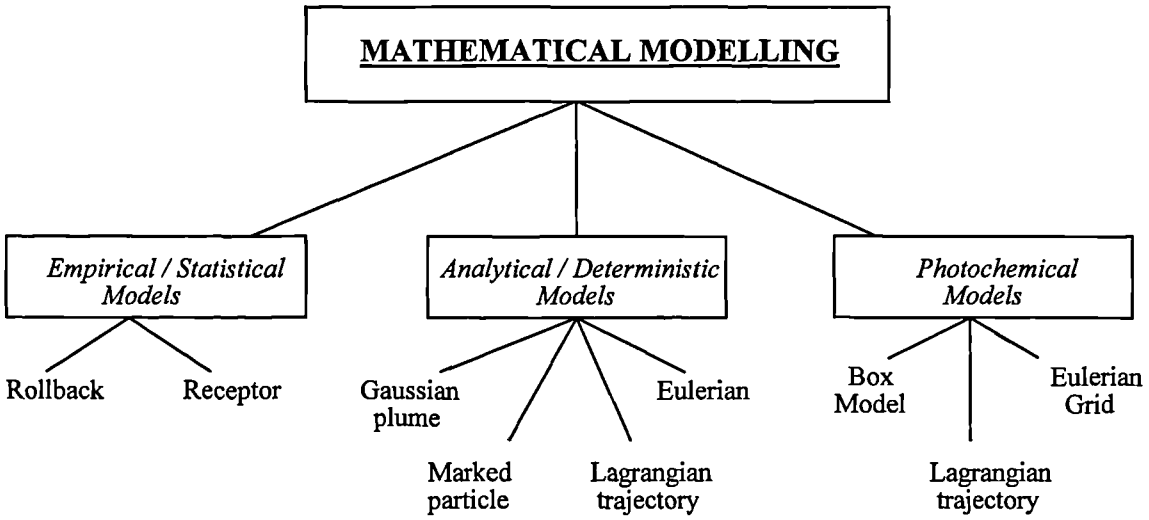
> 'only after the impact of sources have been correctly assessed, will it be possible to devise and implement rational, convincing and effective polices to improve air pollution.'

Dispersion modelling can be divided into two categories. The first, *physical models*, aim to create simulations of the 'real-world' within a laboratory environment (e.g. wind tunnels to test street canyon effects (Bachlin *et al.* 1996; Hall *et al.* 1996; Dabbert and Hoydysh 1991)). The second, *mathematical models*, attempt to describe air pollution concentrations on the basis of physical and chemical processes. Mathematical dispersion modelling can be subdivided into three types: empirical/statistical modelling, analytical/deterministic modelling and photochemical modelling (Russell 1988; Colls 1996; Pavageau *et al.* 1996). A schematic diagram of these models is shown in figure 6.1.

Empirical or statistical models were amongst the first forms of dispersion modelling to be developed. They do not directly apply knowledge of dispersion processes, but instead endeavour to establish and apply statistical relationships between observed levels of air pollution within an area and the source emission patterns (Calvert *et al.* 1993; Russell 1988; Simpson *et al.* 1985; Lee and Pielke 1996). Analytical/deterministic models were developed in the 1970s to describe the complex transport and chemical processes occurring in the environment. These are typically based upon a combination of physical and/or chemical principles, and empirically derived relationships to determine air pollution

concentrations as a function of meteorological, topographical and source characteristics and simple chemical transformations. Photochemical modelling represents the most recent development in dispersion modelling. Photochemical models were developed in the early 1980s to predict concentrations of reactive gasses such as NO_2 and O_3 as a function of emissions. They incorporate complex chemical sub models and are especially useful in urban areas.

Figure 6.1 Schematic diagram of mathematical models



Each of these modelling approaches has both advantages and disadvantages. Empirical models are considered useful as first instance screening models. A major drawback to the accuracy of these models, however, is the simplistic and restricted view of the chemical and meteorological factors involved (Seinfield 1975; Lee and Pielke 1996; Jankowski and Haddock 1996). Photochemical models are considered accurate for detailed analysis, but require extremely detailed input data which is not always available. As all models are only as good as their input data, this seriously reduces the use of photochemical models for broader (e.g. regional) scale applications where such data is not available.

Analytical models are thus probably the most widely used, especially for routine application, and they thus provide the focus of attention in this chapter. Analytical models can be divided into four basic types: Eulerian models, Lagrangian trajectory models, marked particle models and Gaussian plume models.

Eulerian models are potentially the most powerful air quality models, allowing both spatial and temporal variation in the parameters to be estimated. They are consequently the most computationally intensive. They calculate the concentrations of a pollutant at a specific geographical point for a set time-period. The model predicts concentrations based on the effect of new emissions, transport in and out of the area, chemical reactions and dilution on the ambient concentrations. Eulerian models can thus provide very detailed pollution information at a fine geographical and temporal resolution. Nevertheless, they are expensive to develop and use and require detailed and complex input data.

The second type of model, Lagrangian trajectory models, examine the trajectory of a column of air based on meteorological conditions. Simultaneously the model describes the vertical diffusion of the pollutants, deposition, dilution, chemical reactions and the addition of 'new' emissions. Lagrangian trajectory models, although less complex and data-demanding than the previous type, enable chemical reactions and the effect of new sources of pollution to be examined. To be effective, however, they require spatially and temporally resolved wind fields, mixing heights, deposition parameters and data on the spatial distribution of emissions. Another problem is their assumption that the effects of vertical wind shear and horizontal diffusion are negligible (Liu and Seinfield 1975; Lee and Pielke 1996).

Marked particle models are based on the Lagrangian trajectory model. They examine the centre of a mass of parcels of emissions, travelling at local wind velocity. Diffusion about the centre of the mass is simulated by additional random translation which corresponds to the atmospheric diffusion rate (Cass 1981). Again they require extremely detailed input data and thus their application in this project was considered inappropriate.

The most widely used model is the Gaussian plume model. The Gaussian plume approach is based on the distribution of pollutants across the plume in the horizontal (y) and vertical (z) directions. The 'spread' or diffusivity of the pollution plume is characterised by the standard deviation (σ) in a 'normal' or Gaussian distribution. This is shown in Figure 6.2.

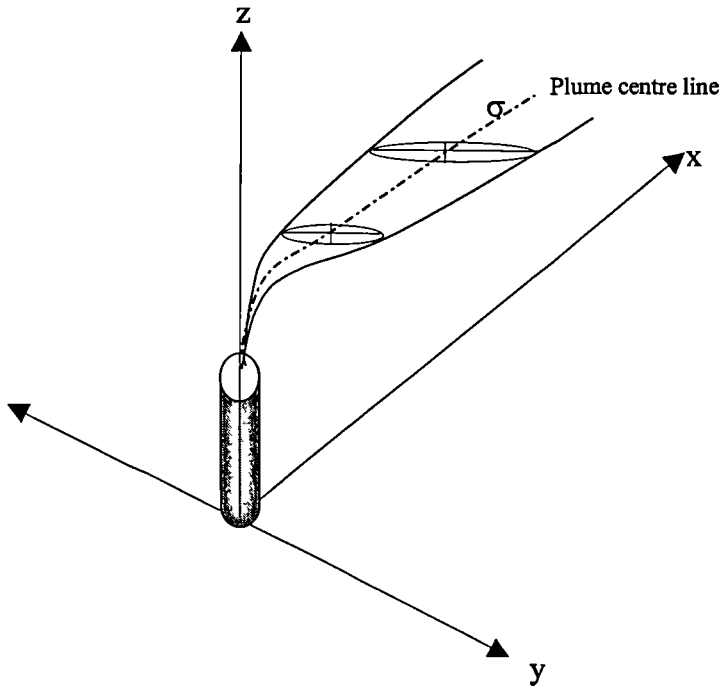
Gaussian plume models have been widely used since they are easy to apply, plume dispersion data is readily available, they are not computationally difficult and they have proved to be relatively accurate (Emak 1977; Taylor *et al.* 1985; 1987; Sawford and Ross 1985; Elsom 1995; Calvert *et al.* 1993). The main advantage of Gaussian plume modelling is that it:

> 'recognises that practical considerations of cost and data availability limit the advantages to be gained from more complex models and that other simple approaches .... are fundamentally incorrect in some situations of interest (e.g. close to the emission source)' (Sawford and Ross, 1985)

In the quest for a balance between accuracy and simplicity, however, the Gaussian model makes a number of assumptions (Hewitt and Harrison 1986, Lyons and Scott 1990). The major assumptions are as follows:

- Deposition does not occur from the plume at ground level.
- Dispersion downwind is negligible compared with transportation of the pollutant downwind.
- There is no effect from surface obstructions.
- No chemical processes take place within the plume which may affect the pollutant levels.
- Constituents are normally distributed, both horizontally and vertically, across the plume in a Gaussian distribution.
- Wind speed and wind direction are constant, spatially, temporally and with height.

Figure 6.2 Diagram of the Gaussian plume from a point source (chimney).
(after Turner, 1969)



Where;
x,y = horizontal or geographic direction
z = vertical direction
σ = diffusivity of the pollution plume

Many of the above assumptions will not occur in 'real-life' situations and therefore they may limit the accuracy of the model. Nor does the model allow for the variability in the environment. The ability of the Gaussian plume model to model multi-point sources may also cause problems, as this method does not consider the possible synergistic properties of combinations of pollutants (i.e. certain combinations of pollutants may exert a stronger effect than their effect as individual pollutants). Other errors may occur due to inaccuracies in the emission and meteorological data.

Recent developments within the field of air pollution dispersion modelling have seen the development of a replacement formula to the Guassian dispersion equation and its inherent limitations. New models released onto the market within the last few years such as the Cambridge developed ADMS and the American PDF model use the "BLP' or buoyancy line plume to describe the relative abundance of connective updraft and downdrafts within the plume. This method attempts to describe the movement of pollution within the plume and does not accept that the pollution is distributed homogeneously throughout the plume. Thus it attempts to better reflect the 'real world' environment within the framework of a mathematical model. The validity of these types of model is considered to be still in doubt by a number of experts within the field of dispersion modelling and indeed a comparison of the performance of the ADMS model and the Gaussian based ISCST model is not favourable, with ISCST providing modelled results which more accurately reflect monitored results (Harvey 1997).

6.2 LINE DISPERSION MODELS

Dispersion modelling was initially developed for point sources, and thus much of the early literature is concentrated on this aspect. Increases in road traffic, however, and the subsequent increase in pollution related to vehicle exhausts, led to the diversification of dispersion models into estimating pollution from line sources (Hickman and Colwill 1982).

Since the development of the Gaussian plume dispersion equation for use in line dispersion modelling, a number of modifications have been made to Pasquill's (1961; 1974) original dispersion curves in order to improve the predictive ability of the models (e.g. Chock 1978; Benson 1979; 1982; 1992; Eskridge *et al* 1991; Gifford and Hanna 1977; 1978; Hunt and Eskridge 1979; Calder 1973; Aron 1983; Matzoros and van Vliet 1992). Such modifications include addition of vertical and horizontal dispersion curves (Benson 1982; McCrae *et al* 1988); a measure of aerodynamic roughness (i.e. type of landuse surrounding the road); the effects of vehicle induced turbulence, buoyancy and vehicle wake (Eskridge at al 1991; Spangler 1986; McCrae and Hickman 1990); emission rates (McCrae *et al* 1988; Benson *et al* 1982); the perception of line sources as a finite line source and not a series of point sources (Benson 1982; Eskridge *et al* 1991); and varying meteorological conditions (Simpson *et al* 1985; Hanna, 1978). The choice of parameters and model formulation, however, varies from model to model. The available models also vary in complexity from Chock's (1978) G.M. model and Hanna's (1978) ATDL simple line dispersion model, to statistically complex models that attempt to allow for almost every traffic-induced and meteorological situation (e.g. Benson 1982; Taylor *et al* 1985; Maddukuri 1982; Matzoros and van Vliet 1992).

The ability of a line dispersion model accurately to represent the concentrations of pollution around a road depends to a great extent on the accuracy of its input data. The volume of input data for a model is often a reflection of its statistical complexity. The following section will examine standard data requirements for line dispersion models in general and then investigate specific data requirements and sources of information for each of the line dispersion models used here, in turn.

Data requirements of the different models vary enormously and are often a factor of the model's age, its statistical complexity and the amount of desired accuracy of the estimated pollution levels required. Nevertheless, it is possible to classify data needs into six general categories listed in Table 6.1.

6.3 DESCRIPTION OF THE MODELS

A number of line dispersion models have been selected for study here. These range from the more complex models, based on the Buoyancy Line Plume and Gaussian equations, to simpler models, which are less data intensive. On the basis of this investigation, the most accurate dispersion model will be identified, and then further used and tested as a basis for mapping air pollution in the study area.

From the available range of simple line dispersion models, two screening models were chosen: the UK Department of Transport DMRB (Design Manual for Roads and Bridges) model (DoT 1994) and Dutch government's

Table 6.1 General dispersion model data requirements.

Name	Definition
Emission Rates	A measure of the vehicle emissions at rest and at speed. Generally measured in g/km, emission factors vary between models, and may be broken down by vehicle speed and composition.
Traffic Characteristics	Most dispersion models include a combination of the following parameters: *traffic volume* (a measure of the flow of traffic on the specific road, usually over time), *traffic composition* (the percentage or fraction of HGV's, buses, light vans, cars, motorcycles etc on a specific road), *traffic speed* (average speed of vehicles travelling on the road, usually expressed in kilometres/hour)
Road Characteristics	The *width* (defined as the "travelled way". i.e. the road over which vehicles travel), *height* (defined as the road's height (in metres) above or below ground level) and *type* (i.e. intersection, junction, with/without traffic lights, straight road, presence of slip roads etc) of a road will affect the dispersion characteristics of the pollution emitted by the vehicle
Site Characteristics	Information on the terrain surrounding the road is important in determining the path of dispersion.
Receptor Location	This defines the point at which concentrations will be calculated. The placing of the receptors must be considered carefully, as most line dispersion models state minimum and maximum distance values outside of which the model is no longer considered reliable
Meteorological Data	These vary greatly from model to model, although most models require some combination of: *Wind Speed* (velocity of the wind, in metres per second), *Wind Direction* (measured in degrees), *Temperature* (ambient temperature at 10m above the ground, measured in degrees Celsius), *Atmospheric Stability* (often measured using Pasquill's stability classification), *Mixing Heights* (the height of the boundary layer, measured in metres)

CAR-INTERNATIONAL (Calculation of Air pollution from Road traffic, International version) model (Eerens *et al.* 1993). Two more complex models were also selected for investigation: the CALINE3 (Rao and Visalli 1985) and CALINE4 (Benson 1992) models, developed on behalf of the US Environmental Protection Agency. The UK ADMS was not selected due to the academic uncertainty surrounding this model and the financial restrictions of this project.

These four models listed above were selected for a number of reasons. One important factor was their availability for this study. Together, they also provide a range of models of varying complexity. Whereas DMRB and CAR International have relatively simple data requirements, making them easy to apply, the CALINE models have more data demands. All the models are also widely used. The DMRB model, for example, is used as the 'official' model for road and bridge design in the UK; the CAR model is extensively used by the twelve municipalities in the Netherlands for road and transport management and environmental impact assessment. The CALINE models have been widely used in the USA as a basis for environmental impact assessment of highways, and have also been used to some extent as a research tool in environmental epidemiology. Whilst all the models have undergone previous testing and validation (e.g. Eerens and Sliggers 1993, Heida *et al.* 1989, Rao and Visalli 1985, Benson 1992), however, a number of limitations are evident in these assessments. In the case of CALINE, for example, some of the data used for testing was collected in carefully controlled conditions, several years before the creation of the models themselves. The vehicles were travelling at a constant speed and thus real driving conditions were not experienced. CAR International has also not yet been rigorously validated outside the Netherlands. Differences in street layout and urban morphology (both important components of the CAR model) may be expected to be significant in this context. None of the models also appears to have been extensively tested and validated at the urban scale, nor used for city-wide pollution mapping.

The four models selected for study vary in terms of their purpose, aims and requirements. The following section examines each of the models in turn and reviews the rationale behind the models and possible limitations which may affect their application.

6.3.1 THE DMRB MODEL

The DMRB (Design Manual for Roads and Bridges) was developed by the Department of Transport in 1993 to assess the impact of road construction and modifications on the environment. It also ensured UK government compliance with the EU Directive on Environmental Assessment (EC/85/337). The DMRB was developed to examine all possible impacts of road traffic schemes on the environment including water quality, geology, ecology and cultural heritage etc. Volume 11 of the DMRB, however, deals specifically with calculating the impacts of air pollution (DoT 1994).

The DMRB was developed as a graphical screening model which used carbon monoxide concentrations as a marker for other pollutants. DMRB evolved from the Department of Transport's earlier 'Manual of Environmental Appraisal' (MEA) which was reviewed in 1991 by the Standing Advisory Committee on Trunk Road Assessment (SACTRA). SACTRA recommended radical changes to MEA to allay increasing concerns over regional and global environmental issues and to ensure compliance with the EU Directive (EC/85/337) (SACTRA 1991).

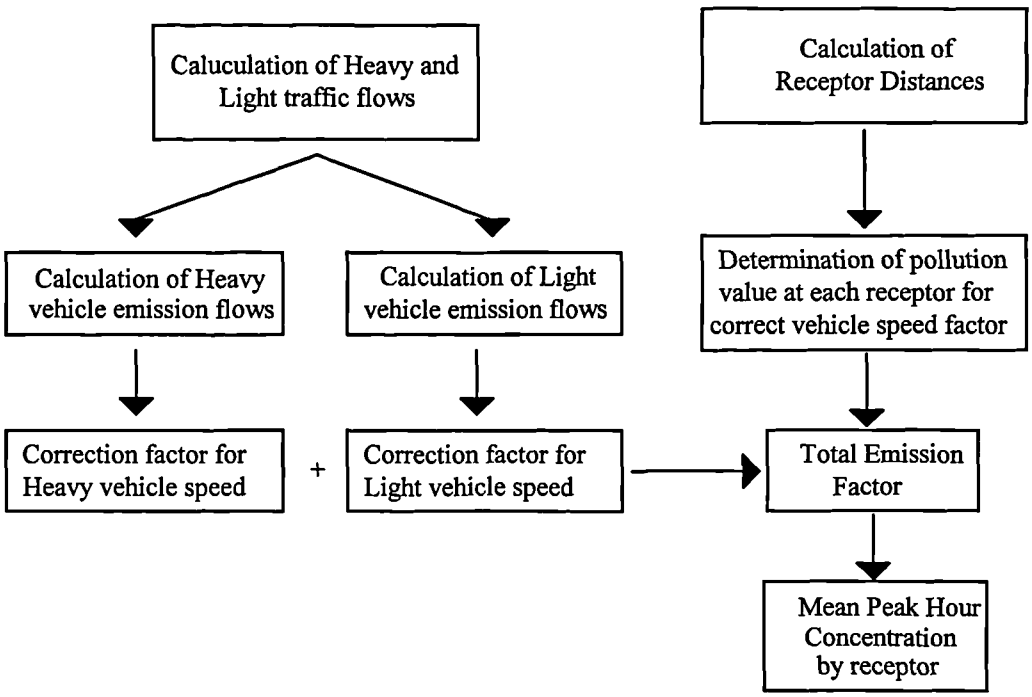
The aim of the DMRB was to provide a screening model for a range of pollutants including carbon monoxide, nitrogen dioxide, particulates and volatile organic compounds, which could be used by non-scientific personnel who would have little or no training in dispersion modelling. In attempting to keep the DMRB model as simple and easy to operate as possible, however, a number of limitations were accepted as part of the model design. Most seriously the model takes no account of monitored meteorological conditions, especially wind direction, and thus does not allow for the transportation of pollution into / out of an area by wind. Consequently these factors may cause the model to overestimate pollution concentrations close to the source under windy

conditions. Assumptions were also made concerning the numerical traffic-related values given in the models and the inter-relationships between those variables. For example, vehicle emission factors have been greatly simplified due to the assumption that vehicle composition conforms to national statistics produced by the Department of Transport and that those vehicles operate at the optimum emission standards (DoT 1994). No account has been taken of the effects of local variation in traffic composition and cold engine starts etc, thus further increasing the possibility of model inaccuracies. In addition, much of the DMRB model structure was based on *forecasts* of future trends (e.g. vehicle growth), thus increasing the uncertainties inherent in the model. Similarly, the model relies on modelled dispersion curves (of pollution concentrations with distance from roads) supplied by the Transport Road Research Laboratory (TRRL). The dispersion curves were originally only supplied and validated for CO, but were then extrapolated to provide similar information for other pollutants such as nitrogen dioxide, benzene and particulates. In addition, only limited account is taken of aerodynamic roughness: i.e. the model allows the area surrounding the road to be described as either *rural* (predominantly open land, with few or no buildings), *suburban* (low density residential or light industrial/commercial areas with a high proportion (>20%) of open space, gardens etc), or *urban* (high density, town centre or built up area, characterised by multi-storey blocks and/or road canyons). No account of the effects of topography was considered. Despite these limitations, however, the model provides a potentially useful means of estimating long-term pollution levels, either for a specific sites or for a network of sites across and area.

As an integral part of the procedure for air quality impact assessment of new or existing roads, the model was designed to be used manually, through a series of look-up tables or graphs. Vehicle traffic flow (in vehicles per hour) by composition (light vehicles, less than 3.5 tonnes; and heavy vehicles, more than 3.5 tonnes) must be defined. Emission rates for both heavy and light vehicle

flows are then calculated from the look-up tables or graphs and a correction factor for vehicle speed applied. A *'total emission factor'* is therefore produced which is a combination of vehicle speed, type and volume. Next, the distance from each receptor, at which pollution concentrations will be modelled, to the road is calculated. From look-up tables (dispersion curves of vehicle speed against distance from road), the pollution values for each receptor is calculated and combined with the *'total emission factor'* to produce an average peak hourly concentration for each receptor. This process is explained graphically in Figure 6.3.

Figure 6.3 Diagrammatic explanation of the DMRB model.



Owing to the numerous calculations involved in modelling pollution concentrations for the receptors, the procedures and lookup tables of the DMRB were programmed, for this study, into the DBASE database package. Additionally, weighting factors for wind speed and wind direction were programmed into the DBASE - DMRB model by defining the proportion of time

in which the wind blows in each of the eight compass bearings. Data requirements for the model are contained in Table 6.2.

6.2.2 THE CAR-INTERNATIONAL

The development of CAR (Calculation of Air pollution from Road traffic) was commissioned by the Dutch Environmental Ministry on behalf of the Dutch Government in the mid 1980s. At this time, the Dutch government believed that local air quality limits for carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), benzene and suspended particulates were being exceeded in approximately 1000-2500 urban streets in medium-sized and large cities throughout the Netherlands (Eerens *et al* 1993, RIVM 1988). The major source of these pollutants in cities was thought to be from road vehicle traffic. Therefore, it was necessary to identify which streets were contravening the 1995 Air Pollution Act (EU/COM(95)312) as a basis for assessing future planning, economic and social decisions. In order to identify those streets exceeding the limit values, a line dispersion model was used. Once identified, measures could then be taken to reduce the air pollution levels in that area.

Most existing line dispersion models assumed homogeneity in terrain around the road and minimal building influence, e.g. HIWAY (Zimmerman and Thompson 1974), CALINE (Beaton 1972, Benson 1979), CALINE2 (Ward *et al* 1975), and the GM model (Chock 1978). Where the effect of the terrain (e.g. buildings, trees) surrounding the road was considered, it was usually in terms of aerodynamic surface roughness and not with regards to the effect of street

Table 6.2 Data requirements for the DMRB model

	Name	Definition	Range	Study Area Data
1	Traffic flow	Represents the hourly traffic flow in both directions. Light and heavy vehicle flows should be reported separately.	Range is between 100 and 150000 vehicles per day.	Traffic flow data was obtained from HETS using automatic and manual traffic counts.
2	Traffic speed	Represents the average speed driving conditions of a road.	Range is from 10km/hr to 100 km/hr. Speeds in excess of this are treated as 100km/hr.	Obtained from field observation of the type of road, and from data provided by HETS.
3	Emission factor	Based on the year of analysis, this figure is automatically set by the model and cannot be altered by the operator.	Range is from 1980 – 2000 and considered changes in fuel technology and engine design.	Obtained from information supplied by the Department of Transport and Kirklees Council.
4	Receptor distance	Distance in metres between the road axis and the specified receptor point.	Between 10 and 200 metres from the road axis. Receptors <10 or >200 metres from a roadway are not considered accurate.	Obtained from site plans supplied by HETS and measurements taken in the field.
5	Receptor classification	For NO_2 only each receptor is classified based on its surrounding landuse.	Three classes: *urban* (high density, town centre or built up areas, characterised by multi-storey blocks and/or road canyons), *suburban* (low density residential/light industrial/commercial areas, with >20% open space, gardens etc), *rural* (predominantly open land with few or no buildings)	Obtained from site visits.
6	Wind direction	Although not built into the original DMRB model, mean wind direction may be included as an optional additional variable in the DBASE model.	Calculated as a proportion of time the wind blows from each of the 8 compass bearings	Obtained from Meteorological station at the University of Huddersfield and Leeds Weather station.

canyons, e.g. PAL (Turner and Peterson, 1975), CALINE3 (Benson 1992). In some cases, specific street canyon sub-models have been employed, (e.g. Johnson *et al* 1973; Yamartimo and Wiegand 1986), but these did not allow for road junctions, a major feature in urban cities. Furthermore, most of the existing models concentrated on calculating concentrations for CO only; no measure of NO_2 and particulates could be estimated. Thus the CAR model was developed to improve on existing models, to fit the specific requirements of the Dutch government.

The aim of CAR was to provide a screening model which could be used by non-scientific personnel who had little experience of dispersion modelling, in order to identify streets contravening the air pollution limits. To this end the model had to fulfil a range of quality criteria set down by the Dutch government (listed in Dekker *et al.* 1991) - i.e. to consider the effect of street canyons, be easy to use and to employ input data which was easily collected.

CAR was based on a previous TNO traffic model which was found to be too detailed and complex. Consequently, the most significant factors in the TNO model were simplified for input into the CAR model. This permitted an acceptable level of simplicity in the calculations without sacrificing accuracy. CAR INTERNATIONAL, the version used here, represented a later development of the original CAR model. CAR-INTERNATIONAL includes modifications of certain parameters, such as emission factors and meteorological conditions, in order to allow the model to be used in other countries.

CAR INTERNATIONAL thus provides a simple to use screening model based on line dispersion principles. Model calculations within CAR allow it to consider intersections, the composition of traffic and the style of driving,

local street emissions, city specific contributions, recirculation contributions and the non-linearity of NO_x – NO_2 relationships. A further advantage of CAR over the more complex line dispersion models is the limited amount of input data required, most of which is easily obtained from site visits and traffic census or local councils. Due to the design specifications, however, CAR-INTERNATIONAL does not have the flexibility of the more complex line dispersion models. Meteorological parameters are defined only by an annual average wind speed. No account is made of the effect of wind direction, wind velocity, temperature, stability class and mixing heights during the measurement period, all of which affect the NO_x – NO_2 relationship and the dispersion characteristics of the pollutants. Data requirements of CAR are shown in Table 6.3.

6.2.3 CALINE3

In 1972 Caltrans published a line dispersion model in response to the American National Environmental Policy Act of 1969. The model, CALINE (California Line Source Dispersion Model), was an attempt to estimate pollution dispersion from roads for inert gases (Beaton 1972). The model consisted of lookup-tables and nomographs and was the forerunner of the present CALINE models. Three years later a FORTRAN version, CALINE2, was developed which was modified to calculate concentrations for depressed roadways and parallel wind conditions. Model verification indicated that CALINE2 gave a two- to five-fold overestimation in concentrations for stable parallel wind conditions (Ward *et al.* 1975). Noll (1977), however, concluded that CALINE2 over-predicted concentrations for parallel wind conditions by 66% for all stability classes. In addition, road length, surface roughness and the type of road could not be specified in CALINE2, thus limiting the number

Table 6.3 Data requirements for the CAR-INTERNATIONAL model.

	Name	Definition	Range	Study Area Data
1	Traffic flow	Represents the daily traffic flow in both directions.	Range is between 100 and 150000 vehicles per day.	Traffic flow data was obtained from HETS using automatic traffic counts.
2	Fraction of heavy-duty vehicles and buses	Amount of heavy duty traffic and buses as a fraction of the total traffic volume.	Range is from 0.0 to 1.0.	Obtained from information on the traffic composition in Kirklees. Supplied by Kirklees Council
3	Speed type	Represents the average speed driving conditions of a road.	Range is from Va Motorway traffic with an average speed of 100 km/hr to Vd Stagnating traffic (e.g. at intersections) with an average speed of 13km/hr.	Obtained from field observation of the type of road, and from data provided by HETS.
4	Road type	Provides a measure of surface roughness.	Range is from V1 (roads through open fields with very few trees and buildings) to V4, (roads with buildings on one side which are more or less attached (i.e. continuous) at a distance of less than 3 times the height of the buildings).	Obtained from site characteristics measured at each site, which were then classified according to CAR's definitions.
5	Tree factor	Represents the influence of trees on the dispersion of air pollution.	Range is from 1.00, very few/no trees on either side of the street to 1.50 trees on both sides of the street with the tops touching.	Obtained from site characteristics measured at each site, which were then classified according to CAR's definitions.
6	Receptor distance	Distance in metres between the road axis and the nearest point of public exposure.	Between 5 and 30 metres from the road axis.	Obtained from site plans supplied by HETS and measurements taken in the field.
7	City diameter	Used to calculate background concentrations.		Obtained from 1:10000 scale O/S maps.
8	Emission factors	CAR separates emission factors for cars and for HGVs / buses by speed.	Measured in μg/m/s/veh	Obtained from information supplied by the Department of Transport and Kirklees Council.
9	Wind Speed	The only meteorological condition used by CAR. Calculated as the yearly average wind speed within the city and in the regional background areas.	Measured in m/sec at an altitude of 10m above ground level.	Obtained from meteorological data measured at the University and at Leeds weather station.
10	Ambient background concentrations	Allows true pollutant concentrations to be predicted. Calculated as the city and regional background concentrations	Measured in $\mu g/m^3$	Obtained from monitored data of the area.

of situations which could be modelled. A third version of CALINE was developed by Benson in 1979. CALINE3 retained the basic Gaussian dispersion equation, common to all three models, but increased its flexibility with the introduction of new horizontal and vertical dispersion curves to allow for the effects of averaging times, vehicle-induced turbulence and surface roughness. Unlike its predecessors, CALINE3 viewed vehicle emissions in terms of an equivalent finite line source and not, as previously, a series of point sources. CALINE3 also allowed multiple roads to be considered simultaneously. Validation of CALINE 3 was conducted by Rao and Visalli (1985) who found it to be similar to other published line dispersion models. In 1980 the Environmental Protection Agency (EPA) in America authorised CALINE3 for 'use in estimating concentrations of non-reactive pollutants near highways' (Benson 1992).

The major advantage of using CALINE3 over its predecessor was its ability to view emissions of the pollutant as a line source and not a modified point source. Consequently, the final prediction of pollution increased in accuracy. The model also allowed for greater flexibility and thus increased the number of situations for which concentrations could be predicted. Finally, although CALINE3 was designed for modelling carbon monoxide (CO), the introduction of a molecular weight variable within the program has enabled the model to be applied to other inert gases and particulates (Benson 1979).

A number of limitations, however, must be considered when using the model. CALINE3 cannot model complex topography and therefore assumptions are made on the homogeneity of the terrain surrounding the road and the meteorological conditions within the study area. Street canyons and bluffs cannot be modelled with any degree of accuracy. The occurrence of very low wind speeds, coupled with parallel wind conditions, still causes the model to over-predict pollutant concentrations (Dabbert and Hoydysh 1991; Hall 1996; Matzoros and Vilet 1992). A further disadvantage of CALINE3 over the simpler line dispersion models such as DMRB and CAR INTERNATIONAL

is that it requires more complicated and voluminous input data. A basic knowledge of line dispersion modelling is assumed. Data requirements for CALINE3 are shown in Table 6.4.

6.2.4 CALINE4

CALINE4, the latest in the CALINE family, was developed in 1984 by Benson (Benson 1992). CALINE4 refined and extended the capabilities of its sister model, CALINE3, in an attempt to increase its flexibility and to reduce the problem of over-prediction in stable, parallel wind conditions. The range of pollutants which could be estimated was extended and allowance was made for chemical reactions of the exhaust gases, using a 'reactive chemical sub-model'. The effects of street canyons, bluffs and intersections were also incorporated by inclusion of an altered vertical dispersion curve. Deceleration, idling, acceleration and cruise speed of a vehicle approaching an intersection were considered in the model as they would affect the concentrations and behaviour of the pollutants. A drawback to the use of intersections, however, is the need for separate emission factors for each of the different stages of a vehicle's approach to an intersection, thus creating the need for a large amount of input data. Lateral plume spread and vehicle-induced thermal turbulence were added to the model using modified horizontal dispersion curves and vehicle-induced heat flux algorithms. In this way, CALINE4 dealt with some of the limitations of CALINE3. The greatest improvement of CALINE4 over CALINE3, however, is its increased flexibility to handle a greater number of situations.

Validation of early versions of this model was carried out by Rao and Visalli (1985) and Benson (1984) who both found that the modifications to CALINE4 produced only slight improvements in the accuracy of the predictions compared to CALINE3. Over-predictions in concentrations still occurred for roads with parallel winds of a low wind speed. Furthermore

Table 6.4 Data requirements for the CALINE3 model.

