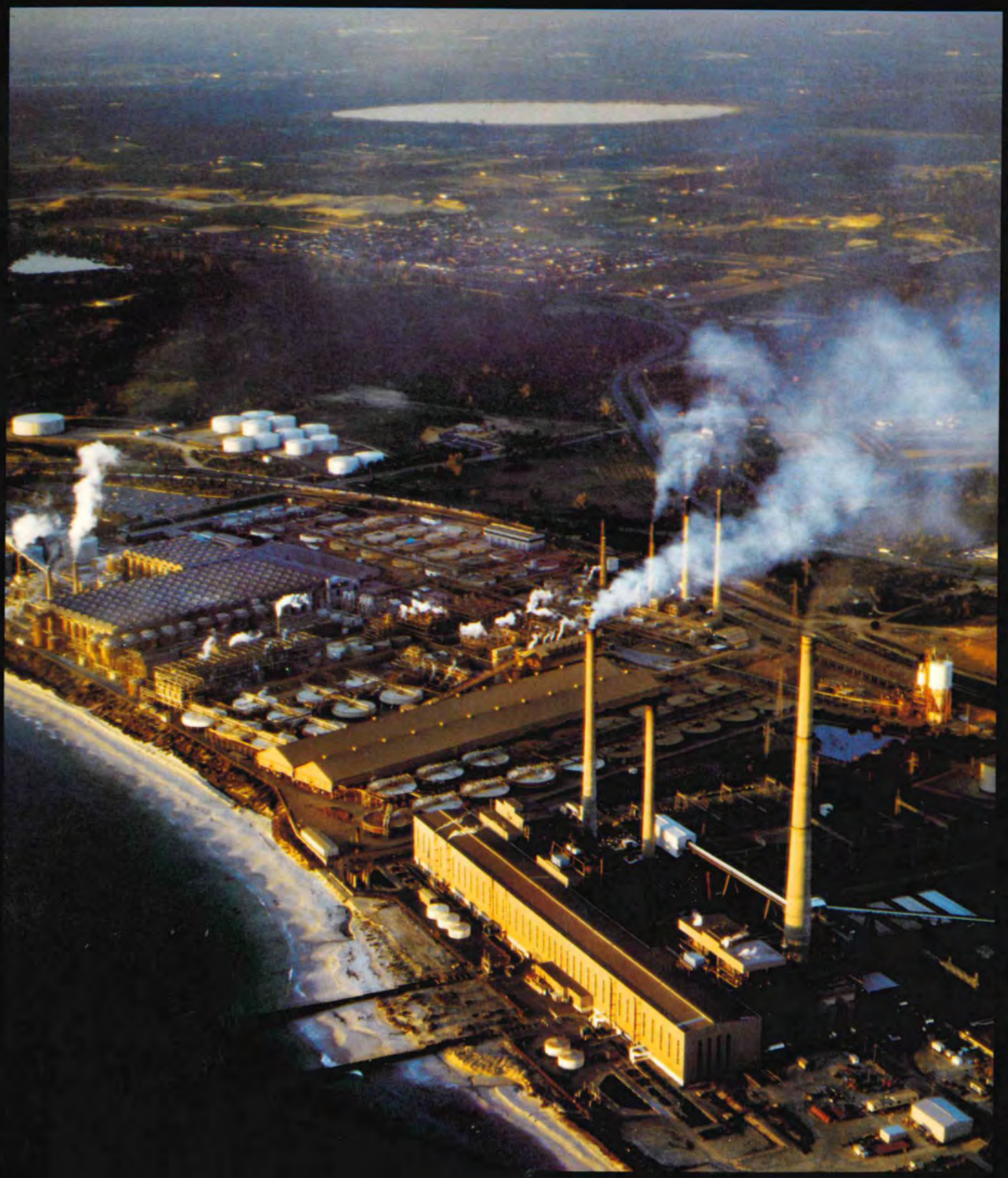
THE KWINANA AIR MODELLING STUDY



Department of Conservation & Environment
Perth Western Australia

Report 10
1982

THE KWINANA AIR MODELLING STUDY

A study promoted by the

Department of Conservation and Environment

and the

Department of Public Health

in co-operation with the

Commonwealth Bureau of Meteorology
State Energy Commission of Western Australia
Western Australian Institute of Technology
Murdoch University
University of Western Australia
and Kwinana Industry.

Department of Conservation and Environment
Perth Western Australia

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Front Cover: Kwinana industry with Wattleup and Thompson Lake in the background.
Back Cover: Kwinana industrial strip looking south.