	Name	Definition	Range	Study Area Data
1	Traffic Flow	Represents the traffic volume by vehicle by hour	Between 0 and 9999999 veh/hr.	Traffic flow data was obtained from HETS using automatic traffic counts for the relevant time period .
2	Emission Factor	Assumed uniformity throughout the road and thus CALINE 3 requires one emission factor.	The emission factor is measured in grammes per minute	Obtained from information supplied by the Department of Transport and Kirklees council .
3	Settling Velocity	Rate at which a particle falls with respect to its immediate surrounding	Measured in cm/sec	Set to 0
4	Deposition Velocity	Rate at which a pollutant can be absorbed / assimilated by a surface	Measured in cm/sec	Set to 0
5	Averaging Time	The period of time over which the model calculates pollution concentrations	Measured in minutes, range is from 3 to 120 mins.	Optimum averaging time of 30 mins was used on the advice of the CALINE manual
6	Surface Roughness	Measure of the aerodynamic roughness of the terrain surrounding the road	Range from 0.001 cm (smooth mud flats) to 370 cm (apartment blocks)	Obtained from site characteristic information measured at each site. t
7	Road Start and End Co-ordinates	Geo-referencing for a straight section of road, having constant width, height, traffic volume and emission factor .	Measured as X, Y co-ordinates	Obtained from 1:10,000 scale O/S maps.
8	Mixing Zone Width	Width of the travelled way (excluding hard shoulder) plus 3m on either side .	Measured in metres	Obtained from information supplied by HETS.
9	Source Height	Vertical distance above or below local ground level or datum .	Range of -10 to 10m	Obtained from site characteristic information measured at each site.
10	Receptor Co-ordinates and Heights	Geo-referencing for measurement points surrounding the road	Between 3m and 10km from the road axis	Obtained from 1:10,000 scale O/S maps.
11	Meteorological Data			
11a	- wind speed	Velocity at which the wind blows	Measured in m/sec	Obtained from Leeds weather station and the University of Huddersfield Meteorological station .
11b	- wind direction	Direction *towards* which the wind blows.	Measured in degrees	as above
11c	- stability class	Upwind/ambient stability class.	Measured on the Pasquill stability class. Range A-F	as above
11d	- mixing height	The height of the top of the surface mixing layer.	Measured in metres.	as above

CALINE4, like its predecessor, still assumed homogeneity of the terrain surrounding the road and the meteorological conditions, and therefore the model is likely to give incorrect results in complex terrain situations. A further drawback to the use of this model, however, is still the large amount of input data necessary to run the model, and the assumption that the user has a basic knowledge of line dispersion modelling; without such knowledge there is a significant risk of misapplication of the model, or misinterpretation of the results. Data requirements for CALINE4 are summarised in Table 6.5.

6.4 MODEL VALIDATION

In order to examine the predictive ability of these various models within this study it was necessary to obtain detailed and simultaneous information on NO_2 concentrations and traffic flows at a range of locations. A detailed monitoring programme of both traffic flows and air pollution levels was therefore undertaken.

i. Traffic Flow data.

Traffic flow data was provided by West Yorkshire Highways Engineering (HETS) who undertook a traffic counting programme within and around the study area. All provisional sites were inspected prior to installation of the automatic traffic counting devices. If considered suitable (i.e. required amount of accessible street / garden furniture available; sites unaffected by industrial pollution sources etc) air pollution monitoring was conducted at the same time as the traffic counting began. Information on traffic flows was provided by HETS at the end of the monitoring period for each road in the study.

Table 6.5 Data requirements for the CALINE4 model.

	Name	Definition	Range	Study Area Data
1	Traffic Flow	Represents the traffic volume by vehicle by hour	Between 0 and 9999999 veh/hr.	Traffic flow data was obtained from HETS using automatic traffic counts for the relevant time period
2	Emission Factor	Assumed uniformity throughout the road unless the intersection option is used. Several emission factors based on vehicle speed may then be required	The emission factor is measured in grammes per minute	Obtained from information supplied by the Department of Transport and Kirklees council.
3	Settling Velocity	Rate at which a particle falls with respect to its immediate surrounding	Measured in cm/sec	Set to 0
4	Deposition Velocity	Rate at which a pollutant can be absorbed / assimilated by a surface	Measured in cm/sec	Set to 0
5	Averaging Time	The period of time over which the model calculates pollution concentrations	Measured in minutes, range is from 3 to 120 mins.	Optimum averaging time of 30 mins was used on the advice of the CALINE manual
6	Surface Roughness	Measure of the aerodynamic roughness of the terrain surrounding the road	Range from 0.001 cm (smooth mud flats) to 370 cm (apartment blocks)	Obtained from site characteristic information measured at each site.
7	Road Start and End Co-ordinates	Geo-referencing for a straight section of road, having constant width, height, traffic volume and emission factor	Measured as X Y co-ordinates	Obtained from 1:10,000 scale O/S maps.
8	Mixing Zone Width	Width of the travelled way (excluding hard shoulder) plus 3m on either side	Measured in metres	Obtained from information supplied by HETS.
9	Road Width Left/Right	Distance between road width and built-up structures, allows the model to consider canyon type streets	Measured in metres	Obtained from site characteristic information recorded at each location
10	Source Height	Vertical distance above or below local ground level or datum.	Range of -10 to 10m	Obtained from site characteristic information measured at each location.

Table 6.5 Data requirements for the CALINE4 model (cont).

	Name	Definition	Range	Study Area Data
11	Receptor Co-ordinates and Heights	Geo-referencing for measurement points surrounding the road	Between 3m and 10km from the road axis	Obtained from 1:10,000 scale O/S maps.
12	Meteorological Data			
a	- wind speed	Velocity at which the wind blows	Measured in m/sec	Obtained from Leeds weather station and the University of Huddersfield Meteorological station.
b	- wind direction	Direction *towards* which the wind blows.	Measured in degrees	as above
c	- stability class	Upwind/ambient stability class.	Measured on the Pasquill stability class. Range A-F	as above
d	- mixing height	The height of the top of the surface mixing layer.	Measured in metres.	as above
e	- ambient temperature	Background temperature of the air.	Measured in degrees Celsius	as above
13	Ambient ozone concentration	Background concentrations of ozone	Measured in parts per billion (ppb)	Obtained from Kirklees Scientific Services monitoring station
14	Ambient nitric oxide concentration	Background concentrations of nitric oxide	Measured in parts per billion (ppb)	Obtained from Kirklees Scientific Services monitoring station
15	Ambient nitrogen dioxide concentration	Background concentration of nitrogen dioxide	Measured in parts per billion (ppb)	Obtained from Kirklees Scientific Services monitoring station

ii. Air Pollution Data.

Air pollution monitoring was conducted using passive diffusion samplers to measure NO_2 concentrations at locations where automatic traffic counts were planned to be conducted. Samplers were placed along transects, perpendicular to, and on both sides of, the roads (as described in Section 4.4.1). The location of the samplers was limited, however, by the suitability of street furniture and willingness of householders. As monitoring was undertaken concomitant to the collection of traffic flow data, the siting of the automatic traffic counts dictated the location and time frame of the NO_2 monitoring. Most surveys, however, lasted for a two-week period. Monitored values obtained from the surveys were then correlated against the predicted estimates of NO_2 obtained from each of the models.

This set of data was an important input parameter for all of the dispersion models (see Section 6.2.1) It should be noted, however, that site N402 was rejected from the study as the results appeared to be anomalous compared to the other surveys - i.e. concentrations appeared to increase with distance from road as opposed to decreasing. This may have been due to the influence of other nearby sources (e.g. the nearby motorway, which may have an indirect influence on the sample site).

It should also be noted that all the models used here provide estimates only of the *additional* NO_2 concentration derived from the modelled road sources; they take no account of regional background concentrations, attributable to other sources. They will therefore tend to underestimate the measured concentrations by an amount equivalent to the regional background levels (typically 15-25$\mu g/m^3$). Assuming that the background concentration is constant across the study area, this will not, of course, affect the results of the strength of the relationship between modelled and measured concentrations. It will, however, result in a large intercept value in any regression analysis comparing measured and modelled concentrations.

6.4.1 DMRB

6.4.1.1 PROCESSING

Data for each of the input parameters required by DMRB was input into the model. The model was run twice, both with and without the meteorological data to allow the effects of this parameter to be investigated. Meteorological data was obtained from the University of Huddersfield and from Leeds Weather station.

6.4.1.2 RESULTS

Modelled pollution concentrations were regressed against the monitored NO_2 values obtained from the sampling programme within the SPSS statistical package. Results of the analysis are shown in tabular form in Table 6.6 and graphically in Figures 6.4 and 6.5.

Results of the regression analysis indicate that the DMRB (excluding meteorological factors) model explains 21.2 per cent of the variation in NO_2 levels (significant at the 10 per cent level). As Figure 6.4 shows, the model gives an intercept value of ca. 19$\mu g/m^3$, close to the monitored background concentrations in rural sites. The slope value (0.514), however, when compared to the monitored results suggests that the model's trend is to over-estimate road traffic pollution at higher pollution levels.

The basic DMRB model does not include any allowance for meteorological factors; as noted in Section 6.3.1; consequently, the model was adapted to include wind direction. This, however, failed to improve the model

performance (see Figure 6.5), and the adjusted R^2 value actually fell to 17.4 per cent, significant only at the 5 per cent level.

Table 6.6 DMRB regression analysis results

Parameters	Excluding Meteorology	Including Meteorology
Degrees of Freedom	1/15	1/15
R Value	0.511	0.475
R^2	0.261	0.225
Adjusted R^2	0.212	0.174
Standard Error	5.267	5.463
Slope Value	0.514	0.136
Constant	18.844	20.6489
F value	5.303	4.360
Significance F Value	0.036	0.054

In an attempt to determine whether performance of the DMRB model was dependent on distance from road, residuals from the regression analysis (both with and without meteorological factors) were plotted against distance from road (Figure 6.6 and 6.7). In both cases, no clear distance-effect is evident, suggesting that errors in the results are inherent in the dispersion model and are not simply a result of poor controls for factors such as surface roughness or the effect of fugitive or more distant emission sources.

6.4.2 CAR-INTERNATIONAL.

6.4.2.1 PROCESSING

Data for each of the input parameters required by CAR-INTERNATIONAL were entered into the model. Where necessary, information given in the CAR

Figure 6.4 Relationship Between Observed and Predicted NO2 Concentrations Using DMRB (Excluding Meteorology)

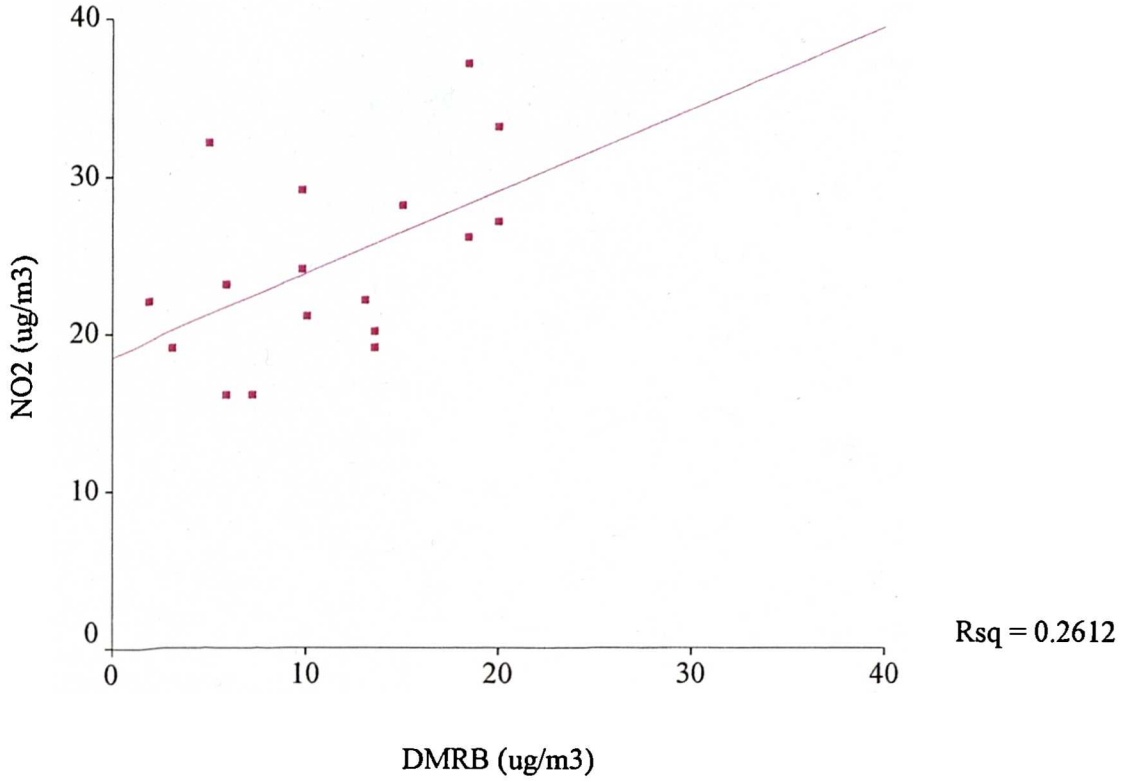


Figure 6.5 Relationship Between Observed and Predicted NO2 Concentrations Using DMRB (Including Meteorology)

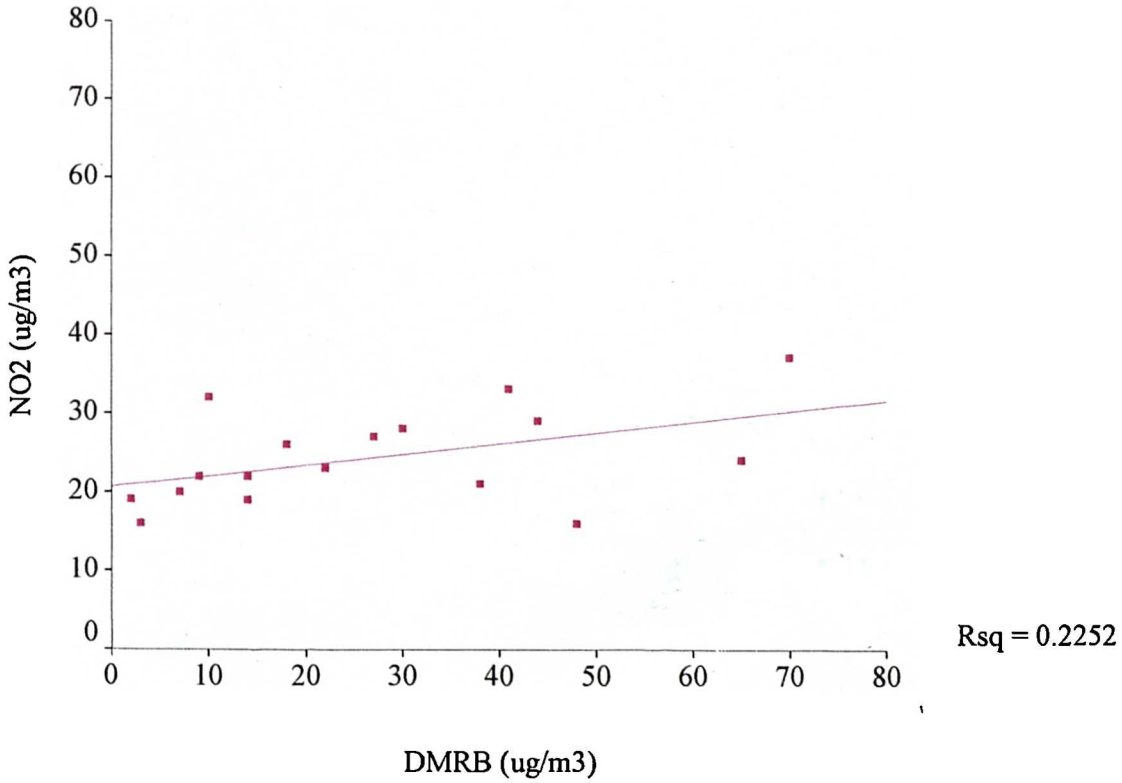


Figure 6.6 Analysis of Residual values for DMRB

(Excluding Meteorology)

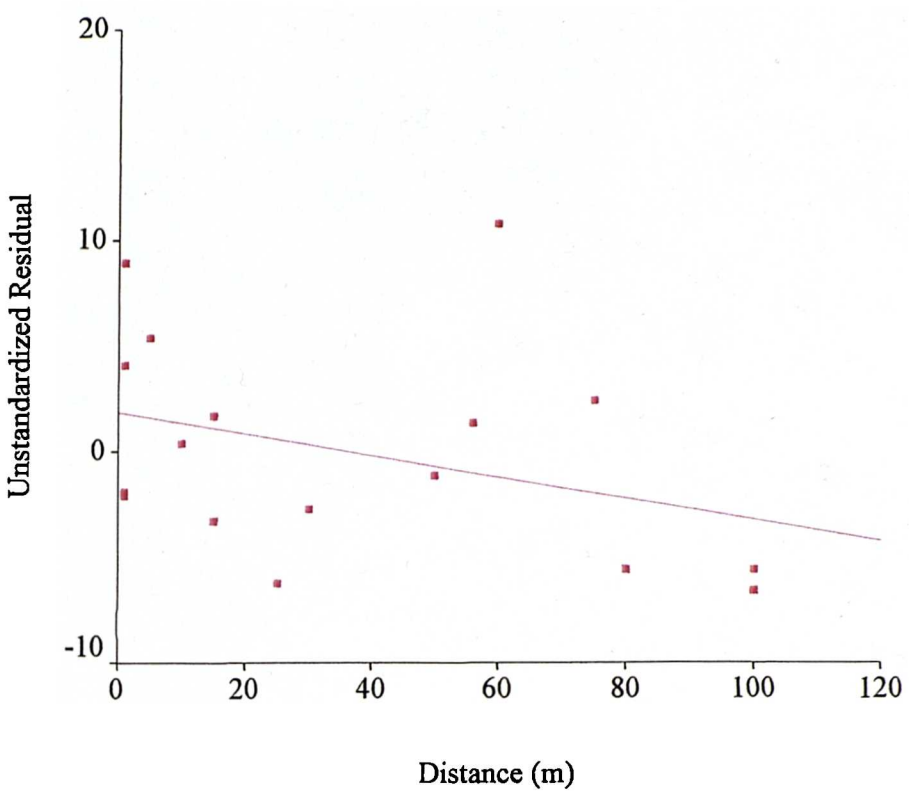
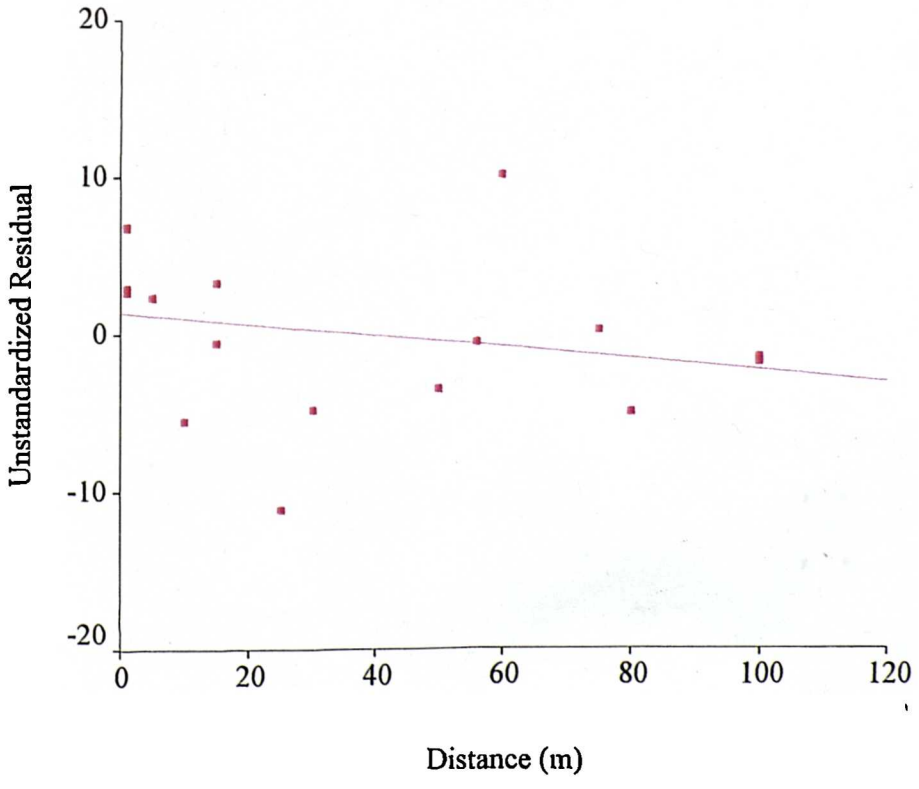


Figure 6.7 Analysis of Residual values for DMRB

(Including Meteorology)



users' manual was used to interpret the field codes used by CAR (see Table 6.3). Certain parameters within CAR-INTERNATIONAL were also altered to enable the model to consider the effects of local conditions (i.e. parameters such as wind speed, emission factors etc which vary from country to country and from city to city). Meteorological data was obtained from the University of Huddersfield Meteorology station and from Leeds Weather Station.

Owing to the receptor limitations of CAR-INTERNATIONAL (i.e. it can only handle 2 receptors per modelling run), once the data had been input into the model, it was run a number of times with increasing receptor distances from the road. This allowed information on the 'shape' of the dispersion curve (i.e. how pollution concentrations alter with increasing distance from a road) to be obtained for each road. The inability of CAR-INTERNATIONAL to predict pollution concentrations at a distance of over 30 metres from the road, combined with the difficulties in siting tubes at regular intervals within this distance, meant that only a small number of monitored sites was available for analysis. The results of the model and the subsequent analysis are noted in the section below.

6.4.2.2 RESULTS

Both the predicted (those obtained from the model) and the observed (those obtained from the monitoring programme) levels of NO_2 were input into the SPSS statistical package and regression analysis performed. Results are shown in Table 6.7 and in Figure 6.8.

Figure 6.8 Relationship Between Observed and Predicted

NO2 Concentrations Using CAR-INTERNATIONAL

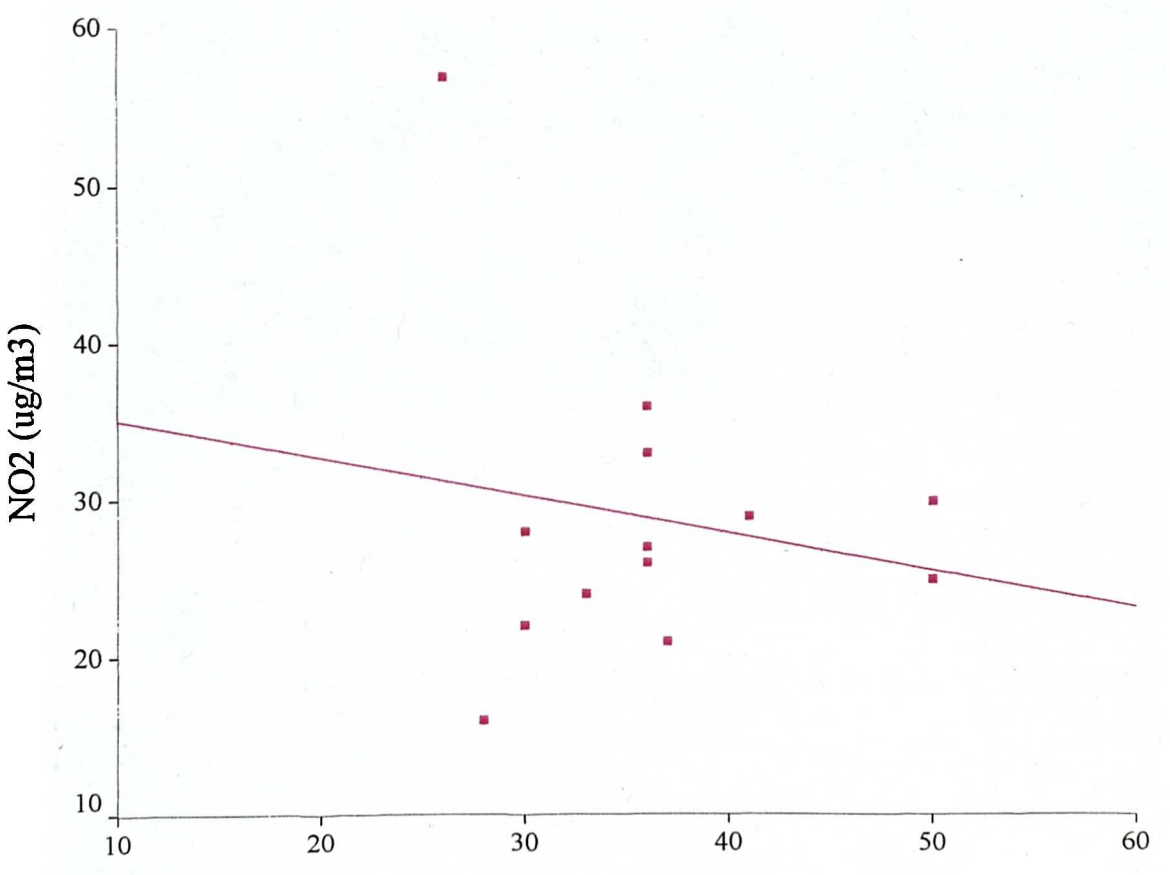


Table 6.7 Regression analysis results for CAR-INTERNATIONAL

Parameters	Values
Degrees of Freedom	1/11
R Value	0.179
R^2	0.032
Adjusted R^2	0.048
Standard Error	9.780
Slope Value	-0.236
Constant	37.380
F value	0.399
Significance F Value	0.540

Results of the analysis indicates that CAR-INTERNATIONAL fails to predict monitored NO_2 concentrations at the survey sites. The adjusted R^2 values are extremely low (Adj R^2 = 4.8 per cent), and not significant at the 5 per cent level. In part, this may be due to the effect of an extreme outlier in the upper left hand corner of Figure 6.8. This site was one of a series of 9 perpendicular to the A62, Leeds Road, at a distance of 30 metres from the road. The reason for this anomaly is not clear, but may relate to the specific character of the site (e.g. wind direction perpendicular to the road). Removal of the site for the analysis considerably improves the R^2 value but the correlation is still not significant at the 5 per cent level. As such, the CAR model is seen to be ineffective in this area.

6.4.3 CALINE3

6.4.3.1. PROCESSING

Data for each of the input parameters required by CALINE3 (Table 6.4) were entered into the model using the information given in the CALINE3 user's manual (Benson 1979). One of the requirements of the meteorology parameter was stability class. This was not available from Huddersfield

University campus weather data. A programme was written, therefore, to calculate stability classes, based on the Pasquill stability class (see appendix 6) (Clark 1979). The meteorological conditions were measured at 15 minute intervals at the university. CALINE3, however, would only allow a maximum of 400 meteorological conditions to be used. Therefore the data was averaged to 1 hour periods, providing 288 meteorological conditions for the two week period of sampling. CALINE3 was then run for each road in turn. The model predictions of pollution were written to an output file which contained estimated concentrations at the receptor sites for every set of meteorological conditions entered. The output files were converted to a database format (dBASE) and miscellaneous information stripped from the files to allow easier data manipulation. The pollutant concentrations at each receptor point were averaged to produce the estimated pollution concentration at each receptor point for every road. Unlike CAR-INTERNATIONAL, CALINE3 allowed the receptors to be spatially referenced and therefore receptor locations were specified on both sides of the road, thus enabling the effect of wind direction to be considered.

6.4.3.2 RESULTS.

As with data from the previous models, the results from CALINE3 were input into the SPSS statistical package. Regression analysis was conducted on the data and the results shown in Table 6.8 and graphically in Figure 6.9 to 6.10.

Table 6.8 Regression analysis results for CALINE3.

Parameters	Values
Degrees of Freedom	1/15
R Value	0.663
R^2	0.439
Adjusted R^2	0.402
Standard Error	4.424
Slope Value	0.609
Constant	7.188
F value	11.759
Significance F Value	0.004

Figure 6.9 Relationship Between Observed and Predicted NO2 Concentrations Using CALINE3

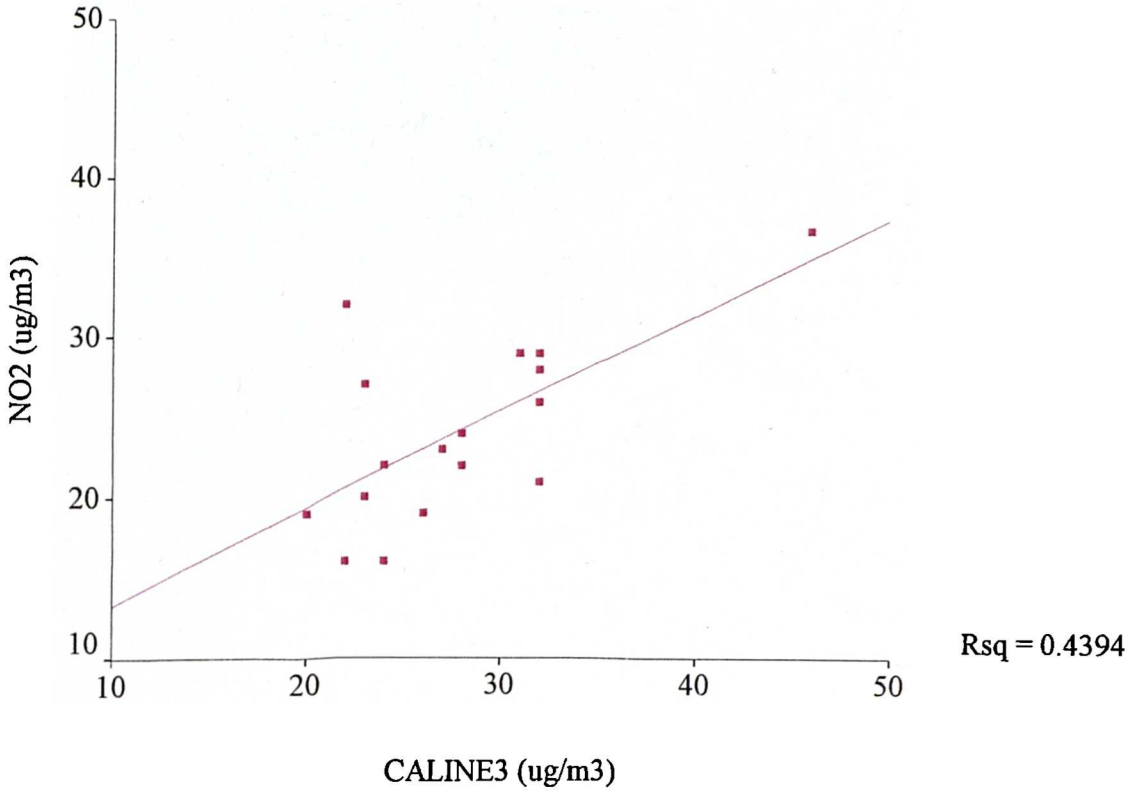
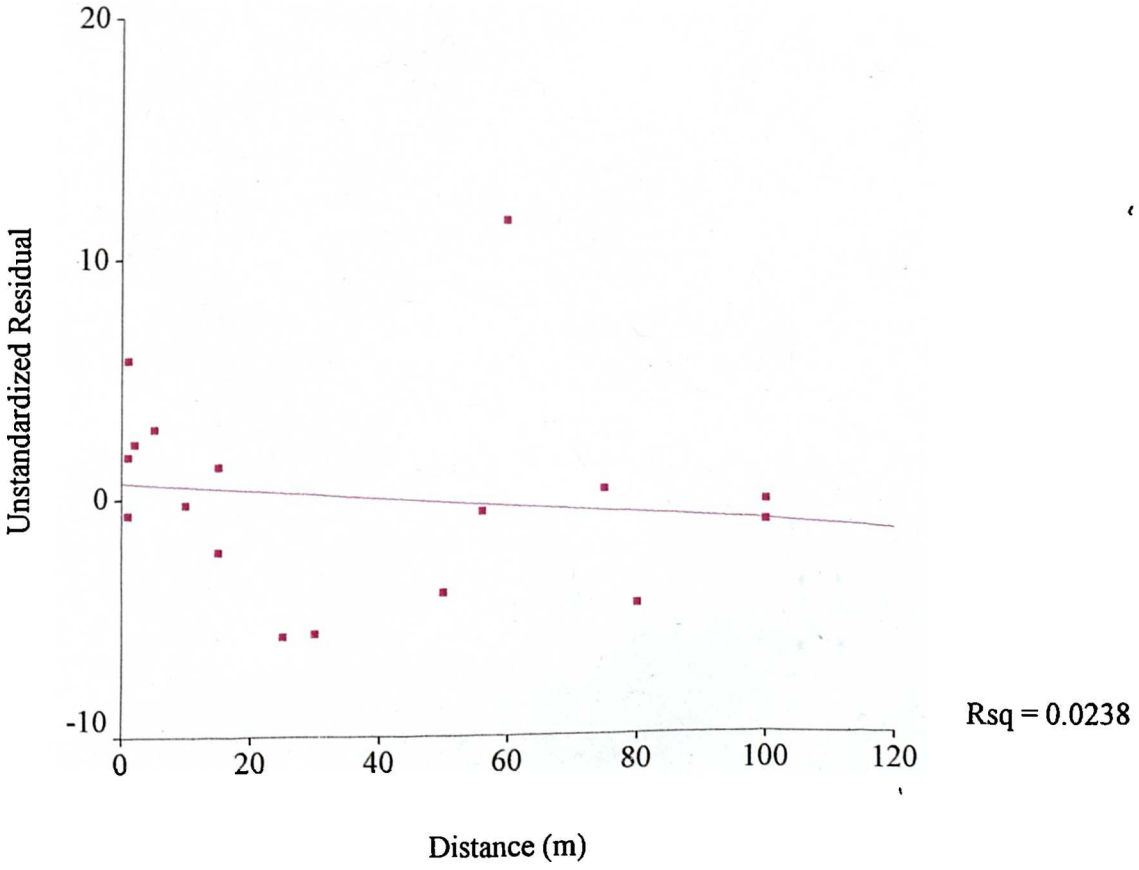


Figure 6.10 Analysis of Residual values for CALINE3



Results indicate that, in comparison to both DMRB and CAR-INTERNATIONAL, the CALINE3 model works well. The intercept value of 7.2μg/m^3 is rather low for background concentrations in the study area - and the slope of the regression line is 0.609, so that the underlying tendency is to over-estimate actual concentrations at higher levels. The fit of the modelled data to the monitored data is relatively good, however, with an adjusted R^2 value of 40 per cent and a standard error of only 4.42μg/m^3, significant at the 0.4 per cent level.

Figure 6.10 shows variations in the residuals for the model with distance from the road. No clear pattern is visible though there is perhaps a tendency for the residuals to become more negative over the first 25-30 metres, beyond which they remain broadly constant at about 3-5μg/m^3.

6.4.4 CALINE4

6.4.4.1. PROCESSING

Data for each of the input parameters required by CALINE4 (Table 6.5) were entered into the model. Meteorological data was obtained from the University of Huddersfield and stability class computed based on the Pasquill stability class as explained in Section 6.4.3.1. CALINE4 allows for the chemical conversion of pollutants in the atmosphere and therefore it was necessary to obtain data on average ozone, nitric oxide and ambient nitrogen dioxide concentrations. These data were obtained from Kirklees Scientific Services and input into the model. The model was run for each road in the monitoring programme and the results of the monitored and modelled concentrations at each site input into the SPSS statistical package.

6.4.4.2 RESULTS

Regression analysis was conducted on the modelled and monitored data and the results shown in Table 6.9 and graphically in Figure 6.11 and 6.12.

Results of the analysis indicate that the CALINE4 model is a small improvement on its sister model (CALINE3) in predicting NO_2 concentrations of pollution, with an adjusted R^2 value of 0.522, significant at the 0.06 per cent level and a standard error of 3.95μg/m^3. The constant of 6.7μg/m^3 is again rather low compared to the monitored background levels in the area. The slope value, however, of 0.735 is closer to unity than the other methods. In addition, there is a marked reduction in the scatter around the regression line (Figure 6.11) which may reflect the increased sophistication of the model. No relationship exists, however, between the distribution of the residuals and the distance from roads (see Figure 6.12), thus suggesting that the model is equally effective at coping with the directional dispersion of road transport emissions for up to 120 metres distance from the road.

Table 6.9 Regression analysis results for CALINE4.

Parameters	Values
Degrees of Freedom	1/15
R Value	0.743
R^2	0.552
Adjusted R^2	0.522
Standard Error	3.954
Slope Value	0.735
Constant	6.695
F value	18.503
Significance F Value	0.0006

Figure 6.11 Relationship Between Observed and Predicted NO2 Concentrations Using CALINE4

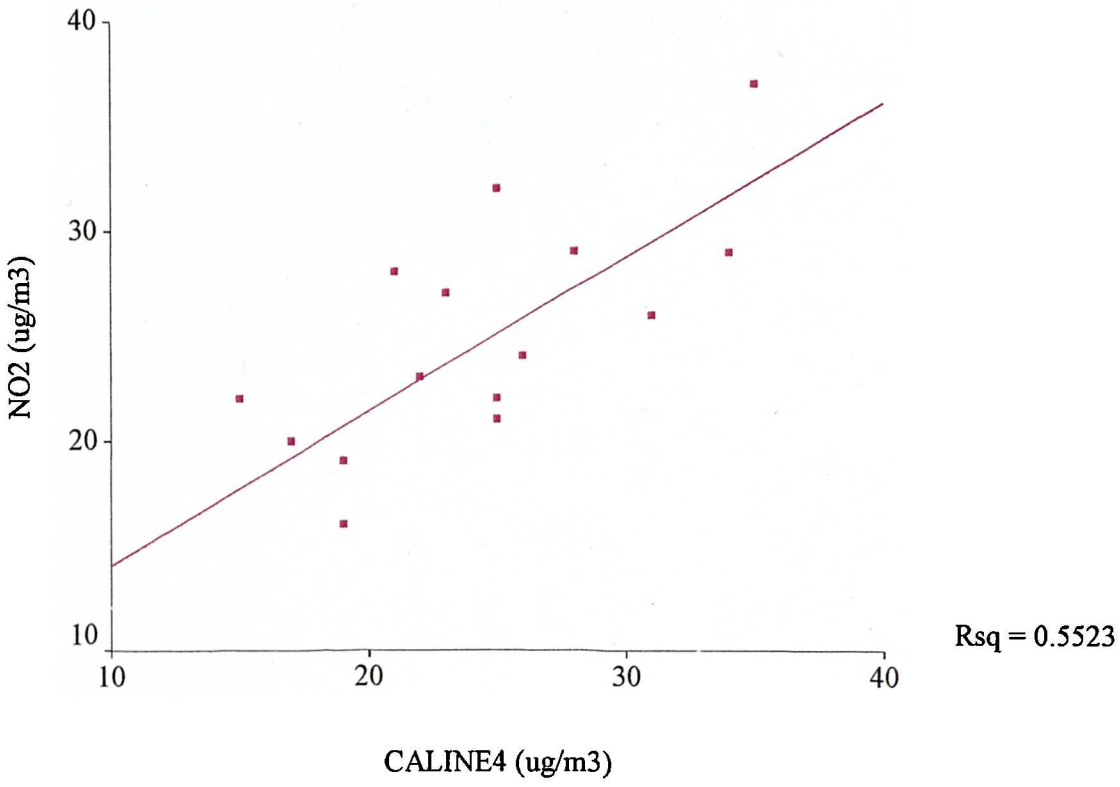
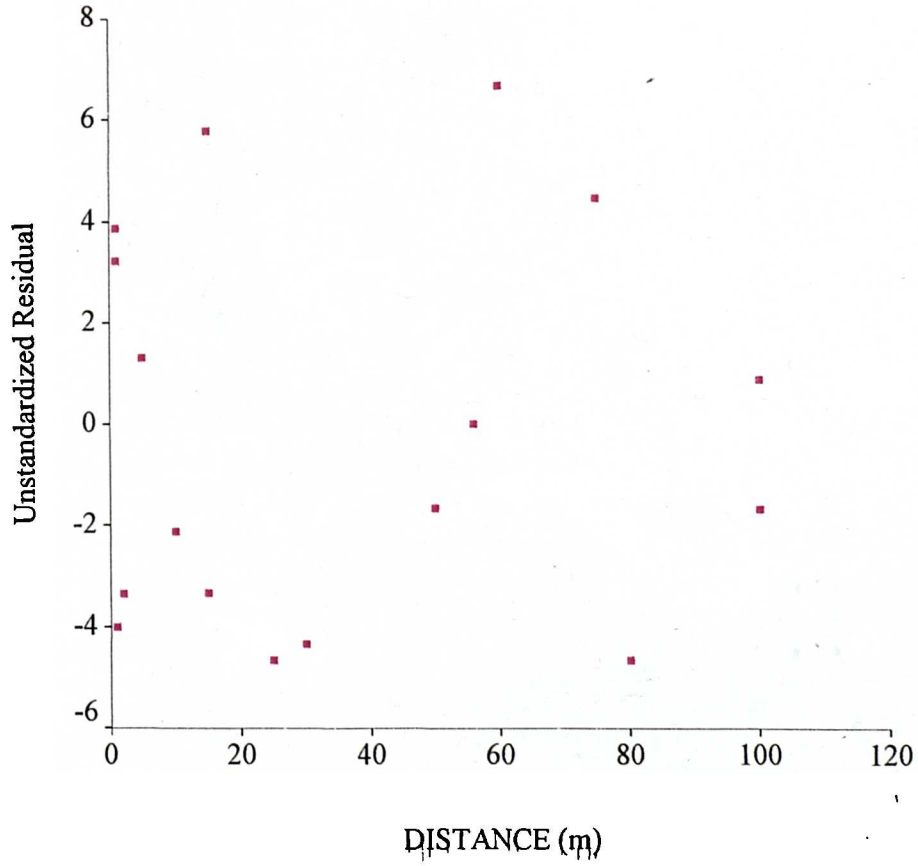


Figure 6.12 Analysis of Residual values for CALINE4



6.5 MODEL APPLICATION

The above section (Section 6.4) indicated a clear trend in the results of testing the various dispersion models, in that the more sophisticated the model, the greater the accuracy of its predictions of NO_2 concentrations. It should be remembered, however, that this analysis related to a small number of specific point locations. The ability of line dispersion models to predict accurately air pollution concentrations over a larger area, for example, the entire study area, could not therefore be evaluated from this data. In order to investigate the mapping capabilities of the dispersion model which had proved most accurate in the preceding tests (CALINE4), pollution concentrations were modelled over the entire study area. For various reasons this was likely to be even more difficult: mapping requires the ability to estimate concentrations across the entire study area (not just the areas close to the roads), and the large number of road sources means that model performance is likely to be limited by data availability.

It was intended that the modelled concentrations could then be compared to monitored concentrations at the 80 core data monitoring sites within the routine NO_2 surveys (S_2, S_3 and S_4) (see Section 4.1) and for the modelled mean of the surveys.

6.5.1 PROCESSING

Location of all motorways, trunk roads, A and B roads was obtained from OS maps. Data on traffic flow was obtained from a combination of automatic and manual traffic counts provided by Kirklees MC. Where traffic flow data was not available, data was extrapolated from similar sites according to roads types (i.e. motorways, trunk roads, A roads, B roads). For example, information on traffic flows for some rural B roads were particularly difficult

to obtain and therefore traffic flows were assigned to roads of a similar type (i.e. rural B roads). Minor roads were not modelled due to the difficulties in obtaining traffic flow information and the shear volume of data required. Meteorological data was obtained from Huddersfield University weather station for the time periods when the surveys took place. Again, ambient pollution data (i.e. ozone etc) was acquired from Kirklees Scientific Services. The model was run using time-specific data for each of the 3 survey periods and for the annual mean values to provide estimates for each of the 80 core sites.

6.5.2 Results

Results from the various CALINE4 model *'runs'* were input into the SPSS statistical package along with the relevant NO_2 data. Linear regression analysis was conducted on the data and the results shown in Table 6.10 and Figures 6.13 to 6.16.

Results of the analysis show that the CALINE4 model is able to explain only a small proportion of the variation in NO_2 concentrations in the study area. For Surveys S_2 and S_3, the adjusted R^2 values were only 4.8 and 5.2 per cent respectively (significant at the 5 per cent level). For survey S_4, the model explained only 0.2 per cent of the variation in pollution levels and this relationship was not significant at the 5 per cent level. The predictive ability of the model improved somewhat when results of the annual mean concentrations were considered (adjusted R^2 = 11.7 per cent significant at the 5 per cent level). Nevertheless, as Figure 6.16 indicates the fit of the modelled results to the measured data is still poor.

Figure 6.13 Relationship Between Observed and Predicted NO2 Concentrations Using CALINE4 For The Core Data Sites

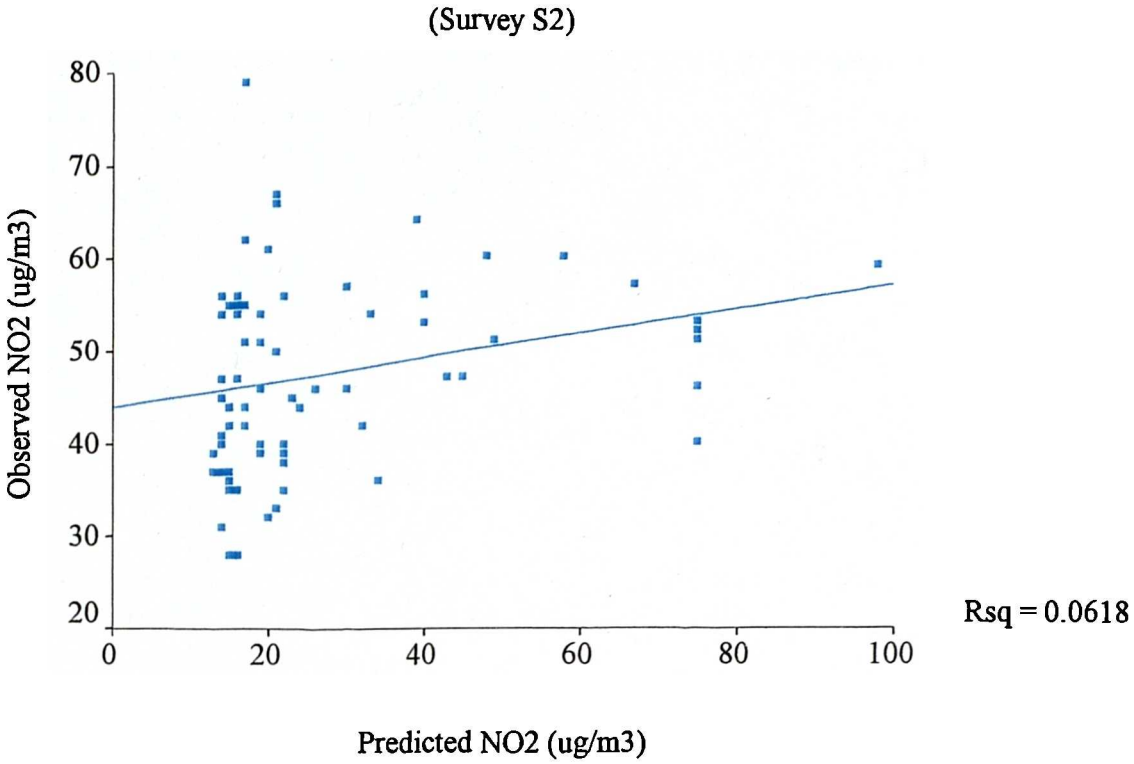


Figure 6.14 Relationship Between Observed and Predicted NO2 Concentrations Using CALINE4 For The Core Data Sites

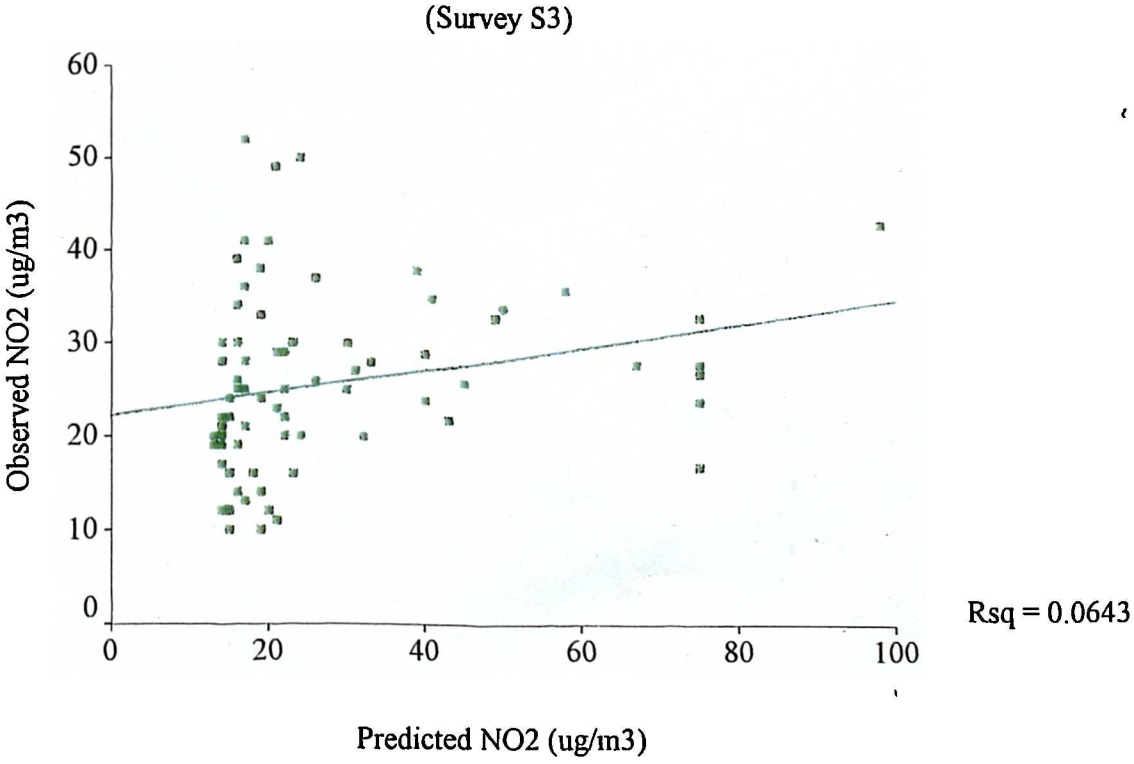


Figure 6.15 Relationship Between Observed and Predicted NO2 Concentrations Using CALINE4 For The Core Data Sites

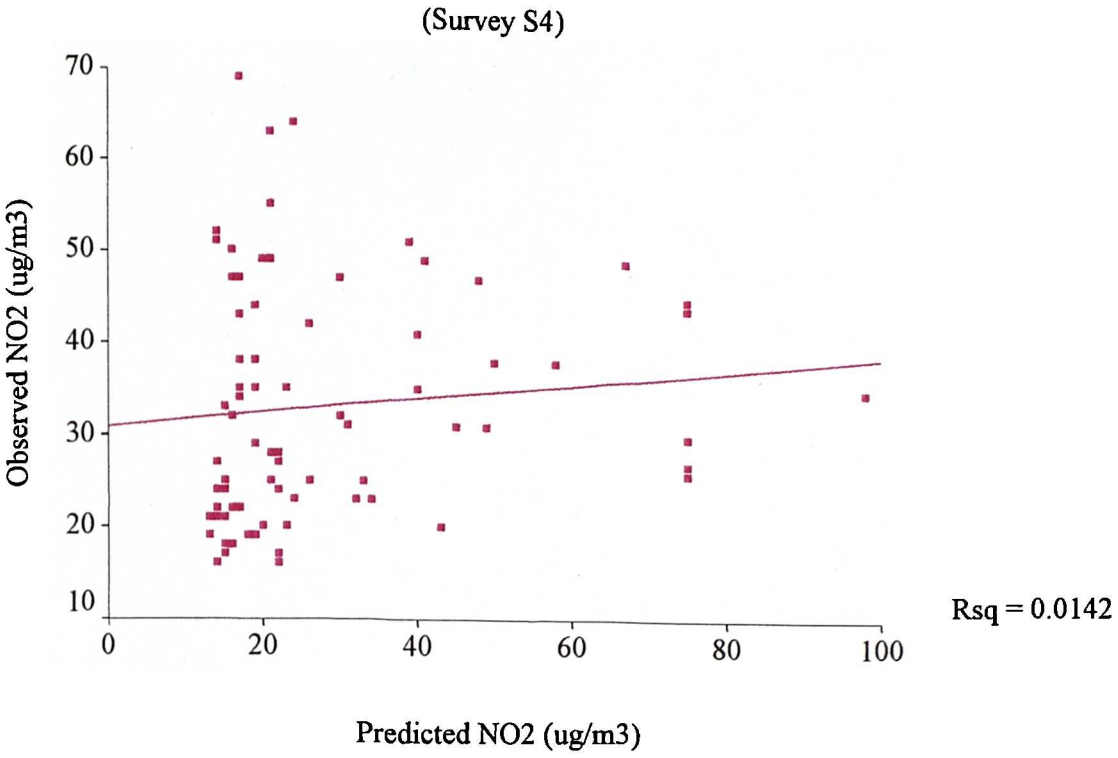


Figure 6.16 Relationship Between Observed and Predicted NO2 Concentrations Using CALINE4 For The Core Data Sites

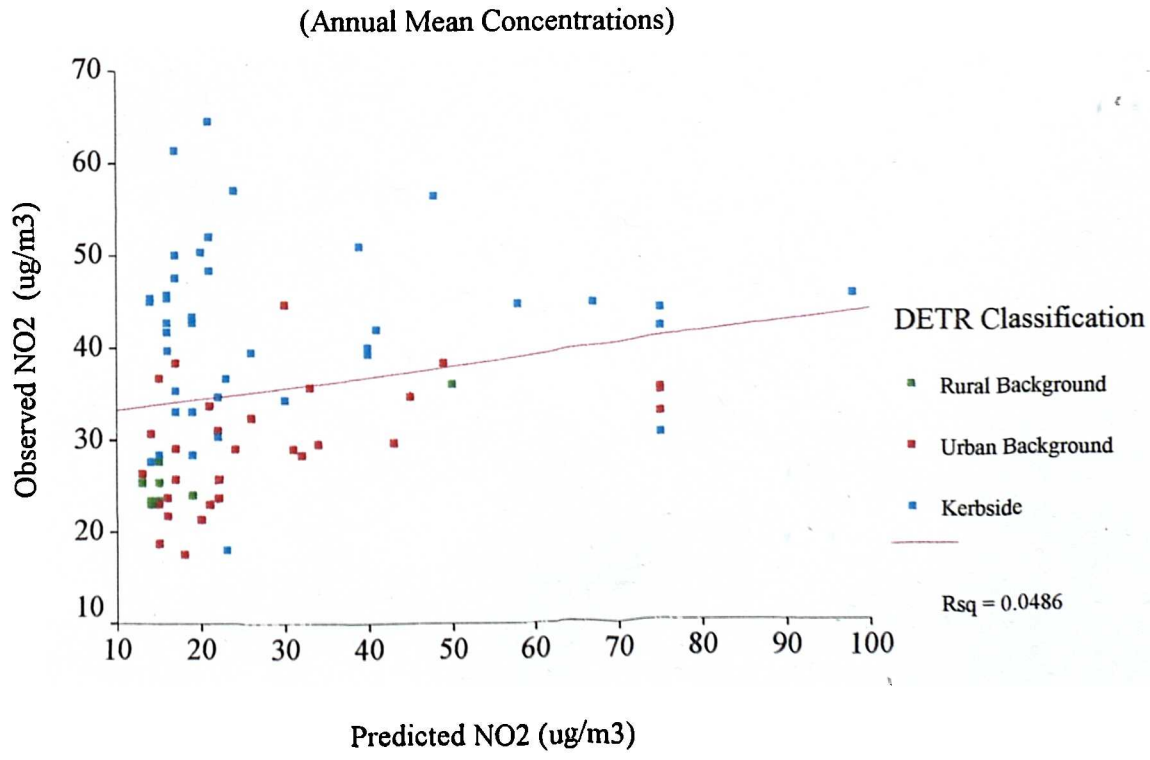


Table 6.10 Regression analysis results for CALINE4 for 80 sites.

Parameters	Survey S_2	Survey S_3	Survey S_4	Annual Mean
Degrees of Freedom	1/67	1/74	1/78	1/79
R Value	0.249	0.254	0.119	0.220
R^2	0.062	0.064	0.014	0.049
Adjusted R^2	0.048	0.052	0.002	0.117
Standard Error	9.979	9.227	12.711	10.188
Slope Value	0.129	0.127	0.079	0.119
Constant	43.939	22.163	30.875	32.041
F value	4.415	5.088	1.126	3.983
Significance F Value	0.039	0.027	0.292	0.049

For all surveys including the annual mean concentrations, five sites, with a predicted NO_2 value of approx. 75μg/m^3 appeared to be anomalies, common to all surveys and located in *duel carriageway and town centre locations.* When these sites were removed, however, no improvement in the regression equation was perceived. Further examination of the graphs indicated that there may be two curves in the data – which may be related to urban/rural locations. Thus the data was re-plotted based on the urban, background and rural classification used in the previous chapter (see Section 5.5.3). Results indicated, however, that there was no effect of land cover type on the data (see Figure 6.16). Overall, therefore, the ability of the model to map small area variation in air pollution, especially in urban areas, is seen to be poor.

As previously, in examining these results, it is important to remember that the model does not allow for variation in background concentrations, attributable to sources other than the modelled roads (i.e. most continuous monitors are in kerbside or rural locations neither of which provides data suitable for suburban background concentrations). This may account - at least in part - for the large intercept value seen in Figures 6.13 and 6.16 and in Table 6.10. This analysis is admittedly approximate. It suggests, however, that the dispersion models perform relatively poorly across the range of pollution levels measured in this area. At low concentrations, the model tends to over-predict pollution levels; at high concentrations, it under-predicts. Overall, it

is not surprising that the model does not predict NO_2 concentrations accurately at the small area level as dispersion models are not generally designed for this purpose. The suggested use of such dispersion models in the UK national air quality strategy (DOE 1996), however, for the definition of 'air quality management areas' should be treated with concern.

6.6 CONCLUSION

From results of the analysis contained within this chapter it is clear that the more sophisticated dispersion models (such as CALINE3 and CALINE4) provide reasonable, though not wholly accurate, estimates of pollution concentrations in the vicinity of roads when detailed site, receptor and meteorological information is known. The predictive ability of these models decreases, however, when large areas are modelled which contain more numerous linear sources and for which less detailed input data is available. Under these conditions, the models are unable to act as a reliable basis for air pollution mapping.

The less sophisticated models (DMRB and CAR-INTERNATIONAL) performed badly in the preliminary tests, and were clearly unsuitable as a basis for air pollution prediction or mapping. In some ways this is not surprising, for the models are, by their very nature, great simplifications of reality, and do not, for example, consider complex meteorological, photochemical or topographic effects of dispersion. The results are, nevertheless, of some significance for air quality legislation in the UK.

7. *REGRESSION MAPPING*

7.1 INTRODUCTION

Air pollution dispersion models (as described in chapter 6) form an integral part of the UK governments National Air Quality Strategy (DOE 1996) and have been widely used in epidemiological studies (Ponka 1991; Pershangen *et al.* 1995; Oosterlee 1996; NILU 1991). Nevertheless, the models tested in the previous chapter do not appear to provide a true representation of the spatial variation observed from monitored pollution data at the small area level, and as such may be considered unsuitable for air pollution mapping or exposure assessment. Consequently, alternative methods of describing and mapping urban air pollution variation are needed to meet the requirements of both air pollution policy and management and environmental epidemiological research.

The available alternatives are extremely limited. Much effort has been put in recent years into improving dispersion models, and this is likely to enhance their ability to predict pollution levels in the complex conditions which characterise urban environments. More sophisticated dispersion models, however, demand more detailed data, and as has been seen limitations of data availability already inhibit the use of many models. New generation dispersion models are therefore unlikely to provide practicable tools in many situations.

As noted in Chapter 2, the main alternative is to use methods of spatial interpolation to map air pollution on the basis of monitored pollution data. These methods have also been greatly enhanced in recent years, not least through the development of GIS. Thus, a wide range of spatial interpolation techniques are now available, as free-standing packages, as part of statistical packages (such as SPlus or SAS), or as part of proprietary GIS. These include triangulation, thin plate splines techniques (Hutchinson 1982), moving window methods (Bailey and Gatrell 1995) and kriging in its various forms (Oliver and Webster 1993, Myers 1995).

These methods have been widely used for environmental mapping, including air pollution (e.g. Wagner 1995) though interestingly few attempts have been made to use them for air pollution mapping in urban areas. Several studies have also compared the different methods (e.g. SEIPH 1996; 1997; Hutchinson 1982; Lajournie 1984; Lam and Swayne 1991) albeit without any definitive conclusions: in general, performance varies according to the quality of the data and the nature of the underlying spatial patterns which are being investigated. In this context, most methods of spatial interpolation suffer from a number of problems when applied to urban air pollution. As was shown in Chapter 5, patterns of spatial variation are extremely complex, with steep pollution gradients in some areas. On the other hand, monitoring is often relatively sparse, so that there are few data points available on which to base spatial interpolation. For many practical applications, access may also not exist to the more advanced interpolation programs which are available only in the more expensive GIS (e.g. ArcInfo) or in specially developed software packages (e.g. GSLib). It may also be noted that many forms of spatial interpolation, by relying solely on data from measurement points, explicitly ignore other potentially useful information, such as data on emission sources or surrounding topography. As Chapter 5 has shown, however, these can help to explain and predict variations in air pollution in urban areas.

What is needed, therefore, is a relatively simple procedure which can perform more effectively than the simpler dispersion models, is less data demanding than the more powerful new generation models, yet makes better use of the available data than most methods of spatial interpolation. One such method, explored here, is regression mapping.

7.2 THE REGRESSION APPROACH

Regression analysis has been widely used as a method for descriptive and inferential purposes, as well as for predictive purposes, in a wide range of disciplines and geographical fields. Regression techniques have been used, for example, to analysis trends in stream runoff (Smith and Bennett 1994), relationships between salmon catches and acidification (Waters 1991), temporal variations in crop production (Tarrant 1984), crop-environment relationships (Briggs 1981; Carter and Jones 1993; Tong 1992), the spread of *Rhododendron* in North Wales (Thomson *et al* 1993) and spatial patterns in landscape quality (Briggs and France 1981; Gregory and Davis 1993)

Regression analysis has customarily been used as a basis either for explanation or prediction. In a few cases, however, this method has also been used for the purpose of mapping. Rodrigue (1994), for example, mapped transportation land use utility values by using regression analysis to provide a weighted equation which was fed into a geographical information system to create a map of possible utility values of land use in Shanghai, China. He then compared the modelled map to the existing situation and identified areas where the land was not being used to its full potential. Similarly, Briggs and France (1981) used a regression equation, developed from an analysis of landscape preferences of a survey team,

to map landscape quality in South Yorkshire. In the field of air pollution, Wagner (1995) used regression analysis to predict urban air pollution concentrations at a network of sites in Innsbruck, Austria. Mapping of the pollution concentrations for the whole of Innsbruck, however, was not undertaken.

The use of regression analysis for pollution mapping requires the construction of an equation which can predict variation in pollution levels on the basis of environmental factors. Assuming no interactive effects between the independent variables, the regression model takes the following general form:

$$Y = a + b_1 x_1 + b_2 x_2 + b_3 x_3 .....b_n x_n + \varepsilon$$

Where $a_1\ b_2....b_n$ represent constants,
$x_1\ x_2....x_n$ represent the environmental (predictor) variables, and
ε is the error term representing the unexplained variation.

Theoretically every variable which might influence the level of air pollution (in this case NO_2) could be used as a predictor of air pollution, including measures of both source emissions (e.g. road length, traffic volume, emission rates) and dispersion characteristics (e.g. wind speed, wind direction stability, surface roughness). The greater the number of variables included, the better is likely to be the explanatory power of the regression model (Yeomans 1968; Wright 1997; Ebdon 1985; Chatfield and Collins 1993; Manley 1994)

In practice, however, increasing the number of variables adds to the problems of data collection. Moreover, it is rarely possible to identify all factors which contribute to the relationship. As a result, there is almost always a percentage of unexplained variance. Additionally, problems typically occur due to the non-causality in the relationships and interactions between the independent variables. If ignored, this may result in the development of counter-intuitive equations, and

in considerable redundancy in the analysis. Only variables which provide a logical link between environmental factors and air pollution and which significantly add to the level of explanation should thus be used.

The main limitations of using regression analysis as a method for air pollution mapping are as follows:

- statistical requirements: regression analysis requires data measured at an interval scale, which conforms to a normal distribution. More specifically, the residuals should have a normal distribution and be independent of each other (i.e. they should be randomly arranged along the regression line). With regards to air pollution, this often does not occur, thus decreasing the validity of regression analysis.
- regression analysis requires the use of preliminary logic and understanding of the variables in order to select variables for inclusion in the regression equation.
- The complexity of the air pollution system means that a large number of variables may be needed to produce the best regression equation possible. However this requires a large commitment to data collection and validation. Also the variables used may not reflect underlying causal relationships. Consequently the final regression equation may not be stable and may reflect relationships which are unique only to that particular data set.

Bearing such limitations in mind, however, regression analysis has been used in this study for a number of reasons:

- it lessens the need for a large scale network of monitoring sites.

- it allows exogenous information (e.g. on emission sources) to be used in the interpolation process.
- it provides rigorous methods for assessing the goodness of fit of the regression models to the field data, thereby giving reliability estimates for the results
- if a stable predictive equation can be generated, the equation can be transferred to different time periods and different areas.
- the equation, if stable, could be used to assess different scenarios, e.g. the effect of increasing traffic volume along a certain road.

Details of the methodology are described below. A further explanation, and comparison with regression-based methods carried out in other SAVIAH study areas is given in Briggs *et al.* (1997).

7.3 POLLUTION DATA

As noted in chapter 3, data on the distribution of nitrogen dioxide (NO_2) were collected at a large number of sampling sites within the study area and at two sites outside this boundary. This monitored data formed the dependent variable for the regression analysis used in the production of air pollution exposure maps. Data from the 80 core sites collected in the routine surveys (S_2, S_3 S_4) was used in the creation of the air pollution maps (Section 4.1). Multi-level modelling was undertaken to provide an annual mean pollution concentration for each site (Section 4.1.3). As noted previously, an additional set of the monitored data (see Section 3.1) was reserved to enable validation and testing of the finished pollution maps. Validation of the maps was undertaken using data from three

different time periods: within-period testing, pre-period testing and post-period testing (Section 4.1). Pre-period testing used data collected in the time period prior to surveys S_2, S_3 and S_4 (i.e. survey S_A, June 1992, and survey S_B, March 1993). Within-period testing used data from the 40 variable sites (which were also measured as part of the routine surveys) and data from the 10 consecutive sites (measured in the consecutive surveys). Temporal data obtained from Kirklees MC which was within the relevant time period was also used to validate the maps. Finally, post-period testing of the maps was conducted using data collected in a fifth survey in June 1994 (S_5).

7.4 POLLUTION INDICATORS

A wide range of variables may potentially be selected as a basis for modelling of urban air pollution levels. These include indicators relating both to emission sources and processes (e.g. emission rates, traffic volume, energy consumption) and indicators relating to pollutant dispersal (e.g. wind velocity, wind direction, atmospheric stability, surface roughness). In practice the choice of variables is greatly constrained by data availability and costs of data collection. As noted earlier, there are also benefits in minimising the number of variables used in regression analysis, since this helps to keep the equation simple and interpretable, and to reduce the problem of spurious or counter-intuitive relationships.

Table 7.1 Preliminary list of independent variables for the creation of the pollution equation.

Variable Name	Data Source	Definition
TOPEX	site measurements	Local topographic exposure (degrees)
RELREL	digital terrain model	Regional topographic exposure (m)
ALTITUDE	digital terrain model	Altitude at site (m)
SAMPLEHT	site characteristics	Height of the sampler above ground level (m)
HIGH DENSITY HOUSING	land use map	Amount of land in which more than 60 per cent of the area is housing
INDUSTRY	land use map	Amount of land in which industry is located
VLD_250	land use map	Total amount of very low density residential housing at a distance of 250m from each site
TVOLBUFF	traffic counts from Kirklees Council	Weighted area traffic volumes for bands of 0-40m and 40-300m radius from each site
TRAFFCAL	traffic counts from Kirklees Council	CALINE4 weighted traffic distance from all 20m bands of traffic volume up to a distance of 300m from each site

The variables considered for inclusion in regression analysis for this study are listed in Table 7.1. Several variables were subsequently rejected, either because of doubts about data reliability or because other variables were considered to provide more accurate indicators of pollution. Others were transformed or combined to produce compound indicators. The following indicators were therefore used in the final analysis:

TVOLBUFF - Traffic volume in a measured distance around the site.
HIGHDEN - Area of high density built-up land in a measured distance around the site.
ALTITUDE - Altitude at the site.
TOPEX - Local topographical exposure.
RELREL - Regional topographic exposure.
SAMPLEHT - Height of the sampler above ground.

The construction and measurement of each of these variables is described below.

7.4.1 TRAFFIC VOLUME (TVOLBUFF)

7.4.1.1 DATA COLLECTION

The amount of NO_2 emitted from vehicles is clearly a major determinant of pollution levels in urban areas (Tolley 1995). Unfortunately, accurate data on vehicle emissions were not available for the study area and, thus, traffic volume was used as a proxy indicator.