PREFACE

In 1974, the Coogee Air Pollution Study recommended that an area of land to the north of major industry at Kwinana was unsuitable for urban development as a result of the levels of air pollution it experienced. The Kwinana Air Modelling Study (KAMS) grew out of the need to determine the air pollution impact on a wider scale at Kwinana and built upon the earlier pioneering work. As suggested by its name, KAMS was largely concerned with the development and use of mathematical models to estimate air pollution dispersion.

The choice of Kwinana as the location of the first major air dispersion modelling study attempted in Western Australia was ideal. In the first instance, the results of KAMS have an important and immediate planning application to ensure that the adverse impact of air pollution at Kwinana is kept to a minimum. Secondly, the implementation of the many field and experimental activities was made easier by the proximity of Kwinana to the Perth metropolitan area. Finally, the contribution of external pollutant sources to the air pollution levels of Kwinana was insignificant, simplifying the analyses required for the study.

The Kwinana Air Modelling Study was undertaken as a co-operative exercise involving Government agencies, academic institutions and Kwinana industry. A senior-level Policy Group was formed in 1976 to guide the development of air dispersion modelling techniques in Western Australia and, in particular, to coordinate the involvement of participants in KAMS. A Technical Working Group, set up by the Policy Group, was responsible for planning the broad technical direction of the study. Routine study activities including meteorological and pollutant monitoring, experimental studies, instrument maintenance, mathematical modelling and technical reporting were undertaken by a Core Group. This was made up of officers from the Departments of Conservation and Environment and Public Health but later included a part-time consultant from the School of Physics and Geosciences at the Western Australian Institute of Technology.

Though the major contributions to the study in terms of capital costs, manpower and technical support were made by the Department of Conservation and Environment and the Department of Public Health, other groups made significant contributions. The most important of these were:

Commonwealth Bureau of Meteorology

Loan of anemometers, anemometer chart digitising, radiosonde releases and analysis.

State Energy Commission

Anemometer chart digitising, 24-hour sulphur dioxide data collection, capital support for acoustic sounder, assistance in field studies.

Western Australian Institute of Technology

Deployment of mobile acoustic sounder, assistance in field studies and review of early study findings.

Murdoch University

Acoustic sounder maintenance and analysis and assistance in field studies.

University of Western Australia

Tracer gas analysis for field studies.

Kwinana Industry

Provision of data to enable calculation of sulphur dioxide emissions.

All technical aspects of KAMS are addressed in a series of 24 separate technical reports which are listed on page vii. These reports follow the evolution of the study and will be of interest to the specialist working in the air pollution monitoring and modelling fields.

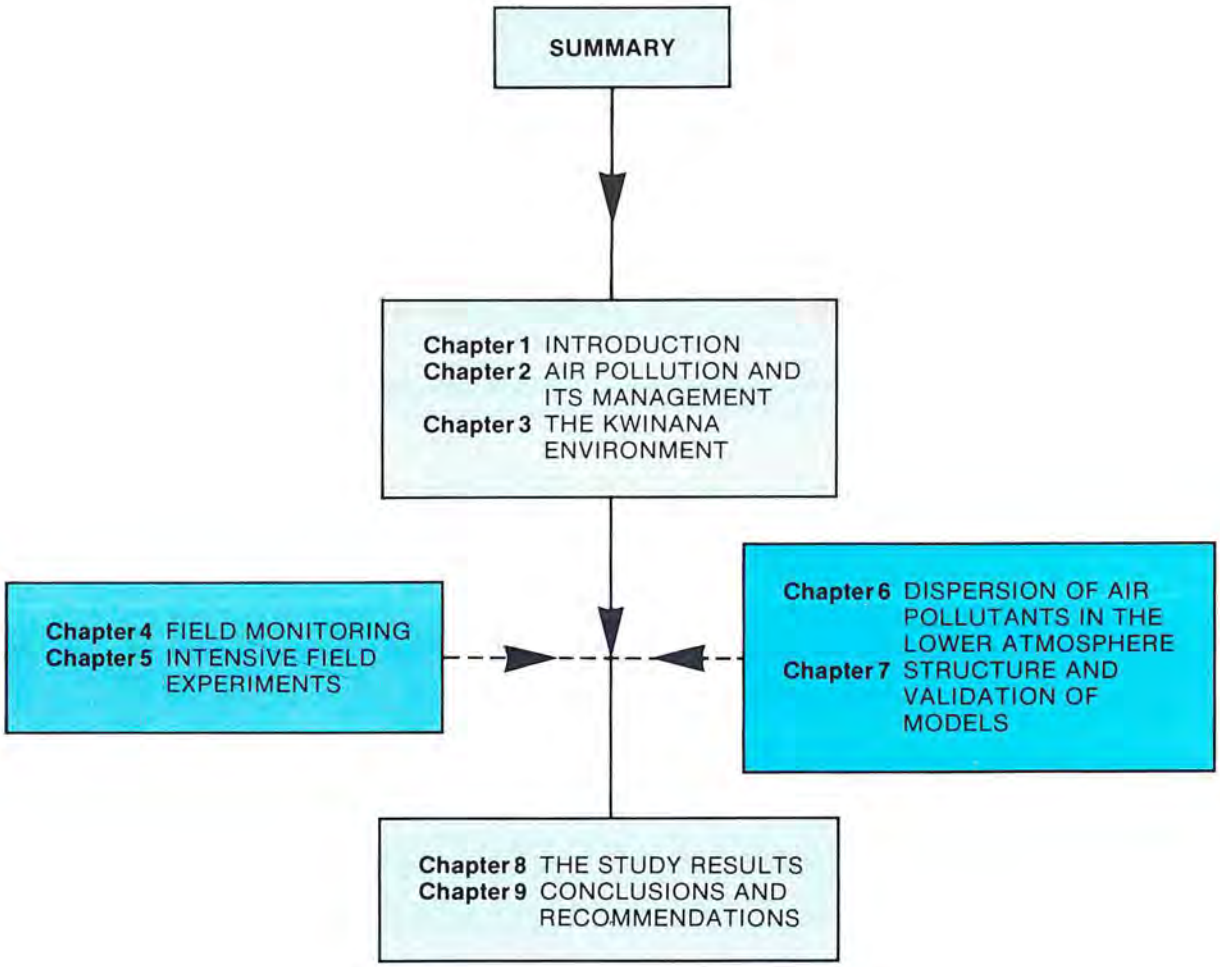
This report considers in general terms the major aspects of air pollution dispersion modelling as they relate to Kwinana and summarises the work covered in many of the technical reports. The magnitude of the air pollution problem at Kwinana is evaluated and management recommendations presented. Consequently, the report will be of particular significance to those agencies responsible for land use planning and air pollution control at Kwinana as well as individuals in the general community with an interest in the area.