Traffic flows, this time for the entire study area, were obtained from two sources, as described in Chapter 4. West Yorkshire Highways and Technical Services Joint Committee, Leeds, provided automatic traffic counts. These were measured at 80 locations within Kirklees and 3 sites at the motorway. Each count provided a 24 hour average traffic flow. Manual traffic counts were obtained from Kirklees Highways Services, Huddersfield. These provided traffic flows in each direction at a site for 30 minute intervals between 07.00 and 18.00 hours, measured on several occasions within the specified time period. However there are a number of limitations in using such data:

- not all roads were covered by traffic counts
- a number of roads had a combination of automatic and manual traffic counts.
- manual traffic counts did not cover a 24 hour period

In order to circumvent these problems of missing traffic data the following protocol was adopted;

- wherever possible automatic traffic counts were used

- if automatic traffic counts were not available, manual counts were used. Information from the nearest automatic count was used to augment and extrapolate the data.

- where no information on road traffic volume was available, local knowledge and field visits to assess the type and location of the roads was used to assign the road a traffic volume.

This provided traffic flow per 24 hours per road-length for A and B roads in Kirklees. This information was then averaged to provide traffic flow in vehicles per hour. Data on traffic flow for minor and estate roads was not available in most cases, and therefore was estimated, on the following basis: roads > 4m wide were given a traffic flow of 11 vehicles per hour, roads < 4m wide were given a traffic flow of 5 vehicles per hour. Tracks and unmetaled roads were allocated a traffic flow of 2 vehicles per hour.

7.4.1.2 PROCESSING

Once collected, the information on the traffic factors was imported into ARC/INFO (UNIX). The road system in the area was digitised into the GIS and each road length given a 'type' classification.

- Data on traffic volume in vehicles per hour was attached to the road segments as attribute data and hence a coverage was created in the GIS for the whole of the study area, showing each road by type (i.e. motorway, duel carriageway, A road, B road, minor roads) and traffic volume (see Figure 7.1). The length of each road section (in metres) was also attached to the coverage as attribute data. A fine mesh ($10m^2$) was then overlaid onto the coverage creating a *grid coverage* (TRAFFVOL).

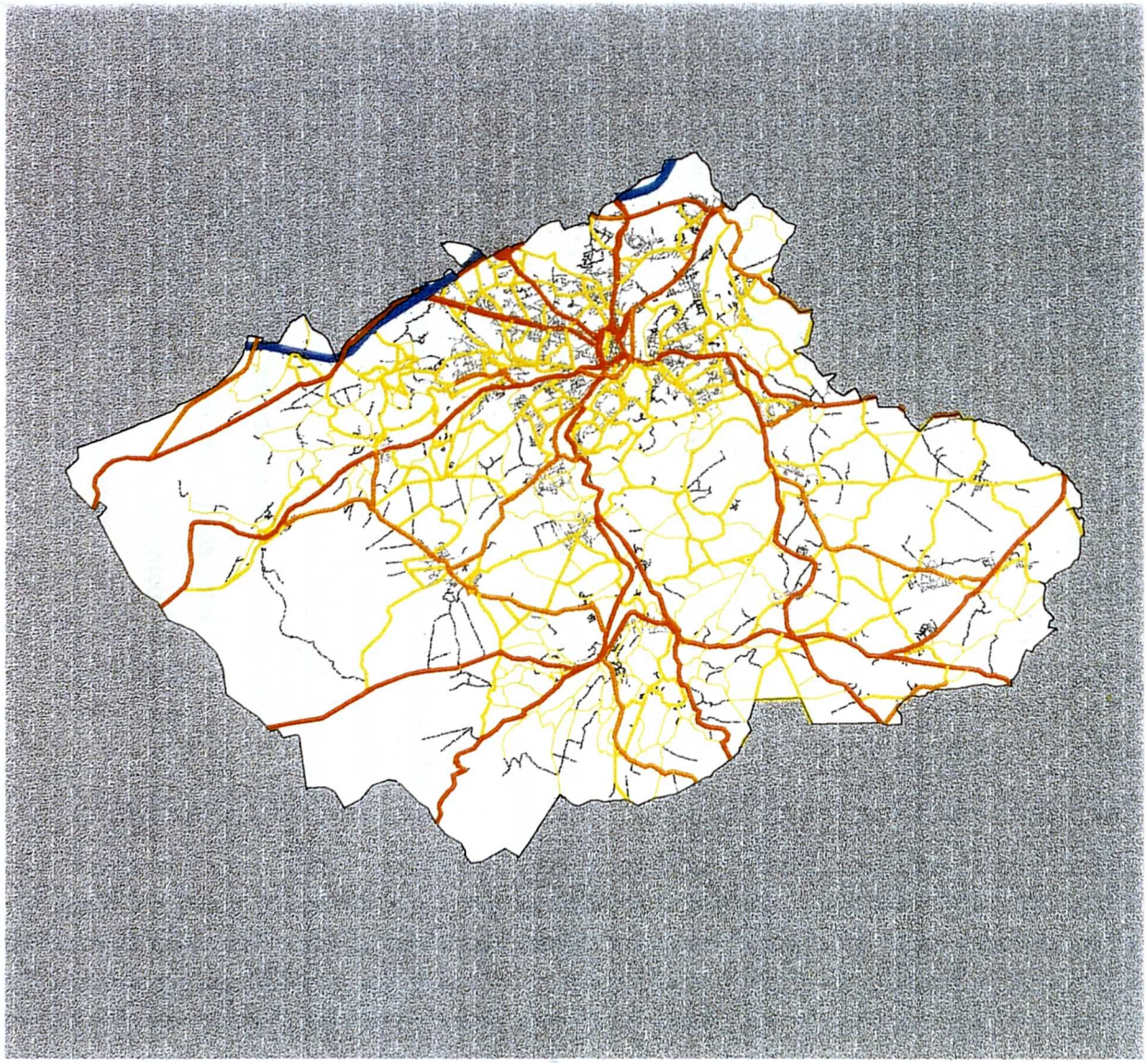


Figure 7.1 Average Traffic Volume by Road Type

Legend

Road Type	Vehicles/hour
Motorway	4594
Trunk Road	1576
Main Road	694
Secondary Road	267
Road > 4m wide	11
Road < 4m wide	5
Other Road	2

-1 0 1 2 3 Km

- The grid co-ordinates of the 80 sample sites were also transformed from DOS to UNIX and then imported into the GIS. Using the GENERATE and BUILD commands, the sites were transformed to a point coverage and then to a grid of the same size as before - i.e. to a mesh cell size of $10m^2$ (MONSITES).

- A circular buffer made up of grid cells with a radius of 300m was then drawn around the 80 sample sites (see Figure 7.2); everything outside the buffer was discarded, effectively performing cookie cutting or masking over the coverage to create MONSITES_1.

- The modified MONSITES_1 coverage was then intersected with the TRAFFVOL coverage to create a third grid coverage (TRAFFFILTER_300) which contained all the information on traffic volume by road length and by road type per grid cell within a radius of 300m from the sample point.

- The road length/type and traffic volume within each buffer was calculated using the FOCALSUM command. The command summed every value within a specified buffer zone and placed it in the central gridcell of that zone. The process was then repeated for the next gridcell in the coverage (Figure 7.3).

- The FOCALSUM command was repeated for different buffer zone bands of different radius ranging from 20m to 300m at 20m intervals.

It would clearly be possible to use the traffic volumes from each of these bands as independent variables in a regression model to predict NO_2 concentrations. For a number of reasons, however, this approach was eschewed. Firstly, it is apparent that complex interdependence actually exists between the component traffic volumes in the different bands, and in reality they are not mutually independent. Secondly, it must be accepted that the data used to compute traffic volumes in each of the bands is open to some doubt. Using so many variables

was therefore seen to be likely to compound errors in the analysis. Thirdly, introducing all these variables into the analysis was likely to lead to unstable and counter-intuitive relationships with some bands having negative effects in the equation.

For these reasons, it was considered appropriate to develop a more aggregated indicator of traffic volume by combining the data from different bands in a weighted aggregation procedure. The logic behind this step was that the pollution at any location is a product of contributions from all sources within the surrounding area, but that nearby sources contribute more than distant sources. A way was thus needed to define the weights to be attached to each band, based upon their relative contribution to the pollution level. A combination of correlation and regression analysis was used for this purpose.

Figure 7.2 Example of a Circular Buffer used in GRID

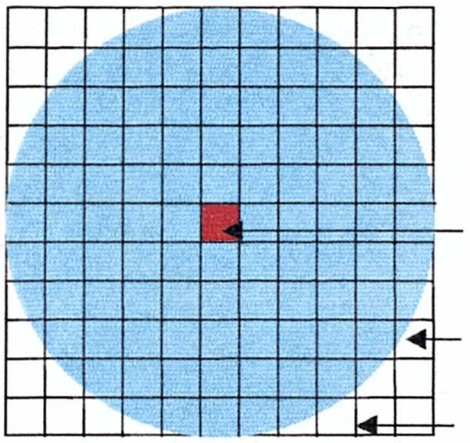
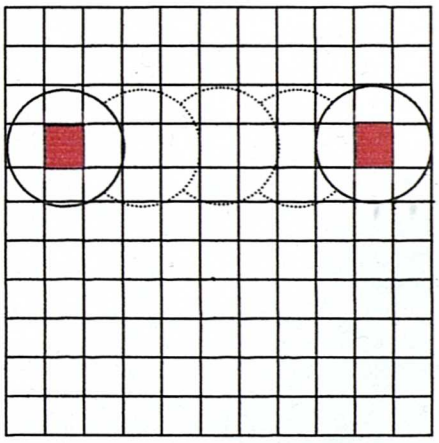


Figure 7.3 Example of a Moving Buffer



Analysis was conducted using the SPSSPC+ statistical package. Correlations were calculated between the arithmetic mean nitrogen dioxide concentrations (A_m) and the calculated traffic volume for each band for the 80 core sample

sites. The R^2 value for each site was plotted (Figure 7.4) and examined to identify possible ways of combining the data into broader bands. No immediate banding was perceived, however, although the R^2 values did tend to peak in the 80-140m zone. Consequently it was felt that more analysis was necessary. Therefore stepwise regression analysis, using all traffic bands (i.e. 20, 40, 60 etc.) as independent variables, was undertaken, again in order to identify possible band combinations. Again no immediately identifiable 'cut-off' points for the zones were distinguishable. Finally, multiple regression analysis was undertaken on a trial and error basis, to seek the best combination of bands to use as a predictor of traffic volume. This was achieved by defining two, three or four zones of varying width around each site, and then using the traffic volumes of the combined zone (e.g. 10-40, 40-160, 160-300) as independent variables against the modelled mean nitrogen dioxide concentrations (M_m). The performance of the different equations were compared in terms of the R^2 value. Results for 13 of the 'best' analyses on this basis are shown in Table 7.2.

On the basis of these results, equation G (with zones of 0-40 and 40-300m) was selected as the optimal equation. Results from the analysis also provided a means of determining weights to combine the two buffer zones into a single, compound traffic volume indicator. The relative contribution of the two zones to the prediction of NO_2 concentrations was shown by the slope value (B). As can be seen, for equation G, the value of B was 0.00008 for the 0-40 metre zone and 0.0000055 for the 40-300 metre zone. The ratio of the two zones was thus approximately 15:1, allowing a compound traffic volume indicator to be compiled as follows:

$$TVOLBUFF = (15 * Traffic_1) + (1 * Traffic_2)$$

Where; $Traffic_1$ is the calculated traffic volume in a 40m radius from a point.
$Traffic_2$ is the calculated traffic volume in a radius of between 40m and 300m around a point.

Figure 7.4 Correlation of NO2 Values and Traffic Volume with Radial Distance from Sampling Site

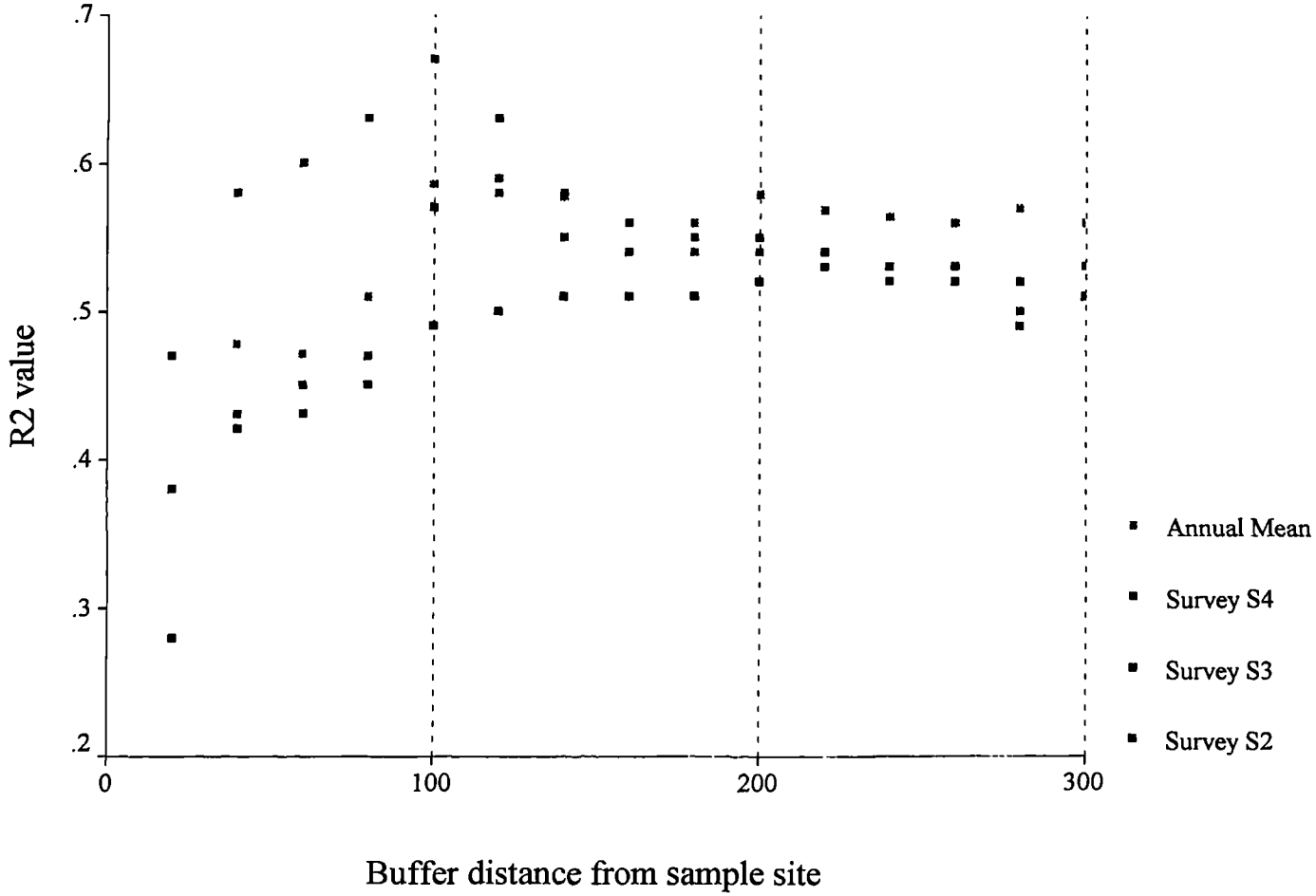


Table 7.2 Evaluation of traffic buffer zones

	Buffer Size	Slope Value B	Degrees of Freedom	Order of Equation	Adjusted R^2	Constant	Significant Value
A	0-20	0.00013200	76/3	2	41.08	26.754	0.0000
	20-100	0.00001960		3			
	100-300	0.00000421		1			
B	0-20	0.00012180	76/3	2	41.34	26.698	0.0000
	20-80	0.00002430		3			
	80-300	0.00000504		1			
C	0-20	0.00009580	76/3	2	42.45	26.673	0.0000
	20-40	0.00007420		3			
	40-300	0.00000546		1			
D	0-20	0.00017150	77/2	2	39.13	27.102	0.0000
	20-300	0.00000585		1			
E	0-20	0.00009580	76/3	2	42.45	26.673	0.0000
	20-40	0.00007420		3			
	40-300	0.00000483		1			
F	0-40	0.00007750	76/3	2	42.5	26.659	0.0000
	40-120	0.00000853		1			
	120-300	0.00000483		3			
G	0-40	0.00008050	77/2	2	43.14	26.669	0.0000
	40-300	0.00000546		1			
H	0-40	0.00007520	76/3	2	42.61	26.62	0.0000
	40-100	0.00001040		3			
	100-300	0.00000495		1			
I	0-40	0.00007695	75/4	2	42.03	26.621	0.0000
	40-100	0.00000932		3			
	100-200	0.00000674		4			
	200-300	0.00000389		1			
J	0-40	0.00007480	75/4	2	41.8	26.745	0.0000
	40-80	0.00001070		3			
	80-120	0.00000748		4			
	120-300	0.00000493		1			
K	0-60	0.00003888	75/4	2	37.43	26.991	0.0000
	60-120	0.00001139		3			
	120-240	0.00000378		4			
	240-300	0.00000453		1			
L	0-100	0.00002714	76/3	2	38.00	26.943	0.0000
	100-20	0.00000361		3			
	200-300	0.00000372		1			
M	0-100	0.00002710	77/2	2	38.85	26.943	0.0000
	100-300	0.00000368		1			

This variable was then entered as the single independent variable in a regression analysis against the modelled mean NO_2 concentrations, and the residuals and regression parameters calculated. The process was then repeated using NO_2 concentrations for each independent survey as the dependent variable, and again

the residuals and regression parameters were calculated. Table 7.3 shows the results obtained from these analyses.

Table 7.3 Results of regression analysis for nitrogen dioxide and traffic volume, for individual and the modelled annual mean (M_m)

Survey No	D.F	Adjusted R^2 Value	Slope Value (B)	Constant	Significance F
M_m	75/4	43.9	0.004	40.94	0.000
S_2	66/2	33.4	0.004	40.83	0.000
S_3	73/2	29.4	0.003	58.06	0.000
S_4	76/3	44.4	0.007	20.04	0.000

7.4.2 Built Land

7.4.2.1 Data Collection

Land cover was also considered to be an important predictor of air pollution, in two different ways. On the one hand, areas of commercial, industrial and residential land may act as stationary emission sources. On the other hand, urban topography (e.g. the density, size and distribution of buildings) affects dispersion processes.

A land cover map had been created using aerial photographs, at a detailed scale (1:10,000), as described in Chapter 4. Oneway Analysis of Variance was conducted, using the SPSSPC+ statistical package, to identify areas of high pollution levels in urban areas. For this analysis, it was decided to disregard rural areas for two reasons: firstly the contribution to emissions of NO_2 from rural sites was likely to be minimal (see section 4.3.3.1), and secondly, the effect of vegetation on dispersion was small in relation to the scale of the project. The

main variation were therefore expected to occur within urban areas, as indicated by the results of the analysis of spatial variation (Chapter 5).

The analysis was conducted on seven land cover classes derived from the land cover map and detailed in Table 7.4. These were compared in terms of their NO_2 concentrations for each of the three surveys (S_2, S_3, S_4) and the annual modelled mean (M_m); results are presented in Table 7.5. Broadly similar levels of NO_2 are seen across all land cover classes in survey S_2. For all other surveys, however, and the annual modelled mean, apparent differences in mean annual concentration are discernible: highest concentrations occur in areas of high density commercial (HDC), industry (IND) and very low density housing; lower values occur in areas of very high density housing, low density housing and disused/recreational land and urban green space. In part, this pattern is understandable. The main exception is the high levels of NO_2 seen in the areas of very low density housing. No obvious explanation can be offered, though it may reflect local siting factors for sites in this land class. Examination of the probability estimates from the Oneway Analysis of Variance showed that the differences in NO_2 concentrations between urban land use classes for surveys S_2 and S_3 were not significant (0.1240, and 0.635 respectively). For survey S_4 and the modelled mean, however, the differences were significant (0.0035 and 0.0173).

Table 7.4 Land cover classes and codes used in preliminary analysis of variance

CLASS	LAND COVER CODE
High Density Commercial	(HDC)
Industry	(IND)
Very High Density Housing/Public Institutes	(VHD/PI)
High density Housing	(HDH)
Low Density Housing	(LDH)
Very low density Housing	(VLD)
Disused & Sequestered Land/Recreation/Urban Green Space	(DIS/REC/UGS)

Table 7.5 Results of analysis of variance for NO_2 concentrations ($\mu g/m^3$) by land cover class

LAND COVER CODE	MEAN				95 % CONFIDENCE INTERVAL FOR THE MEAN			
	S_2	S_3	S_4	M_m	S_2	S_3	S_4	M_m
HDC	56.64	33.84	41.05	40.54	50.99 - 62.29	27.12 - 40.56	34.14 - 47.96	36.17 - 44.91
IND	56.06	33.96	42.01	40.85	44.49 - 67.62	26.26 - 41.67	29.59 - 54.43	32.07 - 49.64
VHD/PI	55.60	19.87	19.13	24.20	1.01 - 110.19	2.44 - 37.29	3.49 - 34.77	6.05 - 42.36
HDH	50.78	25.49	38.64	35.83	44.58 - 56.97	18.81 - 32.18	29.71 - 47.56	29.01 - 42.64
LDH	45.95	24.36	30.21	31.29	42.16 - 49.74	21.30 - 27.41	26.32 - 34.09	28.36 - 34.22
VLD	54.43	30.37	48.63	41.36	47.45 - 61.42	25.01 - 35.72	37.95 - 59.32	38.98 - 43.74
DIS/REC/ UGS	47.80	28.76	28.38	32.59	42.96 - 52.64	11.11 - 46.41	17.29 - 39.47	20.27 - 44.92

7.4.2.2 PROCESSING

The information on all land cover classes was digitised into the GIS, in order to allow subsequent reclassification and disaggregation, if necessary. Separate coverages of the seven land use classes listed in Table 7.5 were then created. A similar operation to that described for the traffic volume variable was then conducted.

- A fine mesh ($10m^2$) was overlaid onto each land use coverage (e.g. high density housing (HDH)) thus creating a *grid coverage* (HDH_GRID).

- The grid coverage of the 80 core sample sites, which had been previously created using cookie cutting for the traffic volume variable (MONSITES_1) (see section 7.4.1.2), was intersected with each of the land use grid coverages (e.g. HDH_GRID) to create a third series of binary grid coverages (e.g. HDH_300). This contained information on the presence or absence of each land use type in each grid cell within a radius of up to 300m from the sample point.

- The amount of each land use type (e.g. high density housing) within each buffer was calculated using the FOCALSUM command. The command summed every value within a specified buffer band and placed it in the

central gridcell of that band. The process was then repeated for the next gridcell in the coverage, as shown in Figure 7.3.

- The FOCALSUM command was repeated for three different sizes of buffer bands, with radii of 40m, 250m and 300m.

- The whole process of cookie cutting and FOCALSUM, was then repeated for *all* seven land use classes, on a grid coverage for the *whole* study area, using buffer bands of 20m intervals, ranging from 20 to 300m radius. This allowed the buffers to be weighted (i.e. higher for nearby buffers, lower for more distant buffers), if necessary, in order to provide a better estimate of land use. This produced a series of new coverages, one for each land use class, which could be used for subsequent mapping of a combined land cover variable.

The creation of the seven land use coverages at differing buffer distances was conducted for a number of reasons: firstly, to reduce the difficulties of data collection; secondly to decrease the complexity of the regression equation; and thirdly because introducing all these variables into the analysis was likely to lead to unstable and counter-intuitive relationships with some land uses having negative effects in the equation. Not all of the land use categories, however, would be expected to affect pollution levels to the same extent. For example, an industrial area might be expected to have a greater effect than an area of open land (e.g. recreation ground). Thus a weighted aggregated variable was needed based upon the relative contribution of each land use type to the pollution level. A combination of analysis of variance, correlation and regression analysis was used for this purpose.

Analysis was conducted in the SPSSPC+ Statistical package. Correlations were calculated between the levels of nitrogen dioxide and the entire urban built-up land at different distances, from 20m to 300m radius. Built up land was defined

as the area of total built land for each band. The results showed that the R^2 value increased gradually with distance from the central point. Consequently, three arbitrary band widths of 40m, 250m and 300m radius for each of the seven land use classes or variables was chosen to allow the buffer zones to be weighted if necessary.

Multiple regression analysis was conducted to identify which of the land use variables and which band radii to use. The residuals from the previous analysis of TVOLBUFF (see section 7.4.1.2) were used as the dependent variables in the regression analysis, to eliminate the effect of TVOLBUFF (i.e. to allow only the unexplained variation, which remained after the use of the TVOLBUFF variable, to be examined).

Different combinations of land use and distance were entered into the equation until the best explanation of variance was found (i.e. the combination giving the highest R^2 value). The results showed that most land use classes did not contribute significantly to the relationship. Also some land use classes produced counter-intuitive results (i.e. gave negative correlations). Strong positive correlations, however, were formed with high density housing and industry, both for a radius of 300m (HDH_300 and IND_300). Positive correlations were also sometimes formed with very low density housing at a band width of 250m (VLD_250). This was considered spurious and therefore the variable was not included in the subsequent analysis. HDH_300 and IND_300 were regressed against the residual values and the B value examined. The weights were then calculated to create a measure of urban land, HIGHDEN:

$$HIGHDEN = (1.8 * HDH\_300) + (1 * IND\_300)$$

HDH_300	A measure of the amount of high density housing in a 300 metre radius around the site
IND_300	A measure of the amount of industrial land use in a 300 metre radius around the site.

The GIS was then used to create a HIGHDEN coverage based on the above equation. The processes involved in the formation of the coverage is explained in section 7.4.1.

7.4.3 OTHER VARIABLES

7.4.3.1 ALTITUDE

Altitude was used as a proxy variable for climatic data at each site, as it was thought that the higher the altitude the lower the pollution levels. This was based on the expectation that most pollution sources lay in the valley bottoms, and that increased wind speed at higher altitudes would aid dispersion and reduce pollution levels. Altitude was defined as the height above ordnance datum at a sample point. Calculations of altitude for the whole of the study area were taken from a DTM of the area (Figure 7.5). Preliminary analysis suggested that the relationship between altitude and nitrogen dioxide concentrations was not linear, and that this non-linearity persisted when altitude was plotted against the residuals derived from the TVOLBUFF analysis. Logarithmic transformations of altitude were therefore used in the subsequent regression analysis.

7.4.3.2 SAMPLE HEIGHT

Sample height was defined as the 'height of the diffusion tube above ground level'. An attempt was made to keep all samplers at a standard height but, due to the risks of vandalism in densely populated areas, some samplers were placed higher. This was expected to have a small effect on the measured results and so sampler height was also introduced into the regression analysis. In this way, it

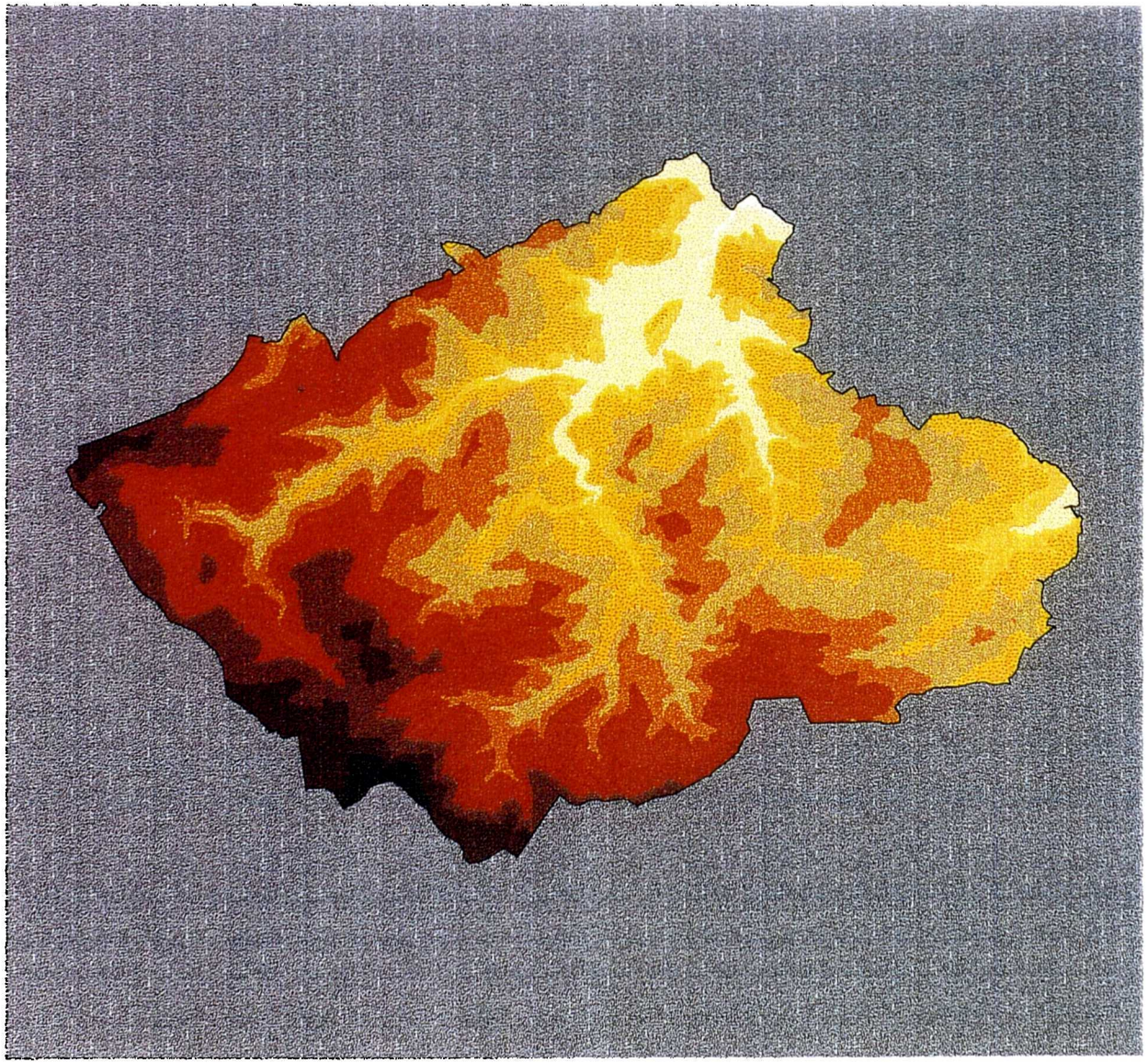


Figure 7.5 Altitude map of the Study Area.

was possible to standardise subsequent pollution maps to a receptor height of 2.5m.

7.4.3.3 RELATIVE RELIEF

Relative relief (RELREL) was defined as the *'altitudinal variation around the site'*. It is thus a measure of the topographical 'openness' of the site. It was calculated from the DTM in the GIS as the mean difference between the altitude of the $10m^2$ cell in which the site lay and the nine adjacent cells.

7.4.3.4 LOCAL TOPOGRAPHICAL EXPOSURE

The local topographical index (TOPEX) was defined as *'a measure of the degree of topographic exposure or openness in the immediate vicinity of a site'*. This allows for the influence of buildings within the vicinity, and was based on the premise that the more exposed a site (i.e. with few surrounding buildings), the greater the likelihood of NO_2 dispersion and, thus, the lower the pollution levels. To calculate TOPEX values, a clinometer was used to measure the angle to the visible horizon for each of the eight compass bearings from the site, and these values were averaged. The computation of TOPEX is explained in more detail in Appendix 1.

7.4.3.5 VERY LOW DENSITY HOUSING

As noted above (section 7.4.2), areas of very low density housing showed relatively high concentrations of NO_2. Because of the counter-intuitive nature of this pattern, the variable was not included in the compound Built Land factor

(HIGHDEN), but it was incorporated as a separate variable in subsequent analysis, to determine whether it added significantly to levels of explanation.

7.5 CREATION OF REGRESSION MODEL

All potential independent variables mentioned in Section 7.2 were input into an unconstrained regression analysis using the modelled mean (M_m) as the dependent variable. Those independent variables which best explained the variation in air pollution concentrations were identified. The resultant regression equation was applied to the individual surveys (S_2, S_3, and S_4) in order to determine the extent to which the equation could explain pollution variation within the surveys (i.e. was the equation temporally stable). This process is explained in more detail below.

7.5.1 REGRESSION ANALYSIS ON MODELLED MEAN

The modelled mean NO_2 values (M_m) were entered as the dependent variable in the regression analysis. The independent variables were as follows:

TVOLBUFF	amount of weighted traffic volume by band (1000 vehicle km/hr)
HIGHDEN	amount of weighted high density housing and industry (ha)
VLD_250	amount of very low density housing (ha)
ALT	altitude (variously transformed) (metres)
RELREL	altitudinal variation around the site (metres)
TOPEX	local topographical exposure (degrees)
SAMPLEHT	height of the sampler above ground level (metres)

All of the above variables were initially entered into the regression equation using unconstrained *stepwise* analysis. Results showed that VLD_250, TOPEX and RELREL did not contribute to the equation at a significance level of 0.05, and were therefore discarded from the analysis. The analysis was then resumed utilising the remaining four variables, using the *enter* method. A number of essentially similar equations were generated, with similar levels of explanation of NO_2 concentrations. The equation which gave marginally the highest R^2 value explained 60.7 per cent (with 75/4 D.F) of the variation of NO_2 in the study area is:

NO_2 = 11.83 + (6.777 * SAMPLEHT) + (0.268 * HIGHDEN) + (0.00398 * TVOLBUFF) + (-0.0355 * LNALT)

The method was then repeated for the three individual surveys (S_2, S_3, S_4) again using first the *stepwise* method to obtain the independent variables. Again VLD_250, TOPEX and RELREL were rejected from the equation. The remaining variables were once more regressed using the *enter* method to produce the final equations for the individual surveys. Once more, several similar regression equations could have been generated, those with the highest R^2 were used. From the results it was found that the equation for survey S_2 explained 38.7 per cent (with 64/4 D.F). For survey S_3 it explained 39.8 per cent (with 71/4 D.F); for survey S_4 it explained 55.0 per cent (75/4 D.F) of the variation in pollution levels.

Survey 2 (S_2)

NO_2 = 48.81 + (1.97853 * SAMPLEHT) + (0.0000218 * HIGHDEN) + (0.000004163 * TVOLBUFF) + (-2.29468 * LNALT)

Survey 3 (S_3)

NO_2 = 50.475 + (1.8663 * SAMPLEHT) + (0.0000098496 * HIGHDEN) + (0.000002767 * TVOLBUFF) + (-6.74495 * LNALT)

Survey 4 (S_4)

NO_2 = 21.14 + (2.56504 * SAMPLEHT) + (0.000039129 * HIGHDEN) + (0.0000061359 * TVOLBUFF) + (-0.87704 * LNALT)

7.5.2 Traffic Volume Variable

The traffic volume variable clearly accounted for the largest proportion of the variation in NO_2 in all surveys. The traffic volume variable used, however, was somewhat arbitrary in its construction. Efforts were therefore made to improve this variable. For this purpose, the line dispersion model, CALINE3, was used to provide weightings for the total traffic volume in the area surrounding the sample points, as follows:

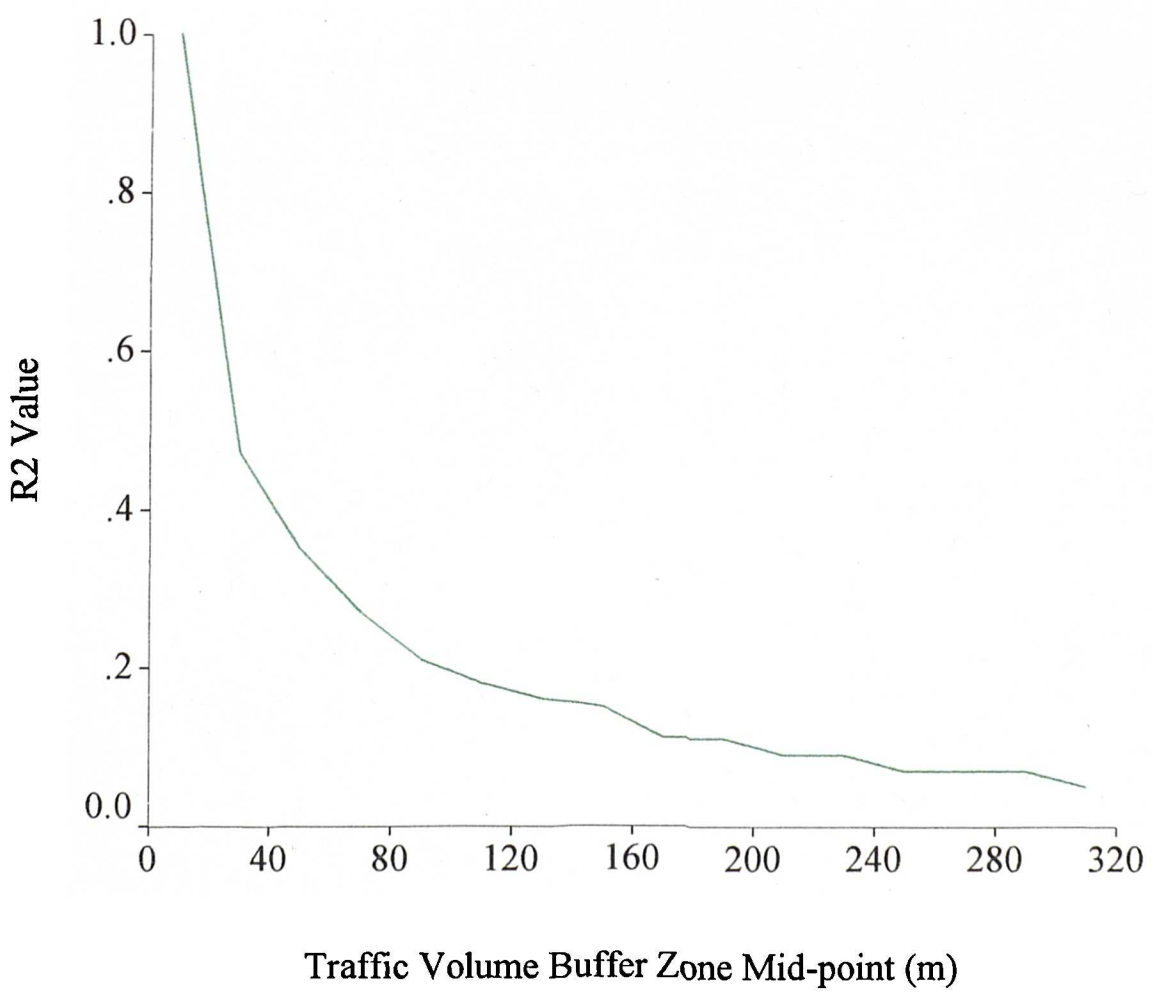
- The traffic volumes for each of the buffer bands was computed from the GIS for intervals of 20m ranging from 20m to 300m radius. These were intersected with the MONSITES_1 coverage (the sample point coverage) to produce the traffic volume by buffer band for each sample site. The values were exported from UNIX to DOS as a database.

- The mid-point of each buffer band (i.e. 5m, 15m, 25m,.. 290m) was input into the CALINE4 linear dispersion model, and a weighting curve under average meteorological conditions (calculated from 15 minute interval weather data obtained from the University of Huddersfield weather station for 1 year) was produced (Figure 7.6).

- The values obtained from the curve were used in following equation which was then applied to all sample sites:

Total Traffic Volume = (1 * traff_20) + (0.455 * traff_40) +
.....+ (0.06800 * traff_300)

Figure 7.6 Traffic Volume Weighting Curve Produced Using CALINE4 Dispersion Model



Thus a new weighted traffic volume variable (TRAFFCAL) was created. This variable was then entered into the regression analysis in place of TVOLBUFF, and equations for the modelled mean and the individual surveys re-computed. Results are summarised in Table 7.6. This shows that the final level of explanation of variations in NO_2 using the TRAFFCAL variable (as shown by the R^2 value) is lower than that using TVOLBUFF in all surveys except survey S_3. The original equation (section 7.5.1) were therefore used for subsequent mapping.

Table 7.6 Results of regression analysis using traffic volume variables

Traffic Variable	Indicator: traffic volume only Adjusted R^2 value				Indicator: complete range of variables including HIGHDEN & SAMPLEHT Adjusted R^2 value			
	S_2	S_3	S_4	M_m	S_2	S_3	S_4	M_m
TVOLBUFF	33.4	29.4	44.4	43.9	38.32	38.50	56.80	55.82
TRAFFCAL	29.3	29.6	37.7	40.2	35.20	38.90	53.45	54.20

Complete equations.

TVOLBUFF = (15*Traffic buffer zone of 40m) + (1*Traffic Buffer zone of 40-300 m)

TRAFFCAL = (1*traff20) + (0.455*traff40) + (0.318 * traff60) + (0.25 * traff80) + (0.21 * traff100) + (0.18*traff120) + (0.16*traff140) + (0.14*traff160) + (0.11*traff180) + (0.11*traff200) + (0.09*traff220) + (0.09*traff240) + (0.07*traff260) + (0.07*traff280) + (0.05*traff300)

7.6 MAPPING

In order to allow the estimated value of NO_2 concentrations to be calculated at any one point in the study area, it was necessary to extrapolate the final equation to the entire area. This was carried out by producing air pollution maps within the GIS. In order do this, coverages for the variables, HIGHDEN and

TVOLBUFF, were created for the entire study area using the following procedures:

TVOLBUFF

- In order to create a coverage based on the equation *Tvolbuff* (section 7.4.1.2), it was first necessary to produce coverages of the variables, $Traffic_1$ (calculated as traffic volume in a 40m radius from a point), and $Traffic_2$ (calculated as traffic volume in a 40 to 300m radius from a point) used in the equation. This was accomplished using a similar process to that described in section 7.4.2.1.

- First, coverages TRAFFIC_1 and TRAFFIC_2 were created by again applying the FOCALSUM command to the original TRAFFVOL coverage. The resultant coverages contained information on the total traffic volume within a 40m radius around each gridcell (TRAFFIC_1) and the total traffic volume within a 40-300m radius around each gridcell (TRAFFIC_2), for the entire coverage.

- The two TRAFFIC coverages were then combined using the Tvolbuff equation to create a weighted coverage of total traffic volume (TVOLBUFF) (Figure 7.7).

HIGHDEN

- In order to produce a coverage based on the *Highden* equation (Section 7.3.2.2), it was first necessary to reproduce coverages of the variables, *Hdh_300* (calculated as the amount of high density housing in a 300m radius for every gridcell), and *Ind_300* (calculated as the amount of industry in a 300m radius for every gridcell) for the entire study area. This was accomplished using a similar process to that described in section 7.4.2.2.

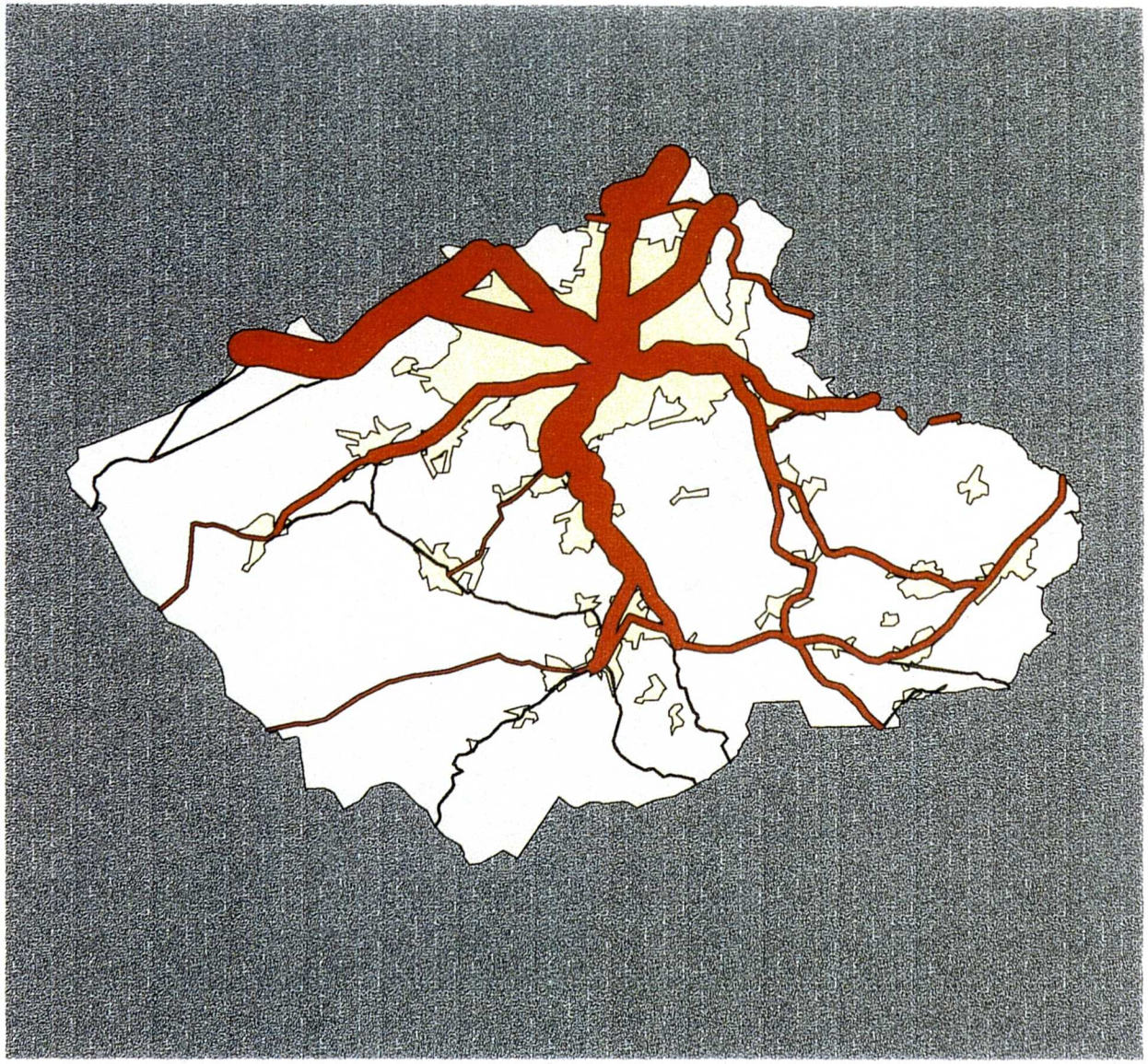


Figure 7.7 Weighted Coverage of Traffic Volume (TVOLBUFF).

Legend

0 > 40.000 veh/hr

-1 0 1 2 3 Km

- Again the FOCALSUM command was applied to the original HDH_GRID and IND_GRID coverages in order to create the two coverages used in the *Highden* equation, Hdh_300 and Ind_300. The resultant coverages contained information on the amount of high density housing in a 300m radius for every gridcell (HDH_300) and the amount of industry in a 300m radius for every gridcell (IND_300), for the entire coverage.

- The *Highden* equation was then applied to the HDH_300 and IND_300 coverages to create a combined weighted coverage, (HIGHDEN) (Figure 7.8).

Once these coverages were created, the final equation, involving all the variables, was entered into the GIS and a map of the estimated air pollution was produced. In this analysis, sample height was set to a standard level of 2.0 metres. This step was repeated for each of the three individual surveys and for the modelled mean values. Results from this procedure are shown in Figures 7.9 to 7.13.

All the pollution maps show broadly similar patterns of relative NO_2 concentrations, although the absolute concentrations do vary, with survey S_2 producing the highest concentrations and survey S_3 the lowest.

For survey S_2 (Figure 7.9), highest concentrations were found, not surprisingly, along the motorway (M62), Leeds road (A62), the Sheffield road (A616) and near the ring road, as these are heavily used roads, which logically would be expected to produce high amounts of vehicular emissions. In all cases, areas of high pollution are associated with major infrastructure and settlements (e.g. within the first 3 - 4 km from the town centre). Lowest concentrations were found in the south-west, an area of moor land, in or near the Peak National Park. Interestingly, for all four maps, increased concentrations are associated with the village of Meltham, in the west, and the B-road which serves it. Overall, the map

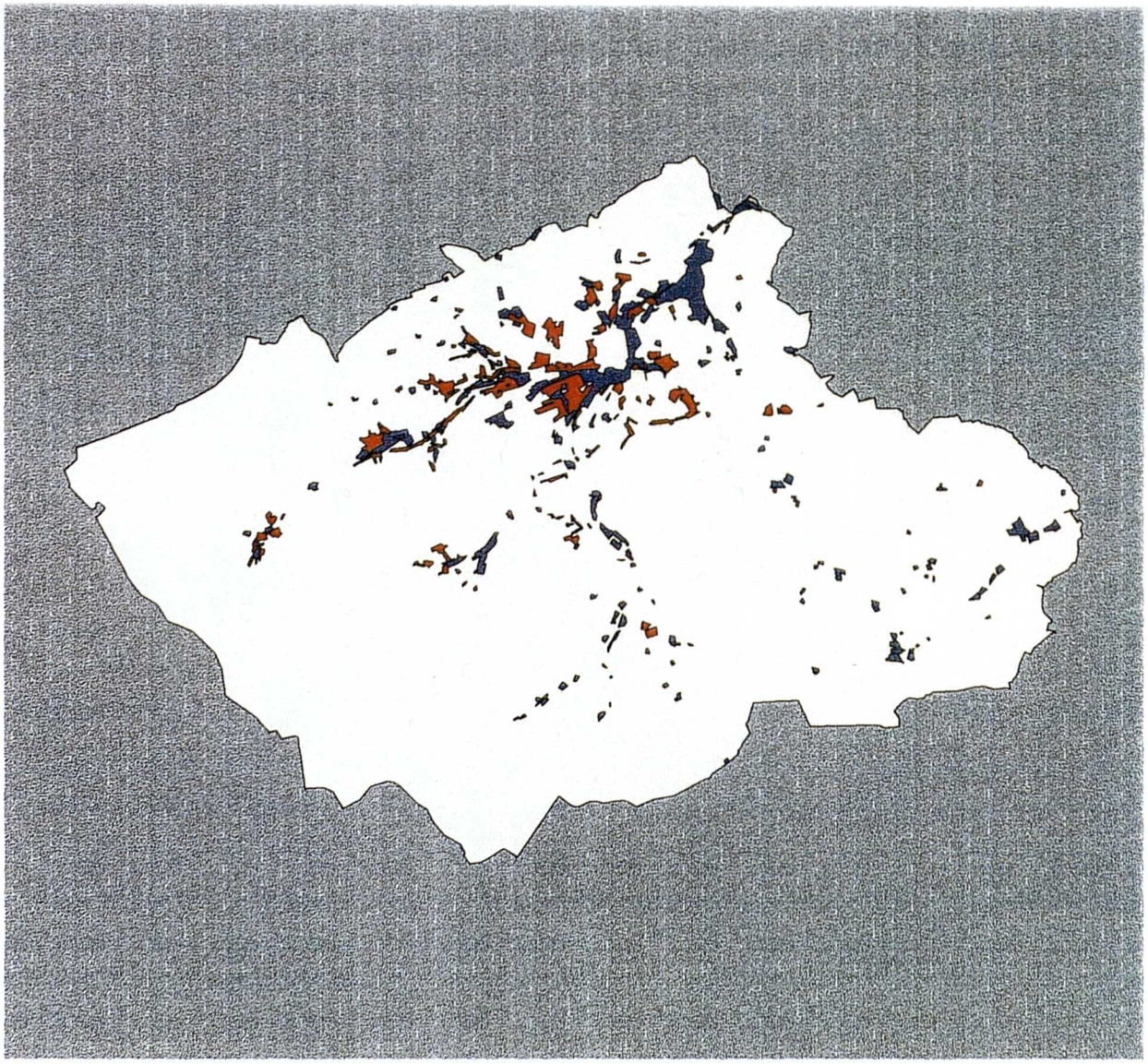


Figure 7.8 Weighted Coverage of Landuse (HIGHDEN).

Legend

High Density Residential

Industry

-1 0 1 2 3 Km

N

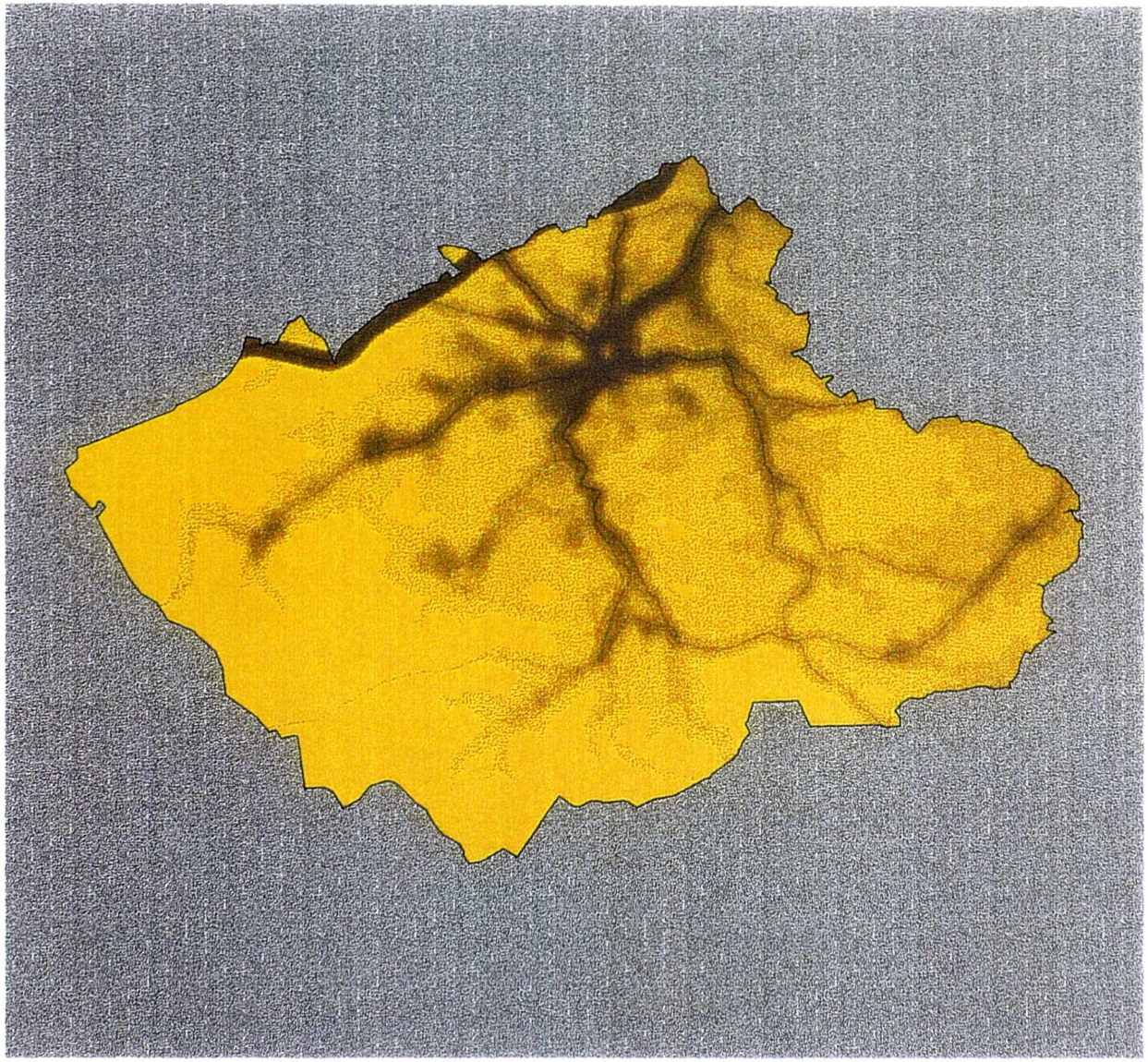


Figure 7.9 Regression map of NO2 concentrations, Survey 2.

for survey S_2 indicates a more concentrated pollution gradient than the other maps, with levels changing rapidly over a short distance.

Survey S_3 (Figure 7.10) shows broadly similar pattern of pollution to survey S_2, with the highest concentrations again associated with the motorway (M62), the Sheffield road (A616) and the town centre. An area in the south-east associated with Denby Dale and Skelmanthorpe also indicated concentrations which were higher than the surrounding area. On the whole, however, the range of pollution values and the gradient between the 'highly polluted' and 'non polluted' areas are much lower than for all other maps. Again, the lowest concentrations are found in the south-west.

The pollution map for survey S_4 (Figure 7.11) again displays a similar pattern of pollution to that of survey S_2. The villages of Denby Dale and Skelmanthorpe are again noticeable as pollution hotspots (concentrations of 50-60 $\mu g/m^3$ compared to concentrations in the surrounding area of 20 to 30 $\mu g/m^3$). Interestingly, although in comparison to the major urban areas, pollution levels associated with the A640 Buckstones road in the north-west of the study area are low compared to the major urban areas, there is a clearly defined pollution corridor allied with the A640 which is not obvious on the other three maps (Figures 7.9 - 7.12).

The annual mean pollution map (Figure 7.12) again displays similar pollution patterns. Areas of pollution which were high in the previous maps are also high in the annual pollution map. A similar pattern emerges for areas of low pollution.

The regression model used in the creation of the maps allows the generation of high resolution pollution maps, as Figure 7.13, an enlargement of the

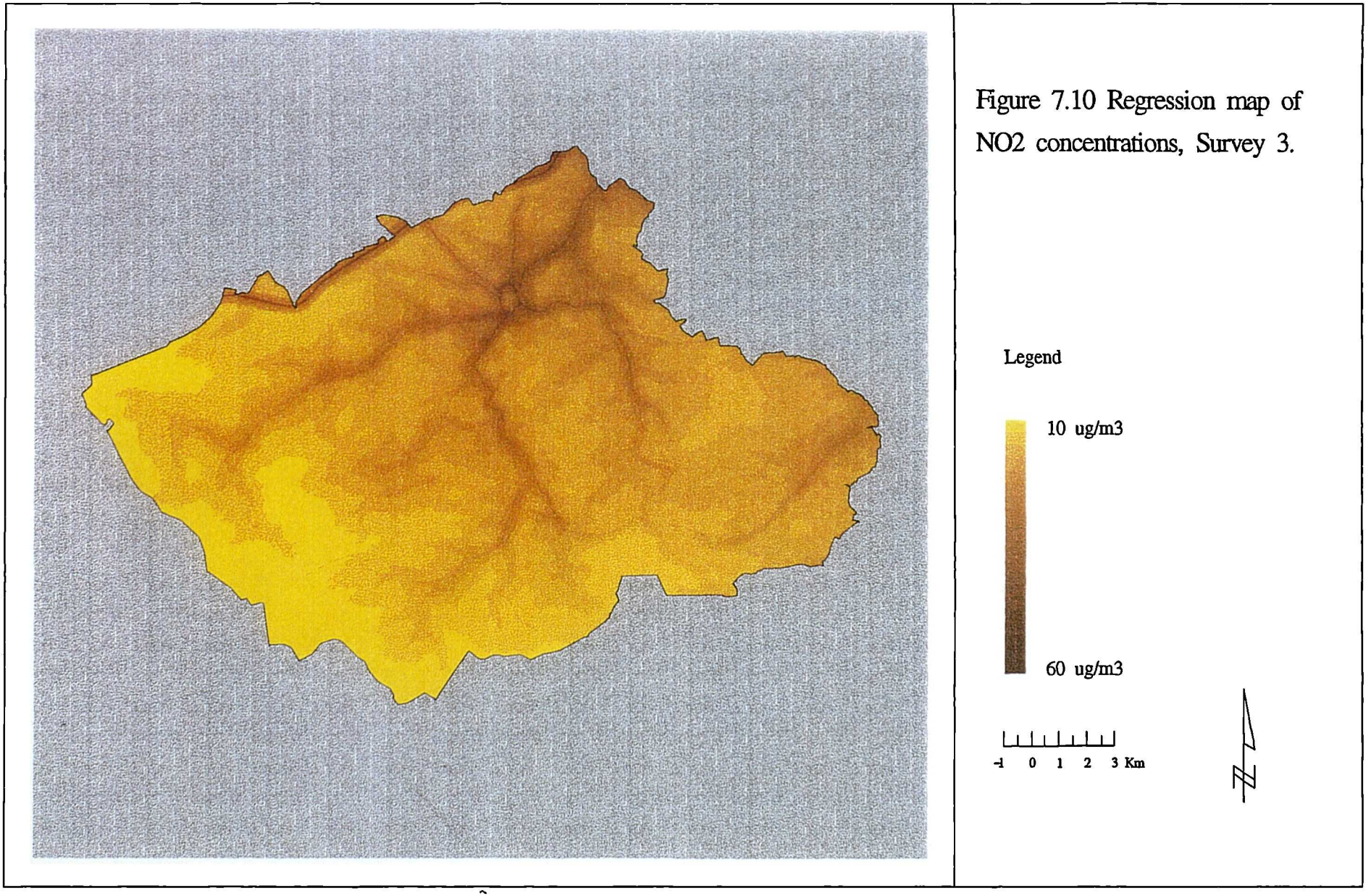


Figure 7.10 Regression map of NO2 concentrations, Survey 3.

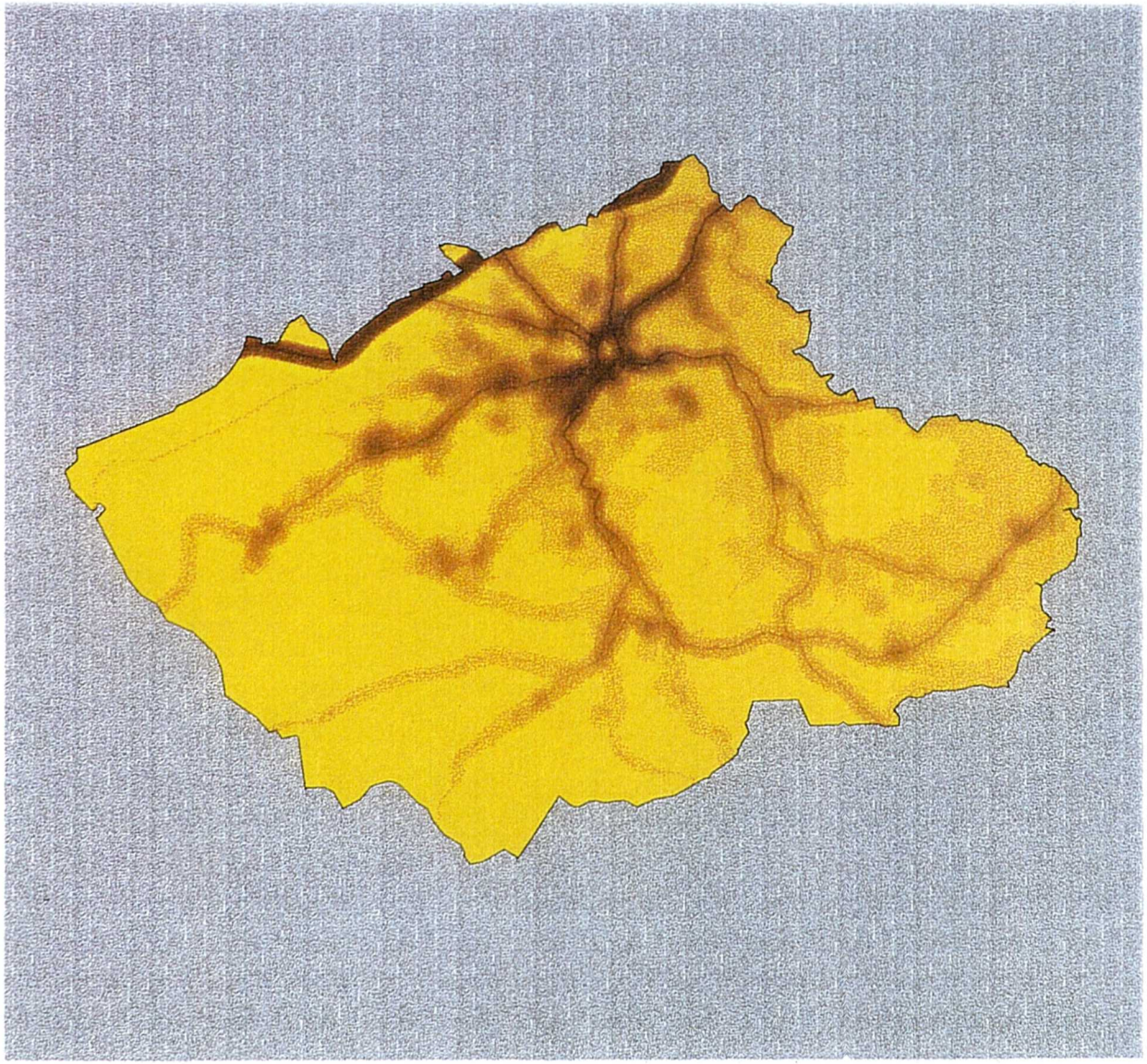


Figure 7.11 Regression map of NO2 concentrations, Survey 4.

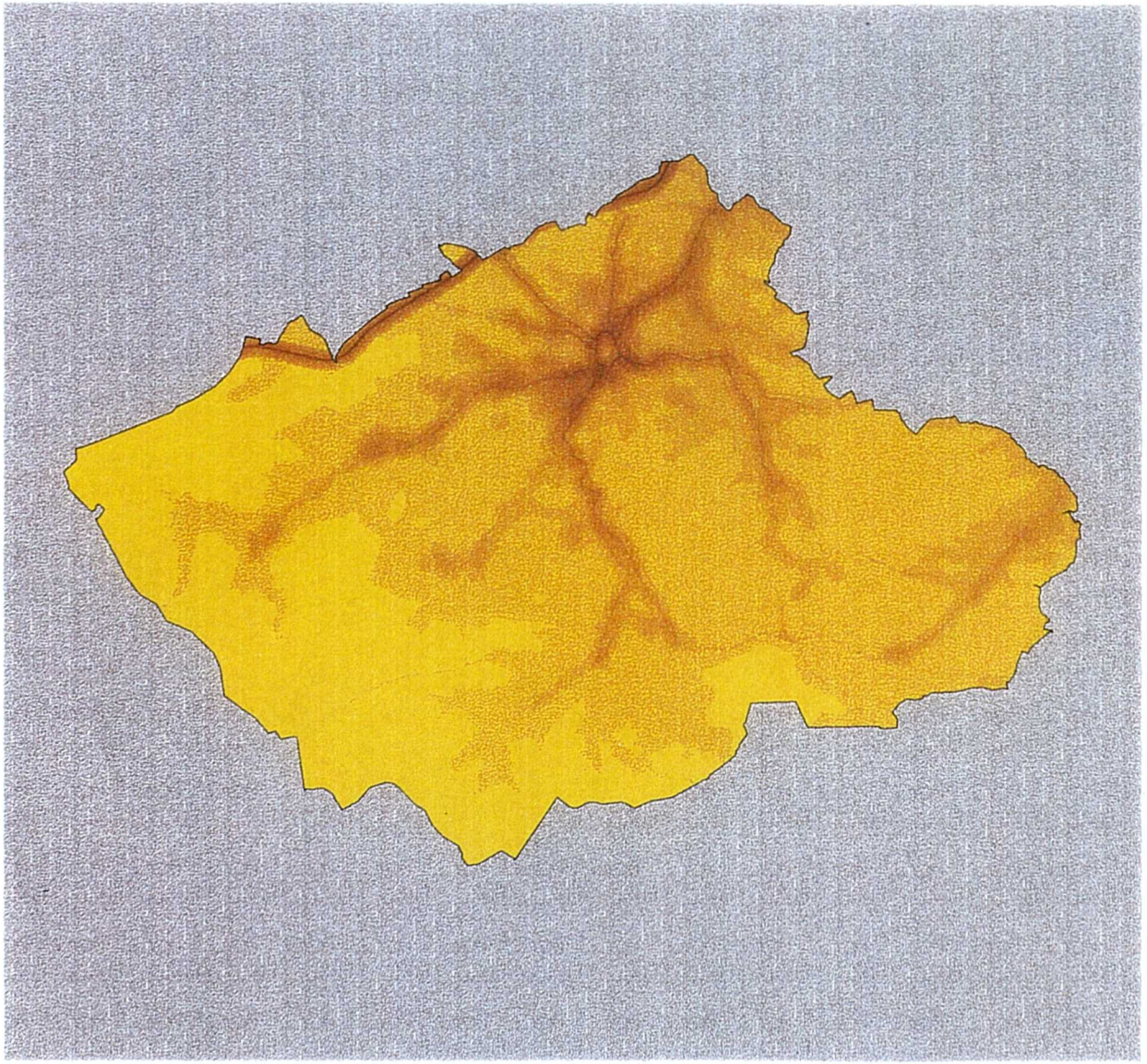


Figure 7.12 Regression map of NO2 concentrations, Annual Mean.