The report can be divided into five main sections as illustrated in the diagram below. Those seeking to obtain a concise overview of the study, its major conclusions and recommendations will be satisfied by reading the summary preceding Chapter 1.

Chapters 1-3 give a general introduction to the study, consider the various facets of the air pollution problem and describe the Kwinana environment in terms of the land use of the area, industrial activity and meteorology. This section is not highly technical and generally will be understood by the layman.

Detailed results of the study, conclusions and recommendations are presented in Chapters 8 and 9.

Those desiring a deeper understanding of the monitoring and mathematical modelling aspects of KAMS are encouraged to read Chapters 4-7. Routine and intensive field monitoring is addressed in Chapters 4 and 5 while Chapters 6 and 7 are concerned with the theory of modelling pollutant dispersion and the validation of the KAMS models. Chapter 6 is presented for the scientist but Chapters 4, 5 and 7 could be understood by the layman with a keen interest in the subject.



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KWINANA AIR MODELLING STUDY
TECHNICAL REPORTS

Report No.	Title
KAMS-01	Glossop, L.G. and Hamilton, B.H. (1977). Tracer methodology II.
KAMS-02	Martin, R. and Rayner, K.N. (1978). Single camera smoke plume photography and a time lapse camera system.
KAMS-03	Department of Conservation and Environment (1978). Kwinana Air Modelling Study, Tracer experiment 1.
KAMS-04	Department of Conservation and Environment (1978). Kwinana Air Modelling Study, Intensive episode study workshop.
KAMS-05	Allen, G.A. and Beer, T. (1979). Kwinana Air Modelling Study – Interim Review Report – Final Report.
KAMS-06	Department of Conservation and Environment (1980). Kwinana Air Modelling Study, Tracer experiment 2.
KAMS-07	Department of Conservation and Environment (1980). Kwinana Air Modelling Study, Intensive episode study 2 workshop.
KAMS-08	Rye, P.J. (1980). A model for pollutant dispersal by the sea breeze; 1. Structure and validation of sea breeze model.
KAMS-09	Lyons, T.J., Kamst, F.H. and Watson, I.D. (1980). A simple sonde system for use in air pollution studies.
KAMS-10	Kamst, F.H. and Lyons, T.J. (1980). The evaluation of diffusivities for a non-uniform site.
KAMS-11	Kamst, F.H. and Lyons, T.J. (1980). A regional air quality model for the Kwinana industrial area.
KAMS-12	O'Connor, B.H. and Chang, W.J. (1981). Kwinana Air Modelling Study – Chemical characterisation of airborne particulate material.
KAMS-13	Rayner, K.N. and Rosher, J.E. (1981). Field study of a radiation inversion.
KAMS-14	Rayner, K.N. and Watson, I.D. (1981). Analysis of Perth Airport radiosonde data for use in the Kwinana Air Modelling Study.
KAMS-15	Rayner, K.N. (1981). Atmospheric surface layer stability modelling.
KAMS-16	Rayner, K.N. (1981). Modelling the atmospheric mixing depth.
KAMS-17	Paparo, V.S. (1982). The deposition of particulate matter from the atmosphere.
KAMS-18	Martin, D.J. (1982). High volume sampling in the Kwinana Air Modelling Study.
KAMS-19	Martin, D.J. and Rosher, J.E. (1982). Kwinana Air Modelling Study emissions inventory.
KAMS-20	Martin, D.J. and Rosher, J.E. (1982). Ambient atmospheric sulphur dioxide monitoring in the Kwinana Air Modelling Study.
KAMS-21	Rosher, J.E., Rayner, K.N., Raich, V. and Martin, D.J. (1982). Kwinana Air Modelling Study data monitoring, processing, analysis and presentation.
KAMS-22	Rye, P.J. (1982). A finite-difference pollutant dispersal model for the Kwinana region.
KAMS-23	Rosher, J.E., Rayner, K.N. and Paparo, V.S. (1982). An efficient Gaussian dispersion model for use in coastal regions.
KAMS-24	Rosher, J.E. and Martin, D.J. (1982). Comparison of two methods of sulphur dioxide measurement.

SUMMARY

THE STUDY PROGRAMME

The Kwinana region, lying about 30 km to the south of Perth, is the centre of the most significant heavy industry complex in Western Australia. About 5000 workers are employed by industries at Kwinana and more than 50,000 people live in the area.