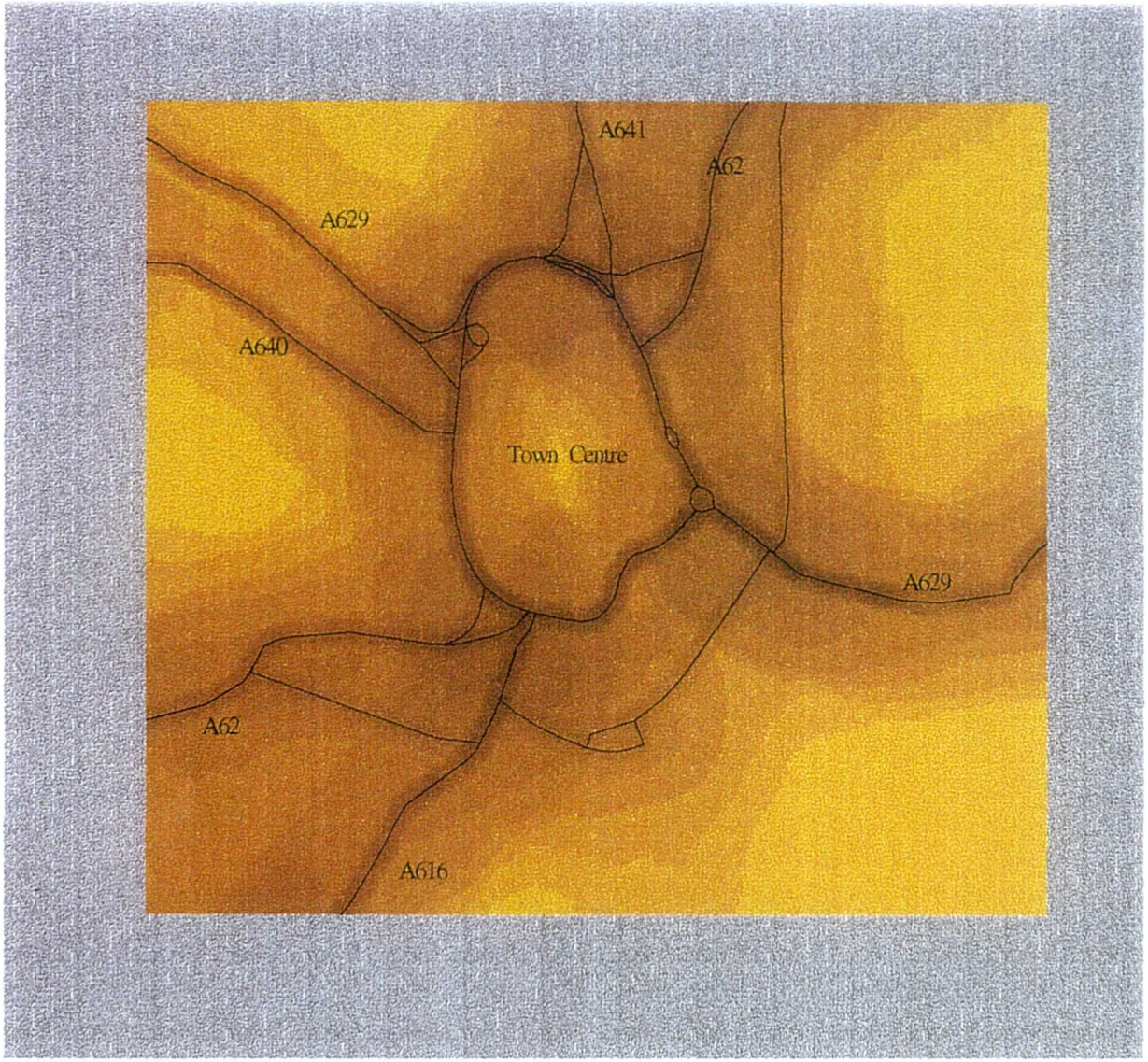


Figure 7.13 Regression map of NO2 concentrations in Hudders–field Centre, Survey 2.

Legend

30 ug/m3

90

-1 0 1 2 3 Km

Huddersfield town centre, illustrates. Notably, even at this scale, considerable variations in pollution levels are visible, reflecting the local variations recorded by Loxen and Noordally (1988) and Hewitt (1991) in detailed studies of small areas. The effect of traffic volume on the maps can also be seen, with the Leeds road (A62) and the Sheffield road (A616) showing much higher levels of NO_2 than the Halifax road (A629) and New Hey Road (A640).

7.7 VALIDATION

The results of the regression mapping were validated against independent data. Subsets of the NO_2 data had previously been withheld from the creation of the model for this purpose (section 4.1). A testing regime was devised to evaluate the capability of the maps to predict actual levels during three different survey periods: concurrent with the modelled period (within-period testing), prior to the modelled period (pre-period testing) and following the survey period (post-period testing).

7.7.1 WITHIN-PERIOD TESTING

From the three individual surveys, NO_2 data from 40 variable and 8 consecutive sites had been reserved for testing and validation purposes. The location and unique identification number (site-id number) of all the sites (the 40 and the 8 sites) were input into the data base and transferred into the GIS.

Comparisons were made between:

- the monitored values at the 40 variable sites for each survey period (S_2, S_3, S_4) predicted from the map for that survey;
- the monitored values at the 40 variable sites for each survey period and the mean annual map;
- the monitored values at the 8 consecutive sites for each survey period and the values predicted from the map for that period;
- the mean concentration for the 8 consecutive sites and the mean annual map.

Results of the analysis are shown in Table 7.7 (see page 212) and Figure 7.14 to 7.25.

7.7.1.1 WITHIN-PERIOD TESTING: VARIABLE SITES

From these results it appears that, on the whole, the maps are a good predictor of monitored NO_2 concentrations for the within-time-period. The 40 variable sites from the third survey (S_3) achieved an R^2 value for the individual map of 35.0 per cent and 44.3 per cent for the annual modelled mean map (M_m). These figures compare favourably with the R^2 values of 38.7 per cent and 56.5 per cent for the individual and modelled mean map derived from the regression equations developed in Section 7.5.1. The results indicate that both the individual survey map and the annual modelled mean map are good predictors of pollution for the 40 variables sites monitored in survey S_3. This can be seen in graphical form in Figures 7.16 and 7.17 and in tabular form in Table 7.7. The slope value for the analysis of both maps was similar (1.42 and 1.37 respectively), reflecting the tendency for the pollution map to overpredict actual pollution levels at the higher concentrations in both cases.

Figure 7.14 Relationship Between Predicted and Observed NO2

For Variable sites in Survey S2

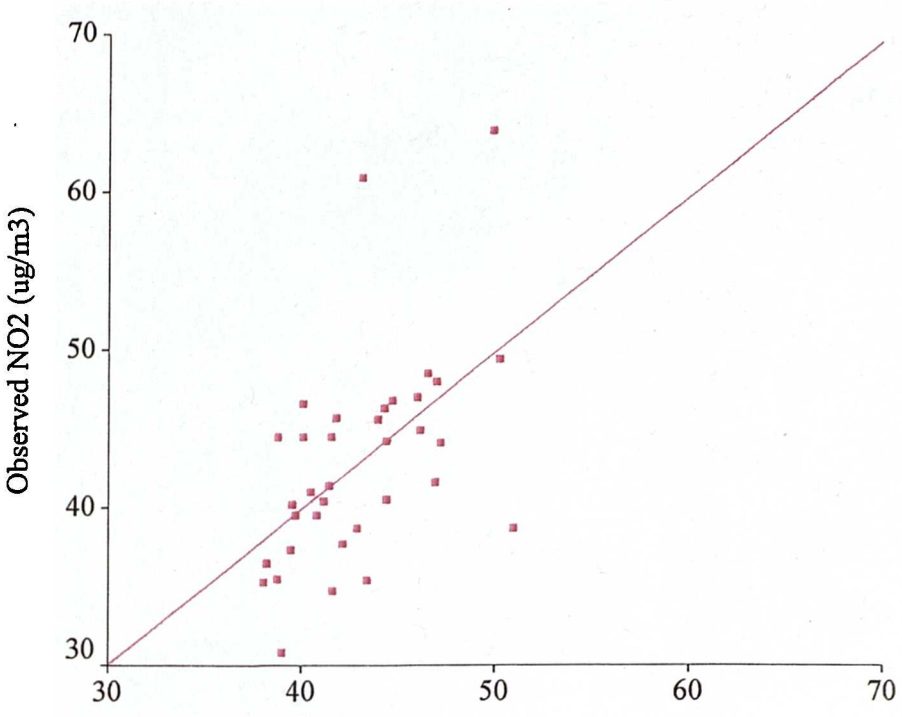


Figure 7.15 Relationship Between Observed and Predicted

Annual Mean NO2 Values For Variable Sites in Survey S2

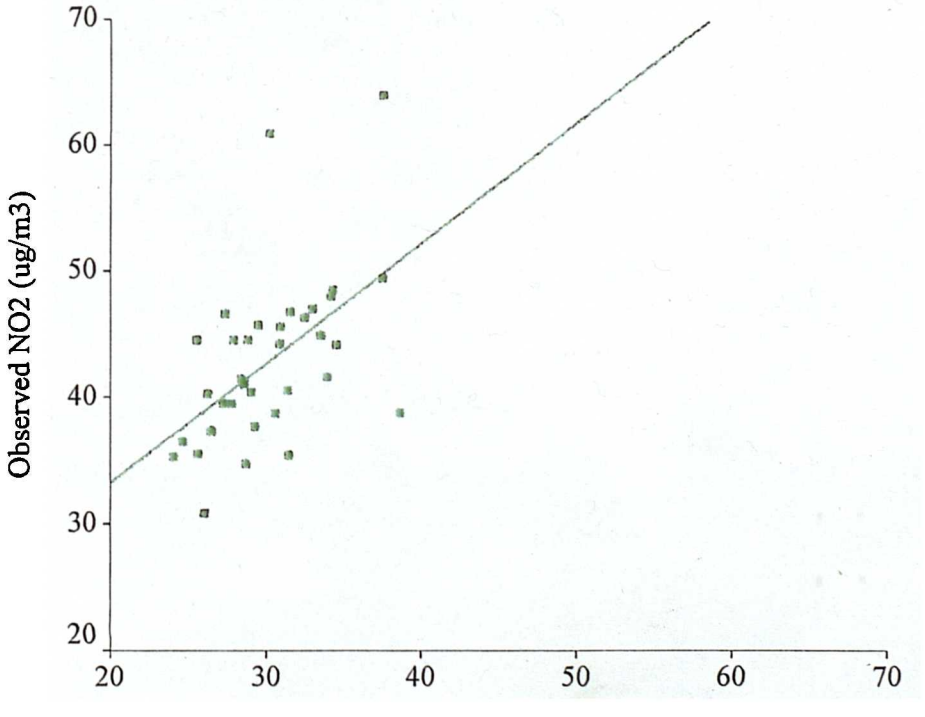


Figure 7.16 Relationship Between Observed and Predicted NO2 Values For Variable Sites in Survey S3

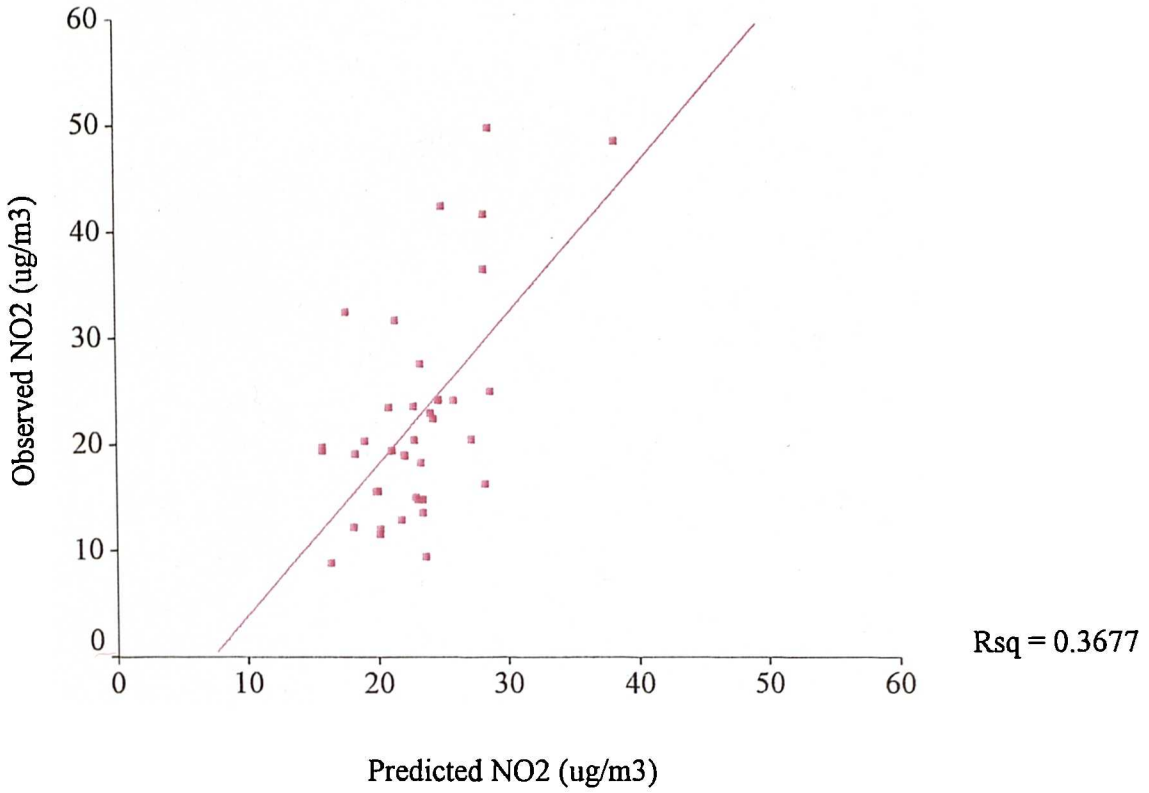


Figure 7.17 Relationship Between Observed and Predicted Annual Mean NO2 Values For Variable Sites in Survey S3

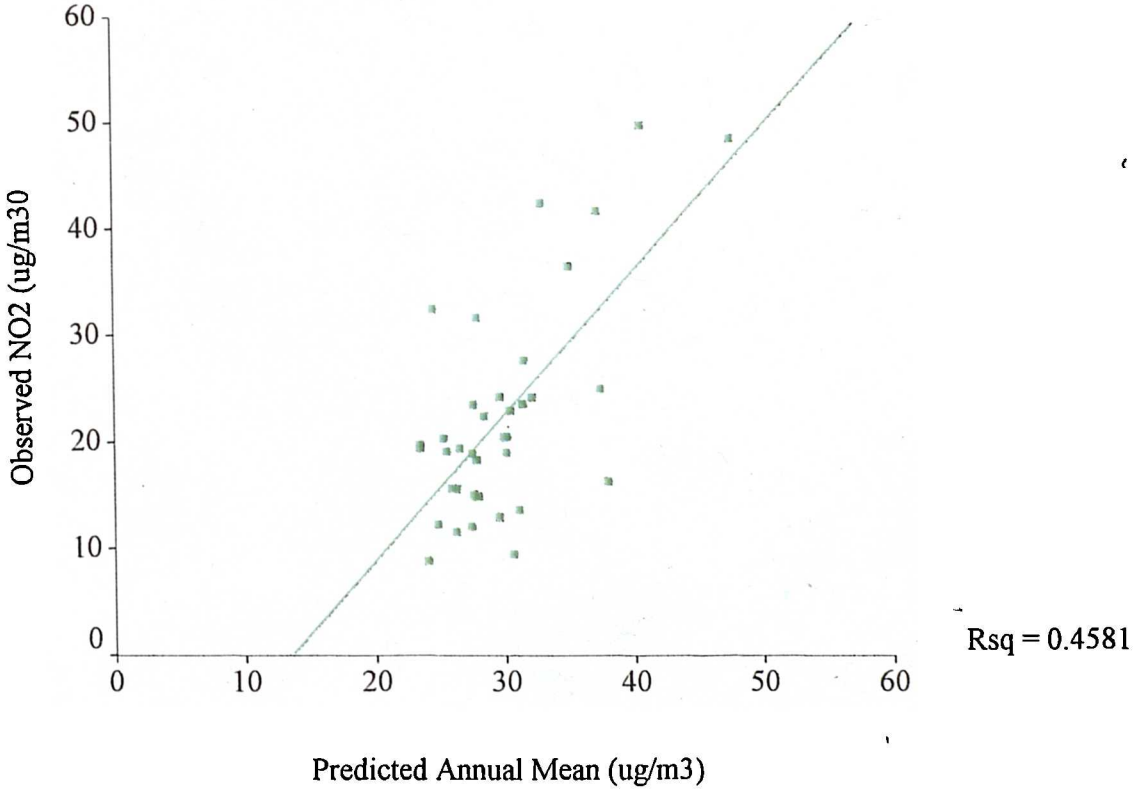


Figure 7.18 Relationship Between Observed and Predicted NO2 Values For Variable Sites in Survey S4

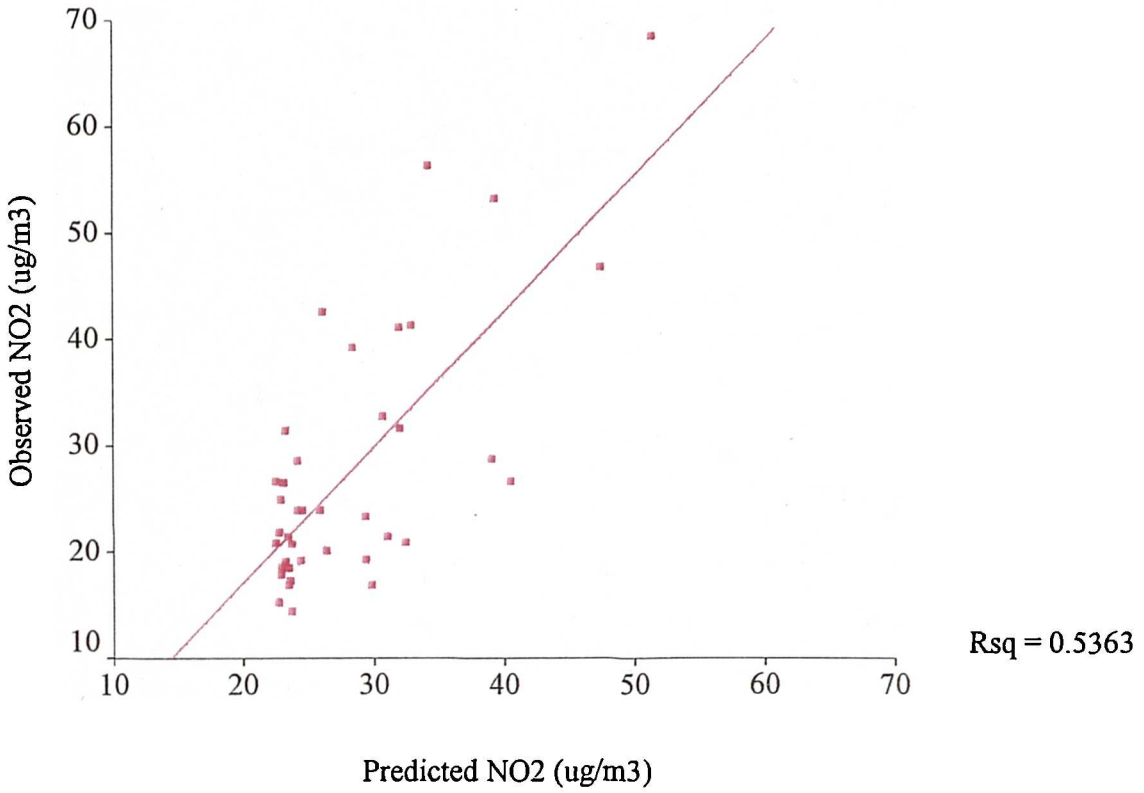
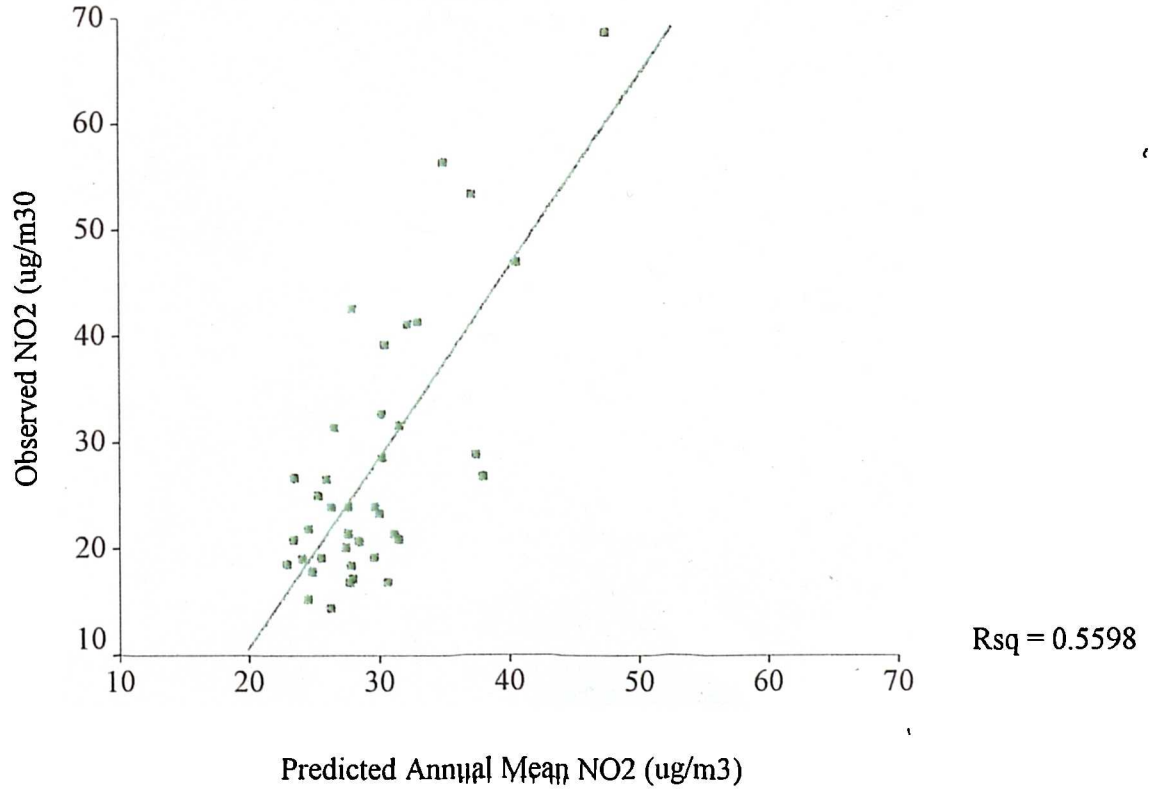


Figure 7.19 Relationship Between Observed and Predicted Annual Mean NO2 Values For Variable Sites in Survey S4



A similar picture was observed from survey S_4. Results showed increased R^2 values of 52.4 per cent (S_4) and 54.8 per cent (M_m) (compared with an R^2 value of 55.0 per cent derived from the equations in Section 7.4.1) indicating that the map gave good predictions for the variable sites (Figure 7.18 and 7.19). The slope values were also similar to those obtained in survey S_3 (1.28 and 1.8 respectively).

For survey S_2, results from both the individual and the annual pollution maps gave an R^2 value of only 25.7 per cent (expected R^2 value, 38.7 per cent) Again this distribution is represented graphically in Figures 7.14 and 7.15. When the slope values are examined, both graphs showed a slope of close to unity: B = 0.99 for the individual maps and 0.804 for the mean annual map. Although the fit to the observed data is poorer in this survey, overall, the maps again imply some consistency between the predicted and measured concentrations.

7.7.1.2 Within-Period Testing: Consecutive Sites

Results from the analysis of the consecutive sites (8 sites) for survey S_2 produced a high R^2 value. The R^2 value for the individual map was 72.9 per cent, while an R^2 value of 74.8 per cent was recorded for the annual map. This is represented graphically in Figures 7.20 and 7.21. The slope values are again close to unity, 1.14 (S_2) and 1.06 (M_m). For survey S_3, again, the results from the analysis of the consecutive sites was higher than results from the variable sites (Figure 7.22 and 7.23). The R^2 value for the individual map was 74.3 per cent (B value of 1.08) and for the annual pollution map 55.5 per cent (B value of 0.87). Results from survey S_4 also showed high levels of correlation, with R^2 values of 69.0 per cent for the individual survey and 82.0 per cent for the annual pollution map (Figure 7.24 and 7.25). However, slope values for this survey were 1.52 for the individual map and 2.15 for the annual pollution map, indicating a tendency to

Figure 7.20 Relationship Between Observed and Predicted NO2 Values For Consecutive Sites in Survey S2

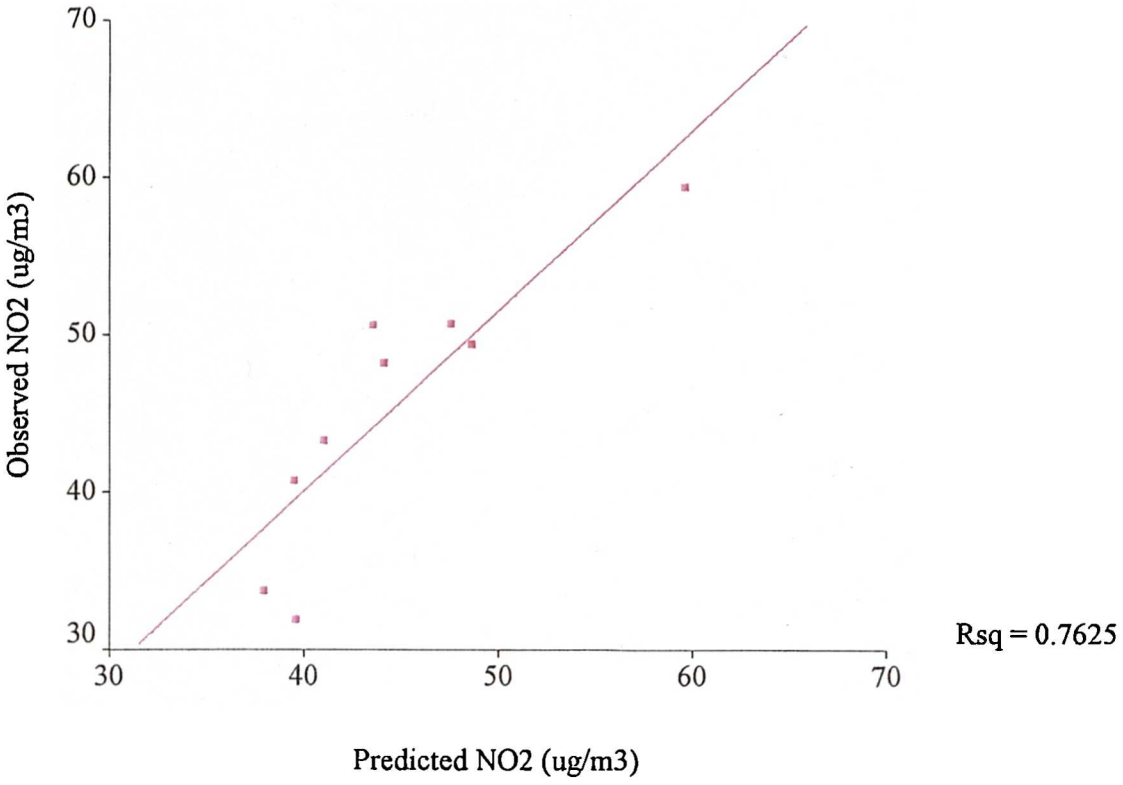


Figure 7.21 Relationship Between Observed and Predicted Annual Mean NO2 Values For Consecutive Sites in Survey S2

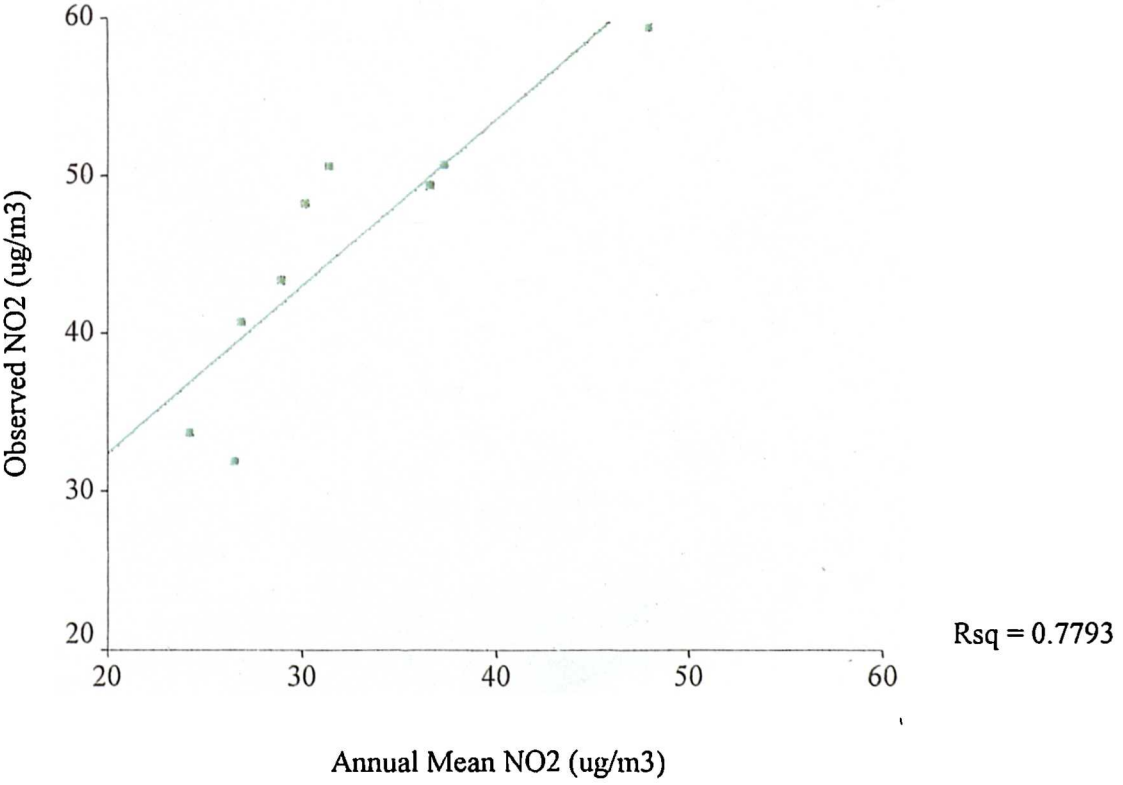


Figure 7.22 Relationship Between Observed and Predicted NO2 values For Variable Sites in Survey S3

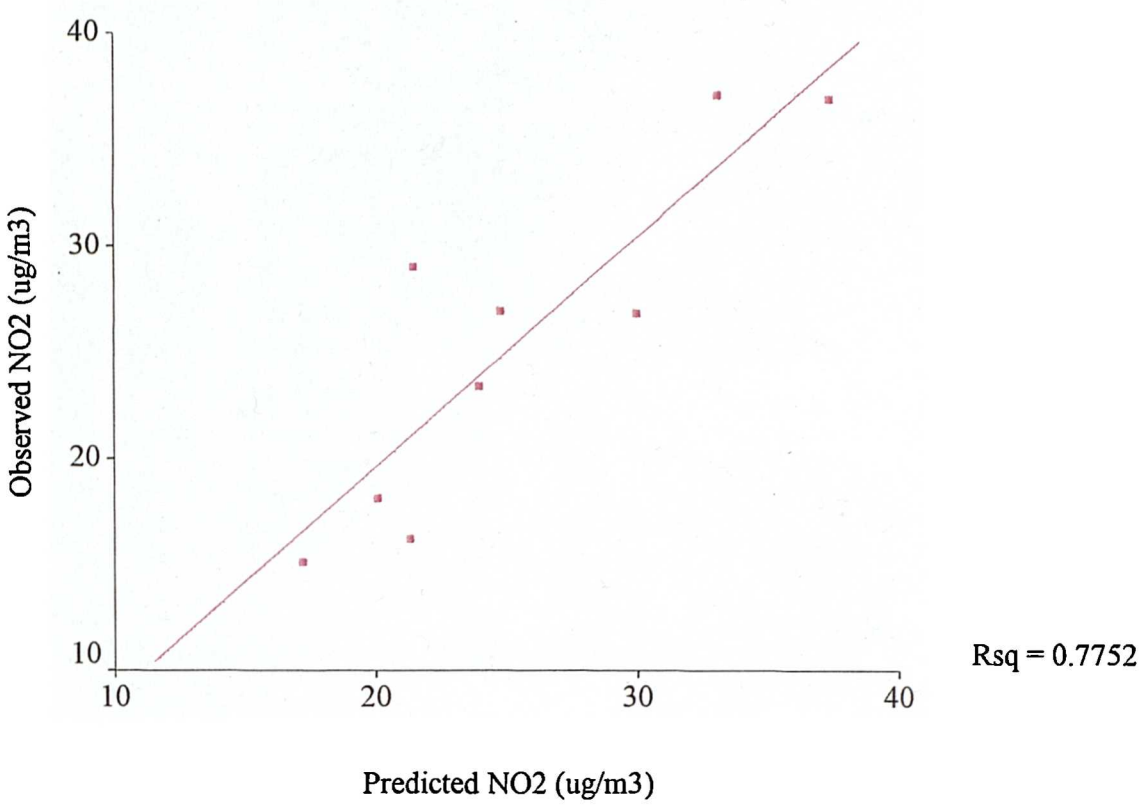


Figure 7.23 Relationship Between *Observed and Predicted* Annual Mean NO2 values For Consecutive Sites in Survey S3