Since it is inevitable that some air pollution is always present near industrial zones, an understanding of its impact on the environment is a prerequisite to effective planning for land use. The Kwinana Air Modelling Study (KAMS) was undertaken primarily to provide accurate air quality information as an input to the planning and development of the Kwinana area.

As a modelling study, KAMS was concerned with developing mathematical techniques that could be used to estimate both the existing impact of air pollution at Kwinana and the impact resulting from changes in the present industrial emission levels. Such techniques, or 'mathematical models' had to take into account the most important atmospheric processes which serve to disperse air pollutants. In addition, a comprehensive field monitoring and experimental programme was necessary to test the estimates produced by the models against actual measurements, so that they could be applied with confidence to determine the air pollution impact over a wide area under various conditions. Much of the work in KAMS was associated with the models: the study of the dispersion mechanisms at Kwinana, the collection of meteorological and pollutant emissions data for model input, the measurement of ambient pollutant concentrations for model validation and the production of pollution impact estimates.

The KAMS field monitoring programme focused on two instrumented base stations which were operated from June 1978 to January 1981. Meteorological parameters and sulphur dioxide concentrations were measured continuously at each station and 10-minute averages recorded automatically.

A number of other instruments, spread widely over the KAMS study area, were also used. These included five anemometers to record wind speed and direction variations, nine instruments to measure daily average sulphur dioxide concentrations and an acoustic sounder to investigate the vertical structure of the atmosphere. These instruments were operated for periods ranging from 3 to 4 years.

With the cooperation of industry, an inventory of sulphur dioxide emitted from more than 50 sources in the Kwinana industrial area was compiled. The emissions for each source averaged over 30 minutes to 8 hours, were recorded for the period July 1978 to June 1980.

All routine meteorological, pollution concentration and emissions data were checked, processed and stored on a computer. A large number of data processing and analysis programs were developed to provide high quality data presentation and input for the mathematical models.

In addition to the continuous monitoring programme, intensive field experiments over short periods were undertaken to study meteorological phenomena of particular interest. The most important of these involved the investigation of the effect of the summer sea breeze on air pollution at Kwinana. Information gained was used both to identify the most important dispersion mechanisms operating at Kwinana, so that they could be included in the formulation of mathematical models, and to provide model validation data in addition to that provided by the routine monitoring. Perhaps the most important result of the field experiment programme was the quantification of the role of the sea breeze in the production of high short-term pollutant concentrations well inland.

The development of the mathematical models required to simulate pollutant dispersion at Kwinana was started during and, in fact, influenced the direction of the KAMS monitoring programme. However, modelling activities increased significantly in early 1981 from which time they dominated the study.

Two mathematical models which treated pollutant dispersion quite differently were developed for KAMS. These were made up of a number of separate components or sub-models which considered various aspects of plume and atmospheric behaviour. Theoretical considerations, published empirical relationships and KAMS monitoring results were all used in the model development.