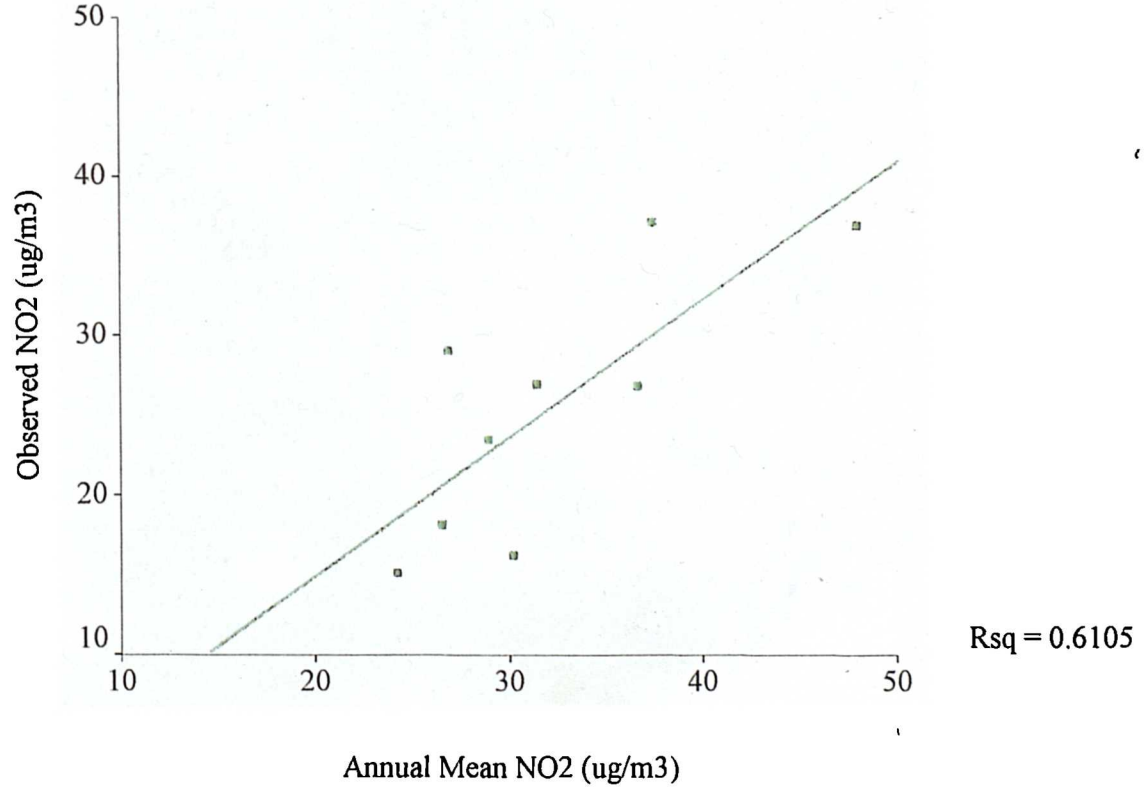


Figure 7.24 Relationship Between Observed and Predicted NO2 values For Variable Sites in Survey S4

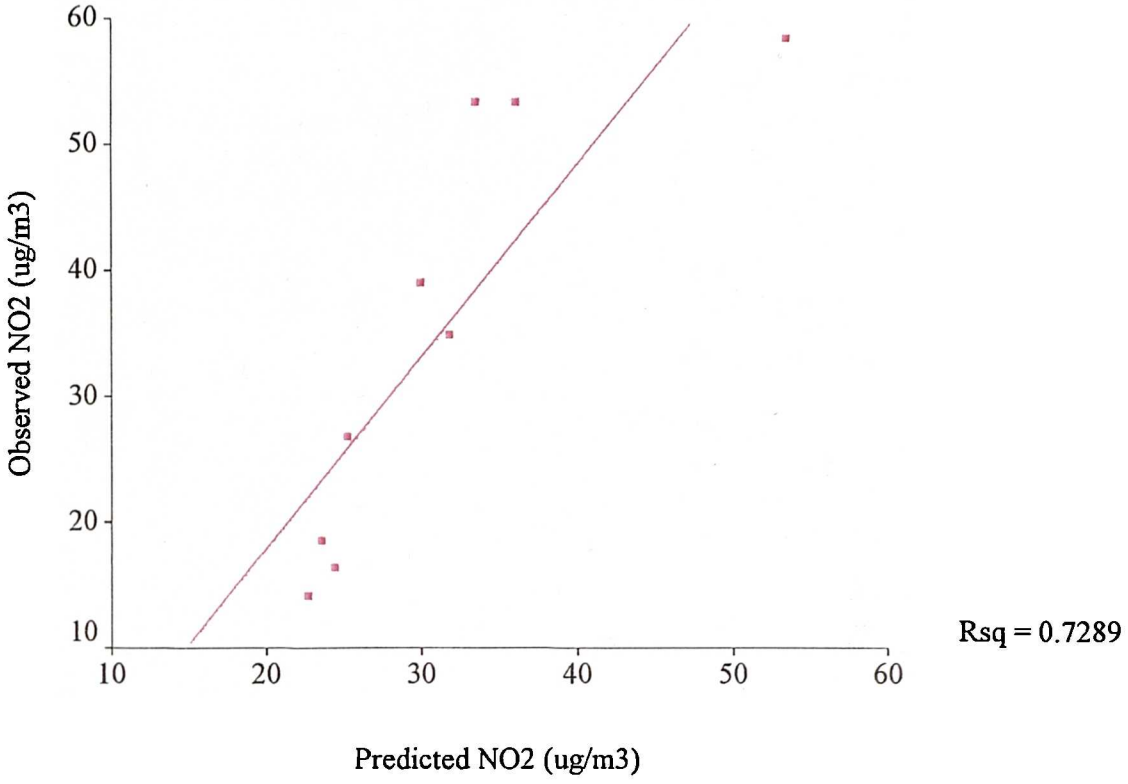
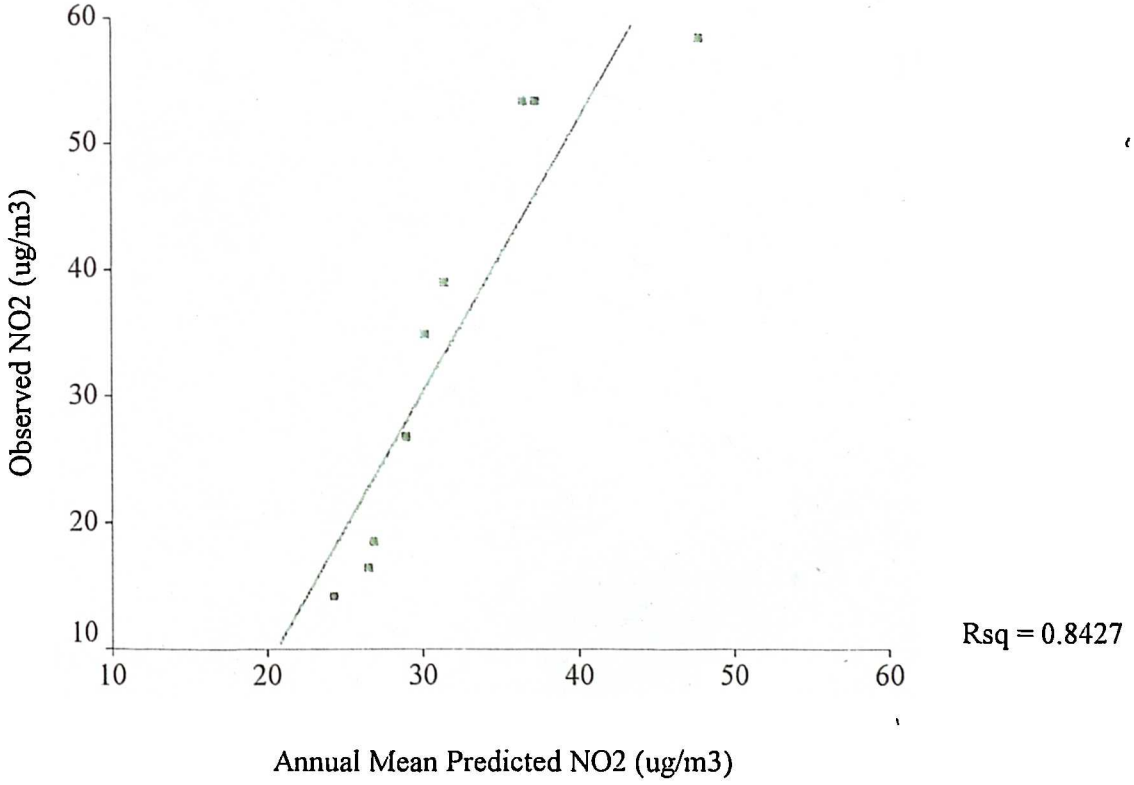


Figure 7.25 Relationship Between Observed and Predicted Annual Mean NO2 values For Consecutive Sites in Survey S4



over-predict at lower concentrations and under-predict at high concentrations. Overall, therefore, results from the consecutive sites appeared to indicate that they were representative of pollution levels in the study area and that the regression maps performs well.

7.7.2 TEMPORAL (ANNUAL) DATA

Data was obtained from 28 sites monitored by Kirklees MC using consecutive diffusion tubes. The location of the Kirklees monitoring sites was identified and those on the edge or outside the study area were labelled as such and initially discarded leaving 15 sites in total. The process of intersection, described in section 7.4, was undertaken. In the first instance each of the sites within the study area were intersected with the annual modelled mean pollution map. Regression analysis was used to compare the monitored and predicted concentrations. This process was repeated using both the 15 sites inside the study area and those remaining Kirklees sites previously considered on the boundary of the study area (total of 21 sites). (The validity of the results of these sites was questionable as the maps edge effects were unknown). The results of the analysis are shown in Table 7.8.

Results from this analysis appear to indicate that a relationship exists between the annual pollution map (M_m) and the data obtained from Kirklees MC. The analysis conducted on *all sites* (21 sites in total) and only those sites within the study area (*selected sites*) (15 sites in total), gave an R^2 value of 33.9 per cent and 31.5 per cent respectively. In interpreting these results, it is important to note that the Kirklees sample sites were, in most cases, deliberately positioned in areas of high pollution in order to fulfil local government policy. They thus show less spatial variation in pollution levels than the other data sets used. In

this context, the results again imply that the regression maps give a satisfactory prediction of pollution levels recorded by the Kirklees MC sites.

7.7.3 Pre-Period Testing

Two surveys, (S_A and S_B) were conducted prior to the collection of data used in the formation of the equations. These surveys were used to examine whether the regression maps accurately predicted pre-survey pollution levels, and thus whether the pollution map is stable over time. Again the LATTICESPOT command was used within the GIS to intersect the location of each of the sample points from the two surveys with the annual mean estimated pollution map. The resultant estimated concentrations were regressed against the monitored NO_2 values by site. Results are summarised in Table 7.9 and Figure 7.26 and 7.27.

The results show that R^2 values are somewhat lower that those obtained for the survey period, suggesting that the mean annual pollution map does not provide such a good predictor of past pollution levels. The R^2 value for survey S_A (June 1992), however, was 39.7 per cent and the slope value was close to unity (1.01), indicating a satisfactory prediction. The same could not be said of survey S_B (March 1993): for this survey, the annual modelled mean pollution map gave an R^2 value of 14.9 per cent. The slope value was also low (0.61). For this survey, therefore, the annual mean modelled map for 1993-1994 does not provide a satisfactory estimate of pollution levels.

7.7.4 Post Period Testing

A further test of the temporal predictivity of the regression map, and the stability of the map over time, a post-period survey was conducted in July 1994 (S_5).

Figure 7.26 Relationship Between Observed and Predicted NO2

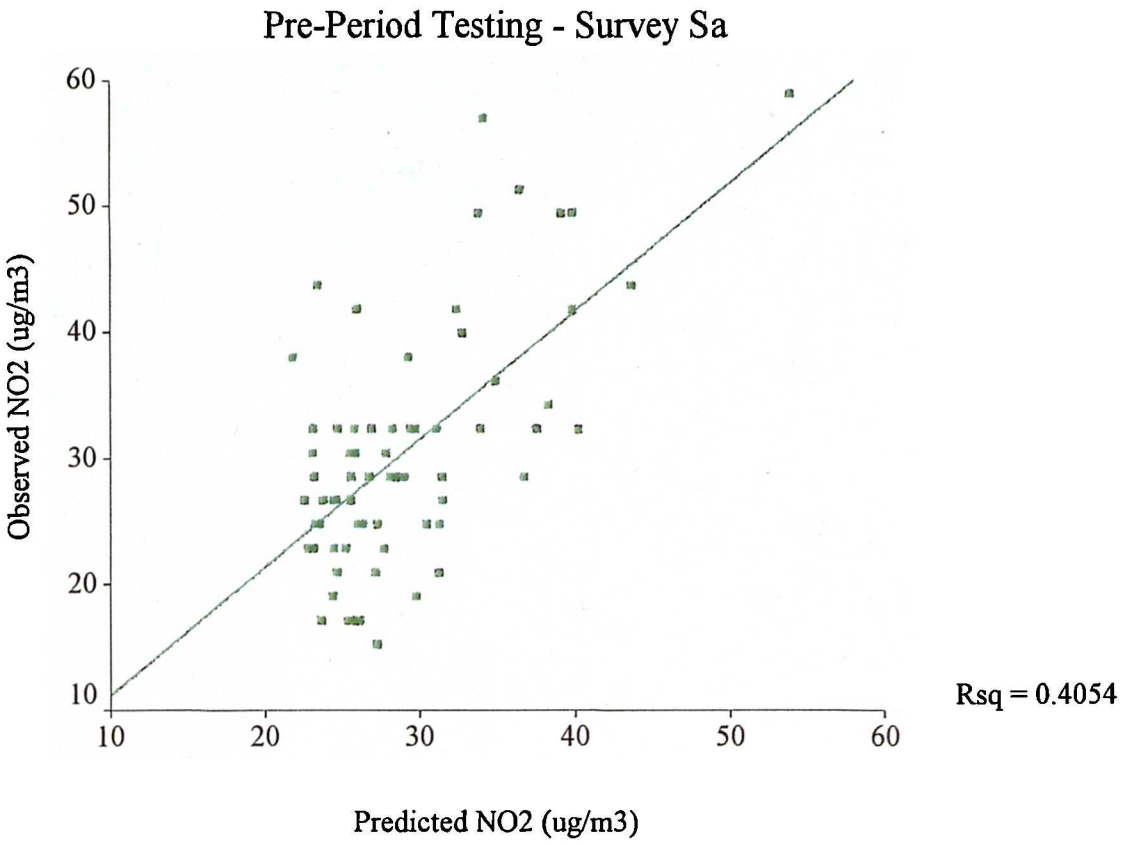


Figure 7.27 Relationship Between Observed and Predicted NO2

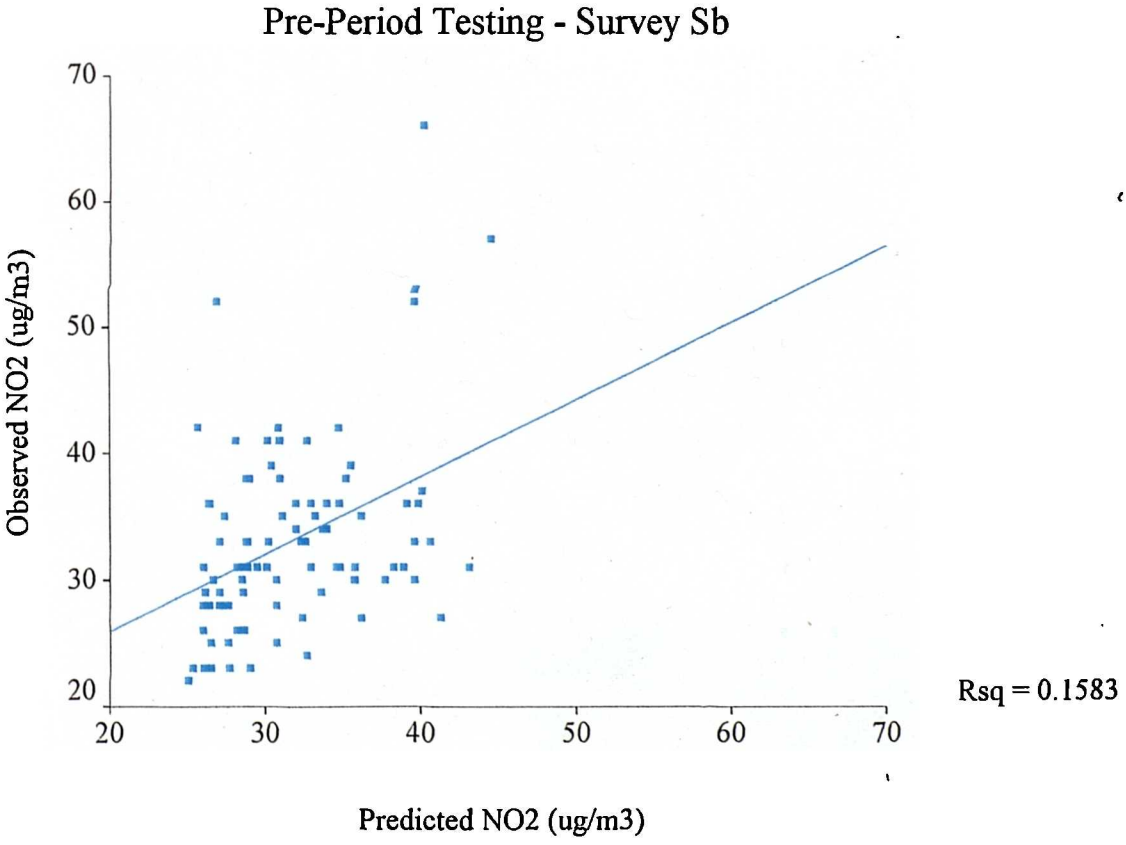


Table 7.7 Regression analysis results of the within-period testing

Survey Name	Dependent Variable	Independent Variable	Number of Sites	Degrees of Freedom	Slope Value B	Adjusted R^2	Constant	Significance Value
Survey 2	Actual NO_2 values	Estimated S_2 NO_2 values	40	33/1	0.98849	25.627	0.35167	0.0011
	Actual NO_2 values	Estimated M_m NO_2 values	40	33/1	0.80385	25.718	14.34438	0.0011
	Actual NO_2 values	Estimated S_2 NO_2 values	10	7/1	1.14257	72.854	-5.68271	0.0021
	Actual NO_2 values	Estimated M_m NO_2 values	10	7/1	1.06023	74.781	11.19516	0.0016
Survey 3	Actual NO_2 values	Estimated S_3 NO_2 values	40	36/1	1.41652	35.014	-10.29183	0.0001
	Actual NO_2 values	Estimated M_m NO_2 values	40	36/1	1.37088	44.309	-18.54073	0.0000
	Actual NO_2 values	Estimated S_3 NO_2 values	10	7/1	1.08428	74.311	-2.10276	0.0017
	Actual NO_2 values	Estimated M_m NO_2 values	10	7/1	0.87067	55.484	-2.52545	0.0129
Survey 4	Actual NO_2 values	Estimated S_4 NO_2 values	40	37/1	1.27887	52.374	-8.51994	0.0000
	Actual NO_2 values	Estimated M_m NO_2 values	40	37/1	1.79608	54.792	-25.21311	0.0000
	Actual NO_2 values	Estimated S_4 NO_2 values	10	7/1	1.52338	69.015	-12.53994	0.0034
	Actual NO_2 values	Estimated M_m NO_2 values	10	7/1	2.15134	82.022	-34.25938	0.0005
Annual Estimated	Annual Actual NO_2 values	Estimated M_m NO_2 values	10	7/1	1.14684	76.272	-3.63507	0.0013

Table 7.8 Results of temporal testing

Survey Name	Dependent Variable	Independent Variable	Number of Sites	Degrees of Freedom	Slope Value B	Adjusted R^2	Constant	Significance Value
K_s (All Sites)	Actual NO_2 values	Estimated M_m NO_2 values	21	1/20	0.06428	33.9	49.38493	0.5834
K_s(Selected Sites)	Actual NO_2 values	Estimated M_m NO_2 values	15	1/14	0.05132	31.5	27.60135	

Table 7.9 Results of pre-period testing

Survey Name	Dependent Variable	Independent Variable	Number of Sites	Degrees of Freedom	Slope Value B	Adjusted R^2	Constant	Significance Value
Survey A (June 1992)	Actual NO_2 values	Estimated M_m NO_2 values	67	66/1	1.01331	39.64	1.07680	0.0000
Survey B (March 1993)	Actual NO_2 values	Estimated M_m NO_2 values	93	92/1	0.61173	14.91	13.63950	0.0001

This survey was also designed to provide some indication of NO_2 levels at the boundary of the study area. Consequently two sets of analyses were carried out: on all sites in the survey area, (total number of sites 42), and secondly, on only those sites within the original study area (total number of sites 32). This allowed an examination of the ability of the model both to predict temporal variation within the study area, and to predict concentrations outside the study area. Again, within the GIS, the LATTICESPOT command was used to intersect the location of each sample site with the annual pollution map. The resultant estimated concentrations were regressed against the monitored NO_2 data by site (Table 7.10).

Table 7.10 Results of post-period testing

Survey Name	Dependent Variable	Independent Variable	Number of Sites	D.F	Slope Value	Adjusted R^2	Constant
Survey 5 (ALL SITES)	Actual NO_2 values	Estimated M_M NO_2 values	42	37/1	1.59465	45.245	22.03702
Survey 5 (ORIGINAL SITES)	Actual NO_2 values	Estimated M_M NO_2 values	32	30/1	1.61746	45.188	22.96051

The results indicate that for survey S_5, like survey S_A, the equation predicts NO_2 concentrations to an acceptable level of accuracy. The R^2 values for both the original sites and all sites was 45.2 per cent. This suggests that the pollution map was stable and can be applied to subsequent years with a high degree of confidence. It also suggests that the model can be applied outside the initial study area, without deterioration in performance. The slope values (B), however, show some departure from unity (1.59 and 1.62 respectively), thus indicating that, while the pattern of pollution remains broadly similar over time, the absolute concentrations vary.

7.8. CONCLUSION

On the basis of the results presented here, it appears that the regression model provides a relatively accurate and reliable map of air pollution within the study area. The regression model appears to be able to predict both forward and backwards in time with comparative confidence. Further monitoring in the study area, during which 20 sites were monitored over a 21 consecutive period (October 1994 to September 1995) confirmed that the predictive performance of the pollution map was maintained. The R^2 value for the relationship between mapped and monitored concentrations was 0.59, with a slope of approximately 1.5. Subsequent research (de Hoogh *pers comm.*) has also shown that the model developed here can be applied, without modification, in other urban areas, with similar levels of success.

Within the time and resource constraints of a rapid survey (i.e. a 2 to 4 week time period), therefore, it may be concluded that the regression approach offers a practical and effective method of mapping urban air pollution. Certainly compared to the dispersion modelling approaches outlined in chapter 6, it appears that the regression approach performs satisfactorily in the Huddersfield area. Nevertheless, improvements in the regression method are no doubt possible. Improved indicators of traffic emissions may be obtainable, for example, given better data on traffic volume and composition. Better indicators of the effects of urban morphology and land use may also be possible, which would reflect the effects on dispersion patterns. Above all, it would be interesting to include in the model temporal indicators (e.g. season, wind speed, etc) which would allow more specific estimates to be made for particular survey periods and conditions. These and other implications and developments of the methodology are discussed in the next chapter.

Further modification to this model may be undertaken in an attempt to increase its accuracy, for example, by further investigating the effects of weather patterns on pollution variation. In terms of this project however, such modification were thought to complicate

the modelling procedure further, thus reducing the possible uses of this model by non-scientific personnel and were also limited due to time constraints. The value of this model is discussed in more detail in the following chapter.

8 *DISCUSSION*

> *"There has been a significant increase in the availability of monitored air pollution data in the UK in recent years with an increase in the number of monitoring sites and the range of pollutants measured. There is, however, still a requirement for maps of pollutant concentrations at a much higher spatial resolution than can be calculated by simple interpolation between monitoring sites"* (AEA 1997).

This statement indicates the continuous need for the development of accurate methods of calculation and mapping of air pollution, especially in urban environments. Moreover, the UK National Air Quality Strategy (DOE 1996) stipulates that areas of poor air quality should be identified through monitoring and modelling techniques and, where necessary, air quality management areas defined - something which is only possible by a method of interpolating from point data to create an air pollution map. In addition, increasing traffic volume and growing concern about the effects of traffic-related pollution on health reinforces the justification for this thesis, namely that there is a need to map traffic-related air pollution at the small area (urban) scale for use in a wide range of fields - from epidemiology to transport planning and the development of structure plans. This chapter will examine the extent to which the research has been successful in fulfilling the aims and objectives stated in Chapter 1, i.e:

- examination of the magnitude, source and patterns of small area variation in traffic-related air pollution in an urban environment, and thus building on such information to allow the;

- investigation of methods of mapping traffic-related air pollution at a small area level.

It will then consider the implications of the research for the wider body of users, both in other research areas and for management and policy and any contribution made to the understanding of variation in pollution levels at the small area level within the urban environment will be assessed.

8.1 THE STORY SO FAR

8.1.1 SOURCES OF VARIATION

Aim: to examine the magnitude, source and patterns of small area spatial variation in traffic-related pollution.

Patterns of variations in air pollution concentrations within the study area are complex and affected by both emission patterns and dispersion characteristics, on a spatial and temporal level. In addition, error propagated during laboratory and fieldwork procedures (measurement error) acts as a third possible influence on the patterns and magnitude of recorded variation in pollution concentrations.

To investigate the importance of these sources of variation, a number of purpose-designed surveys were conducted. Each survey was designed to investigate a particular facet of possible variation in air pollution. The influence of emission factors, including volume of road traffic and land cover type, on patterns of spatial variation in air pollution were considered. Equally, the dispersion characteristics of pollution were examined with surveys designed to investigate the amount of variation in pollution with distance to road, height above ground level and altitude. Inter-survey variations in pollution concentrations were also

assessed. The ability to define 'temporal affinity areas' in the study area was investigated and the relationship between spatio-temporal variation explored. Surveys were conducted using passive diffusion tubes deployed as required by the individual investigation (e.g. variation with distance from road was measured using transects perpendicular to the road; for variation with height diffusion tubes were placed at regular intervals up the side of buildings). A detailed description of the sampling regime and preliminary results of the analysis are given in Chapter 4. Results of the appropriate statistical analysis are given in Chapter 5.

Results of the analysis indicated that the effect of measurement error was small (accounting for only between 1.7 and 4.2 per cent of the total variation recorded in a survey), and could therefore be considered negligible. With regard to the spatial and temporal effect on pollution concentrations, however, a number of interesting patterns of variation in pollution levels were identified.

Results indicated that both traffic volume and distance from the nearest road (up to a distance of 60 metres) were good predictors of variation, although these accounted for only 54.6 and 55.9 per cent of the total measured variation respectively. Sampler height above ground also proved important in predicting urban air pollution and explained ca. 42 per cent of the recorded variation with height. Conversely, neither land cover type (examined in several different ways) nor altitude were perceived to be major determinants of air pollution levels, although both showed weak correlations with measured concentrations.

Temporal influences on patterns and magnitude of pollution concentrations were investigated in a variety of ways. Comparison between data from the 80 routine survey sites indicated that the pollution surface remained stable over time (Adj R^2 of between 57.5 to 70.0 per cent); thus while absolute pollution levels may

vary from one survey to another, the inter-site differences remain broadly the same.

The presence of temporal affinity areas for the study area, as developed by McGregor (1996) were investigated using pollution data which had been collected over a number of years by the local council (Kirklees M.C.) (See Chapter 4). Factor analysis was performed on the data and the results indicated that 92.4 per cent of the variation could be explained by using only three communal factors and that there was coherence between the land cover type of sites in the 3 factor groupings. This has considerable significance for the design of monitoring networks. It means that extrapolation from one site to the surrounding area should be valid within the affinity area of that site. On the other hand, extrapolation to sites in other affinity areas is likely to be misleading. It also suggests that, within any affinity area, the pollution map is broadly stable over time: whilst absolute concentrations may vary, the pattern of variation should remain largely the same. In this study, the large majority of the sites were seen to group into one affinity area, indicating that the pollution maps were thus stable over most of the study area.

Interactions between spatial and temporal influences were also considered using data from the 80 routine surveys. Results indicated that a large proportion of the recorded variation was attributed to spatial influences (ca. 89 per cent) while only ca. 9 per cent was due to temporal variation. Interestingly, 14.6 per cent of the total variation recorded (both explained and unexplained variation) was attributed to the interaction effect between both spatial and temporal variation, indicating that the effect of interactive spatio-temporal variation although relatively small in comparison to spatial variation alone should not be neglected.

From the results of the analysis, it is clear that the sources and patterns of variation are inherently complex and cannot be simply explained by examining

those factors which influence spatial and/or temporal variation in NO_2 concentrations individually. Any attempt at mapping variation in air pollution should allow for the effects of both spatial and temporal variation in emission sources and dispersion characteristics.

8.1.2 Dispersion Modelling

Aim: to investigate methods of mapping traffic-related air pollution at a small area level

The usefulness of dispersion models for air pollution mapping and management was highlighted in the recent UK National Air Quality Strategy (DOE 1997) which advised Local Authorities that, in auditing levels of air quality for compliance with UK government legislation,

> *"monitoring itself cannot provide all the information necessary to manage air quality effectively and efficiently"* and that *"numerical modelling is a powerful tool which aims to relate the emissions of a pollutant to the concentrations measured at an air quality monitoring station (DOE 1996)".*

The suggestion is thus that dispersion modelling should be used to provide additional information for the definition of air quality management areas. Several recent epidemiological studies have also attempted to use dispersion modelling as a basis for deriving exposure estimates (e.g. NILU 1991; Pershangen *et al.* 1994; Oosterlee *et al.* 1996).

The ability of these models to provide maps of air pollution across a wide area remains uncertain (see Section 2.3), and relatively few attempts have been made to test and validate these models under such conditions. Chapter 6 consequently investigated the extent to which dispersion models provide valid estimates of traffic-related pollution levels and, given the high degree of local variation noted

in the previous section, examined the capability of these models to predict and map urban pollution at the small area scale.

The study compared the performance of four dispersion models; DMRB, CAR-INTERNATIONAL, CALINE3 and CALINE4. A number of surveys were designed and conducted to provide NO_2 data for validation of the chosen models. The sampling strategy is explained in detail in Section 4.5.

Results of the preliminary analysis using a small number of sites for which real-time traffic-counts were available indicated that the less sophisticated models such as CAR-INTERNATIONAL and DMRB did not adequately explain variation in pollution (with R^2 values between predicted and monitored pollution levels of ca. 4.8 and 21.2 per cent respectively). Use of CALINE3, which allowed for meteorological data and topographical characteristics, improved the level of explanation (Adj R^2 = 40.2 per cent). The best performance, however, was achieved by the more sophisticated dispersion model, CALINE4, which allowed for the influences of meteorology, topology and photochemical reactions (Adj R^2 = 52.2 per cent). Based on these results, the entire A, B and motorway road network for the study area was modelled using the CALINE4 programme. Concentrations were calculated at receptor sites which matched the geographical location of the routine sample sites (see Chapter 4 for sampling design), thus allowing comparison of the modelled and monitored results to be undertaken. Under these conditions, CALINE4 performed markedly less well, explaining only 4.8 to 11.7 per cent of the total measured variation in NO_2 concentrations. The main reasons for this are likely to be both weaknesses in the model itself (e.g. its inability to cope with complex terrain) and errors and inadequacies in the input data (e.g. the use of estimated traffic flows and data from only two meteorological sites and one continuous monitoring site for ozone for the entire study area).

The ability of less sophisticated dispersion models for mapping variation in air pollution in an urban area thus appears to be poor, and their use for air pollution management systems or epidemiological studies is questionable. More sophisticated line dispersion models appear to perform better, so long as good quality input data (i.e. traffic volume, road wide, meteorological factors and surface roughness) is available. This requirement cannot always be met for urban-scale analysis and, in this case, it seems that these models, too, may not be reliable. Recent developments within the field of modelling, however, have seen the release of 'second generation' dispersion models. These have overcome a number of limitations associated with the Gaussian based models (e.g. replacement of emission factors with fuel efficiency factor; substitution of Gaussian plume equation with the buoyancy line plume). In addition, models such as UK ADMSURBAN can consider a combination of emission sources (point, line and area emissions) within one modelling package. These models have not yet been rigorously validated and are reliant on large amounts of input data and therefore were not considered for use in this thesis. Further validation of these models, using the type of data available in this study would be appropriate.

8.1.3 Regression Analysis

Aim: To investigate methods of mapping traffic-related air pollution at a small area scale.

The inability of dispersion models to provide a true representation of the variation observed in monitored pollution data at the small area level meant that an alternative method of mapping traffic-related air pollution was required. Regression analysis, used in a wide range of fields for descriptive and predictive purposes, has not been widely used for mapping purposes. A range of variables relating to emission sources and dispersion characteristics which best explained

variation in concentrations were selected (e.g. traffic volume and distance from road). Other variables related to field and desktop measurements for each site (e.g. RELREL and TOPEX). A full list of variables is given in Chapter 7. Regression analysis was conducted to identify those variables which best explained variation in pollution levels measured in the routine surveys (see Chapter 4). Once identified the selected variables were input into ARC/INFO GIS and regression analysis conducted for each 10m grid square for the entire study area. The resultant pollution surface was then compared to monitored data not used in the construction of the regression equation (i.e. 40 variable and 10 consecutive sites; pre-period surveys and a post-period survey), to assess the validity of the resultant maps.

Results of the analysis were divided into three time periods, pre-period testing, within-period testing and post-period testing. Comparison of within-period data from the variable and consecutive sites indicated that the regression method was able to explain between ca. 30 to 56 per cent of the variation in pollution concentrations. For the eight consecutive sites the level of explanation was between 61 and 84 per cent. Pre-period testing explained between 16 and 41 per cent of the measured variation in NO_2 concentrations. It should be noted that the lower result was obtained from a survey that was not designed specifically to provide good spatial coverage and therefore may be biased. Post-period testing again indicated that the regression method provided a good explanation of variation in NO_2 concentrations (adjusted R^2 = ca. 45 per cent). These results indicate that the regression model provides a relatively accurate and reliable map of air pollution for the study area which is able to predict both forwards and backwards in time – indicating a stable pollution surface. This agrees with results obtained from the temporal affinity area analysis and the inter-survey correlation (see Chapter 5).

The ability of the regression model to provide accurate and reliable maps of air pollution for a specific area using limited input data is an improvement on the dispersion modelling approach to pollution mapping. Much of the data required for the regression model is easily obtained from local structure plans held by the relevant Local Authority. Data on traffic flows and the road network can be obtained from the relevant Highways Authority and the Ordnance Survey respectively; information on altitude can similarly be obtained from the O/S equivalent sources if required. Indeed the requirement for each Local Authority to conduct a phase one assessment and review of air quality for their district as required by the UKNAQS (DOE 1996) means that much of the data on emission sources and land cover and traffic flows will be readily available. The simplicity of the model enables it to be used by a wide range of people in a variety of locations for numerous purposes. The use of such a mapping methodology will be examined in the following section.

8.2 PRESENT AND FUTURE OPPORTUNITIES

For a research project to be of value, it needs to make a useful contribution to the theoretical and/or applied research community and to the wider society as a whole. The critical evaluation of the project and specifically the results of the regression model detailed in the previous section pre-supposes an exploration of the possible uses of such research and naturally the investigation of further avenues of research.

The application of the results of this work and subsequent further areas of research can be subdivided into three overlapping but distinct areas: management strategy development, policy making and enforcement and research. In terms of

policy, significant developments in the field of air quality have occurred over the last year. In order to fulfil the requirements of the 1995 Environment Act, the Secretary of State was required to prepare and publish a national air quality strategy for public consultation. The subsequent consultation document was released in August 1996, with the revised document published in 1997 – although this is still to become a white paper and thus enforceable. The first stage of the national strategy requires all Local Authorities to conduct a review and assessment of air quality to highlight areas which are not expected to meet the 2005 air quality standards and designate them air quality management areas (AQMAs) (DoE 1997). The government tentatively suggests that dispersion modelling could be used to identify such areas and to undertake further investigation of these areas; the regression method of pollution mapping at the small area level, however, provides a better estimate of the dispersion and magnitude of pollution. Moreover, unlike the more sophisticated dispersion models (e.g. ADMS, CALINE4), the regression model does not require vast quantities of input data, nor detailed knowledge of dispersion modelling for operation. Compliance is also an important issue related to policy. The successful application of the regression model to other areas (de Hoogh *pers comm*) enables local and central government to ensure that legislation is being adhered to and also to ensure that standards set are achievable. It could even be used to enforce legislation in certain areas if necessary.

The management of air pollution and related issues could be enhanced by the use of the regression map. Air pollution is inherently linked, although not directly, to land use, and thus planning. Consequently, using the regression model, scenario modelling could be conducted to assess the impact of various ideas in the development of local structure plans and in the licensing of industrial processes (both process A and B's). Thus, it would be useful to both the Environment Agency and local government respectively. In addition, this approach could be beneficial in the development and preparation of Environmental Statements for

Environmental Impact Assessment (especially in the screening, scoping and mitigation stages). A further use of the regression approach could be within the field of health care. The model provides a simple and easy way of mapping pollution at the small area scale and thus of identifying 'hotspots' – this knowledge could then be used to concentrate epidemiological studies, health care provision, personal monitoring and abatement strategies in areas of greatest need.

Although useful in its present form as shown above, the research project has opened a number of avenues of unanswered questions and opportunities for further research. One of the most obvious questions to be answered relates to the monitoring strategy that is needed. For example, how many monitoring sites would be needed to maintain the pollution surface? - what quantity would be necessary to reflect variations on a seasonal or annual basis? In addition, it would be interesting to see if the regression approach could be transferred to other pollutants such as CO and PM_{10} – a useful adaptation given the expense of monitoring the latter pollutant.

The ability of the model to predict over long and short-term periods would also be a valid research question. Short-term predictions could be used to advise the public on their activities (as is currently done in Paris, France). Long-term predictions would enable the development of appropriate air quality management strategies at the local area instead of national level.

Examination of the variables used, and particularly the inclusion of a meteorological variable for predictive purposes, may lead to an increase in the accuracy and predictive ability of the model. The effect of introducing additional variables, not available at the time of this research – such as a detailed emissions inventory - would be interesting to investigate. Taking the opposite approach, it would be equally useful to investigate the ability of the regression approach to

map air quality in areas where air pollution is known to be a major problem, but which has poorer quality data and little or no resources to fund a monitoring program (e.g. Indonesia, India and Brazil all of whom have major urban air quality problem related to traffic).

Finally, the regression model to date has, out of necessity, concentrated on predicting traffic-related air pollution. It would be interesting to investigate how well this approach could be expanded to other air pollution sources, such as industry or to other types of pollution, such as noise.

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APPENDIX ONE

DESCRIPTION OF SITE MEASUREMENTS

SITE DESCRIPTION NOTES

For every sample site a site plan must be drawn and the following measurements recorded using the site record sheets.

1. **SITE ID** - The unique number/code used to identify this site

2. **SITE NAME/ADDRESS** - The street name or name of location used to identify the site location

3. **GEO-REFERENCE** - The grid reference (e.g. UTM or national grid reference) or geographic co-ordinates (latitude, longitude in degrees, minutes, seconds) of the site. This allows the exact location of the site to be identified. It should be split in to two separate fields, the first field containing the X co-ordinate or the latitude, the second field containing the Y co-ordinate or longitude. Please indicate in the space available the geo-referencing method used (e.g. Lat/Long; UTM)

4. **ALTITUDE** - Indicate the surface altitude (height above mean sea level of the ground) to the nearest 5m

5. **POLLUTANT(S)** - Indicate the pollutant(s) measured.

6. **SAMPLER TYPE(S)** - Indicate the type of sampler(s) used.
   T = Tube
   B= Badge
   C= Continuous monitors

7. **FIXTURE** - Indicate the fixture to which the sampler is attached.
   1 = Free Standing Post (i.e. street light, traffic sign, telegraph pole, cloths post)
   2 = Drainpipe on a building etc
   3 = Wall (eg. directly attached to a wall or window).
   4 = Tree
   5 = Other

8. **SAMPLER HEIGHT** - Record height of the sampler above ground level (in metres).

9. **LAND CLASS** - Indicate the land cover class which best describes the area in which the sample site lies (ca. 50m radius of the site). If two or more land cover classes are present the most dominant should be chosen. See appendix 1 for examples of site classifications.

10. **SOURCE TYPE** = Indicate the nearest known major point or line source(s) of pollution which may affect the site (e.g. motorway, road, chimney). All sources should where possible be indicated and numbered on the site plan.

11. **DISTANCE TO SOURCE** - Give the direct line distance (in metres) to the nearest known major point or line source(s)

12. **SLOPE ANGLE** - Give the slope angle (in degrees or percent) at the site for approximately 20m either side of the site. Indicate the units of measurement used, as appropriate.

13. **SLOPE DIRECTION** - Record the down-slope direction (in degrees) to the nearest 45^{o}.

14. **ASPECT** - Indicate the direction the sampler is facing in degrees (to the nearest 45^{o}).

15. **EXPOSURE VALUE** - This measurement will be used to give the topex value. At each site measure the angle to the horizon (in degrees) for the eight compass points (i.e. N, NW, W, SW, S, SE, E, NE). The horizon is defined in each case as the visible skyline (i.e. the ground level, top of buildings) except in cases of open or very irregular features such as hedgerows, trees etc where the mid-line of the feature should be taken as the horizon.

16. **TOPEX VALUE** - The topex value is an estimate of topographic exposure (i.e. openness) of the site. It is calculated using the following formula

$$T = 90 - \frac{\Sigma\alpha}{8}$$

Where: **T** is the TOPEX value
α is the angle to the horizon in degrees.

SITE DESCRIPTION FORM

SITE ID :_____

SITE NAME/ADDRESS: _____

GEO REFERENCE :(specify units) _____ **ALTITUDE** (m) _____

SAMPLER CHARACTERISTICS

POLLUTANT(S) MEASURED *Please ring as appropriate::*
NO2 SO2 Other (please specify):_____

SAMPLER TYPE(S) *Please ring as appropriate*
Badge Tube Other (please specify): _____

FIXTURE: *Please ring one*
Free Standing Post Drainpipe Building Tree
Other (please specify): _____

SAMPLER HEIGHT ABOVE GROUND (metres): _____

SITE CHARACTERISTICS

LAND CLASS *Please ring one*:

HDC	I	HRH	HD
LD	VLD	PI	UGS
R	RG	P	A
BT	CT	MT	Q
DL	M	PS	B

SOURCE TYPE / DISTANCE (m) *Indicate only sources which directly affect the site:*

Distance / Type	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6
Motorway (M)						
Road (R)						
Industry (I)						
Other (O)						

SLOPE ANGLE : _____ (% or degrees) **SLOPE DIRECTION :** _____

ASPECT (please ring one): N NW W SW S SE E NE

EXPOSURE: (degrees): *Complete the table below:*

N	NW	W	SW	S	SE	E	NE

TOPEX VALUE _____

For explanation, see SiteDescription Notes

APPENDIX TWO

SITE PLANS

IDNO:_____

SURVEY SITE PLANS

SITE NAME:_____

_____

_____

_____

GRID REF:_____

AREA PLANS

SITE PLAN

APPENDIX THREE

PROTOCOL FOR FIELD WORKERS

PROTOCOL FOR FIELD WORKERS.

AIR POLLUTION SURVEYS.

PLEASE READ CAREFULLY.
IF YOU HAVE ANY PROBLEMS, QUESTIONS,
PLEASE ASK ME.

By Kirsty Smallbone.

1. GENERAL INFORMATION

In the field precise and accurate registration of data is required to enable a correct and complete record for all samplers. You should make brief notes of anything which may be of interest. This should be done as part of the **field log.**

There are two types of samplers: badges (these are fastened with Velcro) and tubes (these are fastened with metal clips).

2. START OF THE SAMPLING PERIOD

At the start of the sampling period you will be presented with a field workers pack. Please check that this pack has all the equipment listed below:

2.1 FIELD EQUIPMENT

1. A list of sites to be visited (**Field log**)
2. Enough samplers for your sites plus at least two spares.
3. **Site plans** of those places you are to visit.
4. 1:50 000 scale O/S map of the Huddersfield area.
5. A-Z of kirklees.
6. Spare tape
7. Spare brackets
8. Steps or a bin (in case you have to reach a high sampler)
9. 2 x waterproof pens
10. 2 x biro pens
11. 2 x pencils
12. Watch
13. Scissors/knife
14. Clip bags in which the tubes are sealed during transport.
15. Letter of identification
16. Letters to say the sampler has been placed/removed from the property.
17. On collection make sure you have enough caps/lids for the number of samplers you are to collect plus some spares.

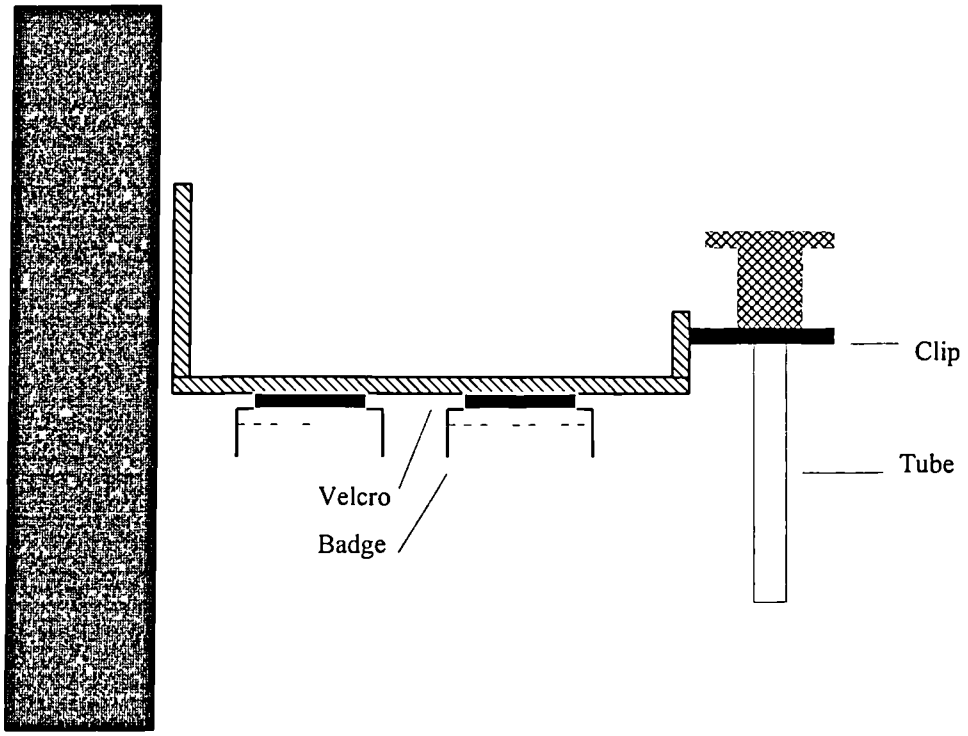
BEFORE YOU START.

1. Check you have all the things listed above, that you know how to get to your sites and that you have worked out a route to follow.

2. Check that you know the contact number which you MUST CONTACT AT THE END OF YOUR SAMPLING. You must also contact this number if you think you are running seriously behind schedule.

3. Check that you understand exactly how the tubes/badges are to be fixed to the bracket. It is imperative that the tubes be placed in the bracket red end upper most, that the yellow cap is removed and that the red cap of the tube rests on the top part of the bracket.

Diagram Of Sampler positioning.



NOTE: AT ANY TIME THE SURVEY RING THE CONTACT NUMBER IN THE EVENT OF PROBLEMS.

3. START SAMPLING.

At a site:

1. Take the number/type of samplers for that site.

2. Note on the field log for the site :
   the ID number of the sampler.
   the time that each sampler was exposed in **24 HR** time.
   any comments you might decide that the local co-ordinator should know.

3. Sampling starts by carefully removing the YELLOW cap from the tubes, or the WHITE lid from the badges. The caps should be kept as they will be needed on collection. If you are given field blanks to be put out attach them to the clips in the same way but DO NOT REMOVE THE CAPS !

4. Place the badges horizontally, and the tubes vertically.

5 For badges you must;
   A. Before attaching the badges check that the membrane has been fixed properly, i.e. it does not appear loose or damaged. If this is the case replace it with a spare sampler.
   B. DO NOT touch the membranes.

4. END OF SAMPLING

Again compare all equipment with the field log to ensure that you have enough caps/lids. Also ensure you have the equipment listed in 2.1 (Field Equipment list). Start visiting the sites.

At a site:

1. Check the membrane of the badges if they appear damaged note this in the field log and recap the sampler.

2. When removing the tubes please press the caps on VERY FIRMLY.

3. Note in the field log beside the site the tube number and time the cap was put on in 24 HR clock.

4. If the sampler ID number is hard to read please copy the number from the field log onto the tube with a waterproof pen.

N.B. Please remove the brackets at this time as well as the tubes.

When you have visited all sites return to I.E.P.A and deliver all material left.
PLACE ALL SAMPLERS IN THE REFRIGERATOR.

CONTACT THE SURVEY CO-ORDINATOR AT I.E.P.A. OR ON THE NUMBER PROVIDED TO REPORT THAT YOU HAVE FINISHED.

CONTACT ADDRESSES:

YOU MUST CONTACT ONE OF THESE NUMBERS IF YOU FEEL YOU ARE RUNNING SERIOUSLY BEHIND SCHEDULE, IF YOU HAVE ANY PROBLEMS AND WHEN YOU FINISH THE SURVEY.

I.E.P.A. TEL:	541946 450802	Do not just leave a message on the answer machine, make sure you speak to the survey co-ordinator.

SURVEY CO-ORDINATOR : _____

AFTER 18.00hr THE SURVEY CO-ORDINATOR IS :

_____

TEL : _____

PLEASE MAKE SURE ALL THESE DETAILS ARE CORRECT AND THAT YOU UNDERSTAND EVERY THING BEFORE YOU START THE SURVEY.

APPENDIX FOUR

FIELD AND LABORATORY LOGS

LABORATORY LOGS

TICK LIST

COUNTRY ..... UK ..... **TUBES** / **BADGES**

(NO2)

Number of Samples

	LAB sends	LC receives	FIELD	LC returns	LAB receives
'Normal'	130	130	Normal continuous	107 + 20	.....
Field blanks	8	8	blanks lost lids	8 / 22	.....
4×20 monthly Spares	80 / 5	55 / 8	spares	8	.....
Total	223	201		165	.....

Use the following symbols:

|	for sample is present
X	for sample is not present

* sampler lost Lid before it arrived.

Notate remarks at the last page.

COUNTRY England

(TUBES) / BADGES

NO_2

ID	LAB		LC	LC	LAB
5001					
5002				X	
5003					
5004					
5005					
5006					
5007					
5008					
5009					
5010					
5011					
5012					
5013			✳	✳	
5014					
5015					
5016					
5017					
5018					
5019				X	
5020					
5021					
5022					
5023					
5024					
5025					
5026					
5027					
5028				X	
5029					
5030					
5031					
5032					
5033					
5034					
5035					
5036					
5037					
5038				X	
5039					
5040					

ID	LAB		LC	LC	LAB
5041					
5042					
5043					
5044					
5045					
5046					
5047					
5048					
5049					
5050					
5051					
5052					
5053					
5054					
5055					
5056					
5057					
5058					
5059					
5060					
5061					
5062				X	
5063					
5064					
5065					
5066				X	
5067					
5068					
5069					
5070					
5071				X	
5072					
5073					
5074					
5075					
5076					
5077					
5078					
5079					
5080					

COUNTRY England.

TUBES / BADGES

NO_2

ID	LAB	LC	LC	LAB
5081		|	|	
5082		|	|	
5083		|	|	
5084		|	|	
5085		|	|	
5086		|	|	
5087		|	|	
5088		|	|	
5089		|	|	
5090		|	|	
5091		|	|	
5092		|	|	
5093		|	|	
5094		|	X	
5095		|	|	
5096		|	|	
5097		|	|	
5098		|	|	
5099		✳	✳	
5100		|	|	
5102		|	|	
5103		|	X	
5104		|	|	
5105		|	|	
5106		|	|	
5107		|	|	
5108		|	|	
5109		|	|	
5110		|	X	
5112		|	|	
5113		|	|	
5114		|	|	
5115		✳	✳	
5116		|	|	
5117		|	|	
5118		✳	✳	
5119		|	|	
5120		|	|	
5121		✳	✳	
5122		✳	✳	

ID	LAB	LC	LC	LAB
5123		|	|	
5124		|	X	
5125		|	|	
5126		|	|	
5127		|	|	
5128		|	|	
5129		|	|	
5130		|	|	
5131		|	|	
5132		|	|	
5133		|	|	
5134		|	|	
5135		|	|	
5136		|	X	
5137		|	|	
5138		|	|	
5139		|	|	
5141		|	|	
5142		|	|	
5143		|	|	
5144		|	|	
5145		|	|	
5146		|	|	
5147		|	|	
5148		|	X	
5149		✳	✳	
5150		|	|	
5151		|	|	
5152		|	|	
5155		|	|	
5156		|	|	
5157		✳	✳	
5158		|	|	
5159		|	|	
5160		|	|	
5161		|	|	
5162		|	|	
5163		✳	✳	
5164		|	|	

COUNTRY England

TUBES / BADGES

NO_2

ID	LAB	LC	LC	LAB
5165		✳	✳	
5166		|	|	
5167		✳	✳	
5168		|	|	
5169		|	|	
5170		|	|	
5171		|	|	
5172		|		
5173		|		
5174		|		
5175		|		
5176		✳	✳	
5177		|		
5178		|		
5179		|		
5180		|		
5181		|		
5182		|		
5183		✳	✳	
5184		|		
5185		|		
5186		|		
5187		✳	✳	
5188		|		
5189		✳	✳	
5190		|		
5191		✳	✳	
5192		|		
5193		|		
5194		|		
5195		✳	✳	
5196		|		
5197		|	|	
5198		✳	✳	
5199		✳	✳	
5200		|		
5201		|		
5202		✳	✳	
5203		✳	✳	
5204		|		

ID	LAB	LC	LC	LAB
5205		|		
5206		|		
5207		|		
5208		|		
5209		|		
5210		|		
5211		|		
5212		|		
5213		|		
5214		|		
5215		|		
5216		|		
5217		|		
5218		|		
5219		|		
5220		|		
5221		|		
5222		|		
5223		|		
5224		✳	✳	
5225		|		
5226		|		
5227		|		
5228		|		

COUNTRY UK TUBES / BADGES

NO2

BLANKS:

ID	LAB	LC	LC	LAB
5156		1	1	
5155		1	1	
5152		1	1	
5151		1	1	
5158		1	1	
5159		1	1	
5160		1	1	
5161		1	1	

SPARES:

ID	LAB	LC	LC	LAB
5162		1	1	
5164		1	1	
5197		1	1	
5168		1	1	
5166		1	1	
5170		1	1	
5169		1	1	
5171		1	1	

Remarks:

* 80 tubes are included for four months of continuous sampling; please store them in the refigerator until use!
* all Sampler-ID's are listed by LAB on the previous page(s). It is up to the local centres, which ones are used for (field) blanks and spares. Therefore left open on this page by LAB.
* Some tubes look dirty, but it is just the outside!

* We needed to use more spares because we had 5 teams putting out tubes & it was felt that more than 1 spare should go out with the teams

* tube N° 5052 had been tampered with therefore, I suggest the lab analyses it & careful note of the results obtained.

FIELD LOGS

USE 24hr Clock

START DATE: 1 /10/

END DATE : 1 1 9

NAME : Matth

PLEASE FILL IN

				START		FINISH	
SITE No	ADDRESS	AREA	TUBE No	START TIME	TUBE No	END TIME	
49	6 Park Lane ✓	Birds Edge	5061	—		17:11	
117	134 Penistone Rd / Sovereign Junct	Lane Head	5074	—	5094	10:45	
	Post		5049	—	5049	10:45	
	PLEASE PUT UP TWO NEW TUBES AT THIS SITE			10:45			
				10:45			
74	1pst opp 66 Abbey rd ✓	Shepley	5067	—	5064	10:40	
75	46 Abbey rd (Bk garden) ✓	Shepley	5064	—	5067	10:38	
118	1pst outside 37 Greenside	Denby Dale	5030	—	5030	11:14	
119	10 Wakefield rd	Denby Dale	5059	—	5059	11:11	
120	1pst outside 198 Barnsley rd	Denby Dale	5055	—	5055	11:06	
121	4 Popular Rise	Skelmanthorpe	5045	—	5045	11:29	
122	telqrph pole nr church on Barnsley rd / Spring Grove	Scissett	5051	—	5051	11:20	
52	39/41 Victoria rd (on telqrph pole opp) ✓	Clayton West	5042	—	5042	11:25	10
	" " "	"	0011	—	0011	11:25	
	" " "	"	0012	—	0012	11:25	
123	1pst N°7, Saville St / School Lane	Emley	5040	—	5040	11:43	43
124	entrance N°49, nr Emley Tower Denton Nook, Royd House off Winterbourne Titus Lane	Emley moor	5060	—	5060	11:49	
56	white gate post, down track at side of Kirby Grange farm off Roughlee ✓	nr Flockton	5070	—	5070	11:58	58
55	8 Rutland St	Flockton ✓	5041	—	5041	12:05	
125	1pst at grange moor Junct of A642 / A637 / B6118	Grange Moor	5072	—	5072	12:14	
45	1pst outside 6 Greaves House Terr ✓	Lepton	5109	—	5109	12:22	
46	1pst on corner of Greaves House Terr / Wakefield rd ✓	Lepton	5091	—	5091	12:21	

START DATE: 18/ 3
END DATE : 1 / 1
NAME : MH

SITE No	ADDRESS	AREA	START TUBE No	START START TIME	FINISH TUBE No	FINISH END TIME
53	17 Brooklyn Ave	Dalton	5065	/	5065	12:29
126	1pst N°24, outside 142 Long Lane	Dalton	5066	/	Stolen	
70	4pst outside 36 Longdale Drive	Riddgreen	5056	/	5058	12:40

APPENDIX FIVE

LAND COVER CLASSIFICATION

Land Cover Classification

(Classification used to compile both the land cover map and sample site characteristics

HDC	High Density Commercial	Office blocks, shopping centres
IND	Industry	>80% of area is industrial
VHD	Very High Density Housing	Tower blocks, residential buildings over 4 stories high
HD	High Density Housing	>60% of area is housing; excluding road area
LD	Low Density	25-60% of area is housing; excluding road area
VLD	Very Low Density	<25% of area is housing; excluding road area
PI	Public Institutes	Hospitals, schools etc
R	Recreation Facilities	Sports grounds, parks etc
RG	Rough Grassland	Unimproved pasture
P	Pasture	Permanent pasture
C	Cultivated	Crop land at the time of the survey
BT	Broadleaf Trees	>80% of area is broadleaf
CT	Coniferous Trees	>80% of area is evergreen
MT	Mixed Trees	20-80% of area is both broadleaf and evergreen
Q	Quarries	Used and disused excavation
DL	Disused Land	Wasteland, derelict land, sequestered land
H	Health	Heather, ling and associated species
PS	Peat Sedge	Peat hags with thin vegetation/bare peat
B	Bracken	>75% of area is covered with bracken
MG	Moorland Grass	*Mollinia, Juncus* etc

APPENDIX SIX

PASQUILL STABILITY CLASS PROGRAM

Stability Program

(Calculates Pasquills stability class from meteorological data within the DBASE4 database)

```
GO TOP
A=1
DO WHILE .NOT. EOF()
      REPLACE SEQ WITH A
      A=A+1
      SKIP
      ENDDO

GOTO 1
REPLACE ALL RAINCLASS WITH 1 FOR RAINFALL <0.1
REPLACE ALL RAINCLASS WITH 2 FOR RAINFALL =>0.1 .AND. RAINFALL <.5
REPLACE ALL RAINCLASS WITH 3 FOR RAINFALL =>.5 .AND. RAINFALL <1
REPLACE ALL RAINCLASS WITH 4 FOR RAINFALL >.99 .and. rainfall <2
replace all rainclass with 5 for rainfall >1.99


goto 1
replace all tempclass with 6 for temp <5
replace all tempclass with 5 for temp >5 .and. temp =<10
replace all tempclass with 4 for temp >10 .and. temp =<15
replace all tempclass with 3 for temp >15 .and. temp =<20
replace all tempclass with 2 for temp >20 .and. temp =<25
replace all tempclass with 1 for temp >25

goto 1
REPLACE ALL DAYTIME WITH 1 FOR TIME =>'06:00' .AND. TIME <'20:00'
REPLACE ALL DAYTIME WITH 2 FOR TIME =>'20:00' .AND. TIME <'24:00'
REPLACE ALL DAYTIME WITH 2 FOR TIME =>'00:00' .AND. TIME <'06:00'

GOTO 1
REPLACE ALL WINDDEG1 WITH 1 FOR WINDDEG =>0 .AND. WINDDEG <22.5
REPLACE ALL WINDDEG1 WITH 1 FOR WINDDEG =>337.5 .AND. WINDDEG =<360
REPLACE ALL WINDDEG1 WITH 2 FOR WINDDEG =>22.5 .AND. WINDDEG <67.5
REPLACE ALL WINDDEG1 WITH 3 FOR WINDDEG =>67.5 .AND. WINDDEG <112.5
REPLACE ALL WINDDEG1 WITH 4 FOR WINDDEG =>112.5 .AND. WINDDEG <157.5
REPLACE ALL WINDDEG1 WITH 5 FOR WINDDEG =>157.5 .AND. WINDDEG <202.5
REPLACE ALL WINDDEG1 WITH 6 FOR WINDDEG =>202.5 .AND. WINDDEG <247.5
REPLACE ALL WINDDEG1 WITH 7 FOR WINDDEG =>247.5 .AND. WINDDEG <292.5
REPLACE ALL WINDDEG1 WITH 8 FOR WINDDEG =>292.5 .AND. WINDDEG <337.5

GOTO 1
REPLACE ALL WINDVEL1 WITH WINDVEL*(1000/3600)

GOTO 1
REPLACE ALL WINDVEL2 WITH 1 FOR WINDVEL1 <2
GOTO 1
REPLACE ALL WINDVEL2 WITH 2 FOR WINDVEL1 =>2 .AND. WINDVEL1 <3
REPLACE ALL WINDVEL2 WITH 3 FOR WINDVEL1 =>3 .AND. WINDVEL1 <5
REPLACE ALL WINDVEL2 WITH 4 FOR WINDVEL1 =>4.99 .AND. WINDVEL1 <6
REPLACE ALL WINDVEL2 WITH 5 FOR WINDVEL1 >5.99

GOTO 1
REPLACE ALL WINDVEL2 WITH 1 FOR WINDVEL1 <2
GOTO 1
REPLACE ALL WINDVEL2 WITH 2 FOR WINDVEL1 =>2 .AND. WINDVEL1 <3
```

```
REPLACE ALL WINDVEL2 WITH 3 FOR WINDVEL1 =>3 .AND. WINDVEL1 <5
REPLACE ALL WINDVEL2 WITH 4 FOR WINDVEL1 =>4.99 .AND. WINDVEL1 <6
REPLACE ALL WINDVEL2 WITH 5 FOR WINDVEL1 >5.99

replace all stab1 with 1 for rainclass=1 .and. tempclass=1 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=1 .and. tempclass=1 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 2 for rainclass=1 .and. tempclass=1 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass=1 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass=1 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 1 for rainclass=1 .and. tempclass=2 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=1 .and. tempclass=2 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 2 for rainclass=1 .and. tempclass=2 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass=2 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass=2 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=1 .and. tempclass >2 .and.
tempclass<5 .and. windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=1 .and. tempclass >2 .and.
tempclass<5 .and. windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass >2 .and.
tempclass<5 .and. windvel2=3 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass >2 .and.
tempclass<5 .and. windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=1 .and. tempclass >2 .and.
tempclass<5 .and. windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=1 .and. tempclass>4 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass>4 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=1 .and. tempclass>4 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=1 .and. tempclass>4 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=1 .and. tempclass>4 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 1 for rainclass=2 .and. tempclass =1 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=2 .and. tempclass =1 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 2 for rainclass=2 .and. tempclass =1 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass =1 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass =1 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 1 for rainclass=2 .and. tempclass =2 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=2 .and. tempclass =2 .and.
windvel2=2 .and. daytime=1
```

```
replace all stab1 with 2 for rainclass=2 .and. tempclass =2 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass =2 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass =2 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=2 .and. tempclass >2 .and.
tempclass <5 .and. windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=2 .and. tempclass >2 .and.
tempclass <5 .and. windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass >2 .and.
tempclass <5 .and. windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=2 .and. tempclass >2 .and.
tempclass <5 .and. windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=2 .and. tempclass >2 .and.
tempclass <5 .and. windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=2 .and. tempclass >4 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass >4 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=2 .and. tempclass >4 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=2 .and. tempclass >4 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=2 .and. tempclass >4 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 1 for rainclass=3 .and. tempclass =1 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=3 .and. tempclass =1 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 2 for rainclass=3 .and. tempclass =1 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 3 for rainclass=3 .and. tempclass =1 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 3 for rainclass=3 .and. tempclass =1 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=3 .and. tempclass >1 .and.
tempclass <5 .and. windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=3 .and. tempclass >1 .and.
tempclass <5 .and. windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=3 .and. tempclass >1 .and.
tempclass <5 .and. windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=3 .and. tempclass >1 .and.
tempclass <5 .and. windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=3 .and. tempclass >1 .and.
tempclass <5 .and. windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=3 .and. tempclass >4 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 3 for rainclass=3 .and. tempclass >4 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=3 .and. tempclass >4 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=3 .and. tempclass >4 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=3 .and. tempclass >4 .and.
windvel2=5 .and. daytime=1
```

```
replace all stab1 with 2 for rainclass=4 .and. tempclass =>1 .and.
tempclass <4 .and. windvel2=1 .and. daytime=1
replace all stab1 with 2 for rainclass=4 .and. tempclass =>1 .and.
tempclass <4 .and. windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=4 .and. tempclass =>1 .and.
tempclass <4 .and. windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=4 .and. tempclass =>1 .and.
tempclass <4 .and. windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=4 .and. tempclass =>1 .and.
tempclass <4 .and. windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=4 .and. tempclass >3 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 3 for rainclass=4 .and. tempclass >3 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=4 .and. tempclass >3 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=4 .and. tempclass >3 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=4 .and. tempclass >3 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 2 for rainclass=5 .and. tempclass =>1 .and.
windvel2=1 .and. daytime=1
replace all stab1 with 3 for rainclass=5 .and. tempclass =>1 .and.
windvel2=2 .and. daytime=1
replace all stab1 with 3 for rainclass=5 .and. tempclass =>1 .and.
windvel2=3 .and. daytime=1
replace all stab1 with 4 for rainclass=5 .and. tempclass =>1 .and.
windvel2=4 .and. daytime=1
replace all stab1 with 4 for rainclass=5 .and. tempclass =>1 .and.
windvel2=5 .and. daytime=1

replace all stab1 with 6 for rainclass=1 .and. tempclass =>1 .and.
tempclass <5 .and. windvel2=1 .and. daytime=2
replace all stab1 with 6 for rainclass=1 .and. tempclass =>1 .and.
tempclass <5 .and. windvel2=2 .and. daytime=2
replace all stab1 with 5 for rainclass=1 .and. tempclass =>1 .and.
tempclass <5 .and. windvel2=3 .and. daytime=2
replace all stab1 with 4 for rainclass=1 .and. tempclass =>1 .and.
tempclass <5 .and. windvel2=4 .and. daytime=2
replace all stab1 with 4 for rainclass=1 .and. tempclass =>1 .and.
tempclass <5 .and. windvel2=5 .and. daytime=2


replace all stab1 with 5 for rainclass=1 .and. tempclass >4 .and.
windvel2=1 .and. daytime=2
replace all stab1 with 5 for rainclass=1 .and. tempclass >4 .and.
windvel2=2 .and. daytime=2
replace all stab1 with 4 for rainclass=1 .and. tempclass >4 .and.
windvel2=3 .and. daytime=2
replace all stab1 with 4 for rainclass=1 .and. tempclass >4 .and.
windvel2=4 .and. daytime=2
replace all stab1 with 4 for rainclass=1 .and. tempclass >4 .and.
windvel2=5 .and. daytime=2

replace all stab1 with 5 for rainclass >1 .and. tempclass =>1 .and.
tempclass <6 .and. windvel2=1 .and. daytime=2
replace all stab1 with 5 for rainclass >1 .and. tempclass =>1 .and.
tempclass <6 .and. windvel2=2 .and. daytime=2
replace all stab1 with 4 for rainclass >1 .and. tempclass =>1 .and.
tempclass <6 .and. windvel2=3 .and. daytime=2
```

```
replace all stab1 with 4 for rainclass >1 .and. tempclass =>1 .and.
tempclass <6 .and. windvel2=4 .and. daytime=2
replace all stab1 with 4 for rainclass >1 .and. tempclass =>1 .and.
tempclass <6 .and. windvel2=5 .and. daytime=2

replace all stab1 with 5 for rainclass >1 .and. tempclass >4 .and.
windvel2=1 .and. daytime=2
replace all stab1 with 5 for rainclass >1 .and. tempclass >4 .and.
windvel2=2 .and. daytime=2
replace all stab1 with 4 for rainclass >1 .and. tempclass >4 .and.
windvel2=3 .and. daytime=2
replace all stab1 with 4 for rainclass >1 .and. tempclass >4 .and.
windvel2=4 .and. daytime=2
replace all stab1 with 4 for rainclass >1 .and. tempclass >4 .and.
windvel2=5 .and. daytime=2
```