Mathematical models can be considered to be adequate only when they are able to reproduce pollutant concentration data to an acceptable degree of accuracy. As previously mentioned, this validation process utilised the sulphur dioxide data obtained during routine monitoring as well as data from the field experiments. Each of the KAMS models was able to simulate dispersion within the bounds commonly accepted in air pollutant dispersion studies.

In essence, the models were able to take pollutant emissions and meteorological data as input and produce estimates of concentration at any point within the study area. On the basis of the validation process the KAMS models were found to have different but complementary strengths. Whilst one of the models was most suited to the calculation of long-term or low short-term concentrations, the other was able to estimate more accurately the occurrence of high short-term concentrations.

The study results consisted of an analysis of measured and modelled sulphur dioxide concentration data. In both cases concentrations were determined for long- and short-term pollution episodes with averaging periods ranging from 1 year to 1 hour. For some averaging periods the frequency of concentrations exceeding certain limiting values related to health standards was also calculated. The most significant results take the form of:

- Month by month variation of sulphur dioxide concentration measured at Wattleup for averaging periods of 1-month, 24-hours, 3-hours and 1-hour (Table 8.3, page 75).
- A summary of sulphur dioxide concentration statistics from measurements at Wattleup for the years 1979 and 1980. The averaging periods are for 1 year, 1 month, 24 hours, 3 hours and 1 hour (Table 8.4, page 76).
- Modelled contours of annual average sulphur dioxide concentrations over the study area (Figure 8.6, page 77).
- Modelled contours of the frequency of 24-hour average sulphur dioxide concentrations exceeding two particular levels (Figure 8.8, page 78).
- Modelled contours of the frequency of 3-hour average sulphur dioxide concentrations exceeding a given level (Figure 8.9, page 79).
- Modelled contours of the frequency of 1-hour average sulphur dioxide concentrations exceeding a range of levels (Figures 8.10-8.13, pages 80-83).

In addition, the effect on ambient concentrations of a number of possible changes in sulphur dioxide emissions at Kwinana is presented in Figures 8.14 and 8.15 (page 86 and 87). The influence of the coast on dispersion and the consequent impact on ground level concentrations is illustrated in Figure 8.16 (page 88).

In order to provide guidance to land use planners and control authorities, the results were evaluated against a range of ambient sulphur dioxide standards or objectives (Table 8.2, page 74), which are reflected in the levels chosen for the tables and figures. Since Western Australia does not have statutory air pollution objectives, limiting values were chosen from Victorian, United States and World Health Organisation objectives to cover long- and short-term episodes. It was clear from these comparisons that there is a significant difference between the impact of long-term and short-term air pollution episodes with the latter being more severe. Figure 9.1 (page 92) shows the major air pollution impact area at Kwinana based on certain criteria chosen for comparison.

On the basis of the measured and modelled air pollution levels at Kwinana, a number of conclusions were reached and recommendations made. The most important of these are summarised below while others are presented in Chapter 9.

KEY CONCLUSIONS

1. The study has identified the location of the major air pollution impact areas to the north and north-east of industry at Kwinana. These areas are strongly dependent on the geometrical configuration of the existing pollutant sources and the meteorological characteristics at Kwinana.

2. Air pollution at Kwinana is dominated by short periods of relatively high concentrations of sulphur dioxide during the summer months. These episodes are commonly of 1 to 5 hours duration and generally coincide with the sea breeze.

3. Pollutants emitted into the sea breeze from tall chimneys near the coast disperse quite slowly until they encounter a growing turbulent boundary layer a few kilometres downwind of the source and are brought rapidly to ground level. This results in the production of relatively high pollutant concentrations as far downwind as 7 kilometres.

4. On the basis of the model validation procedure carried out with all available data during KAMS, it is considered that the mathematical models developed adequately represent pollutant dispersion at Kwinana. The models have the capability to produce concentration estimates for most industrial air pollutants emitted and for any source configuration located on the Perth coastal plain.

5. A number of widely accepted ambient air quality objectives are not met in a significant portion of the study area, particularly to the north, north-east and east of the major industrial sources.

6. On the basis of the objectives chosen for the study, the interim buffer zone (Figure 9.1) proposed in 1980 as conservative, is less than conservative in its northern part. In particular, the area to the north-east of Wattleup extending beyond Thompson Lake is also likely to be subject to a considerable air pollution impact.

KEY RECOMMENDATIONS

1. It is recommended that the Air Pollution Control Council consider the role of short-term ambient air quality objectives and adopt a range of criteria covering both long- and short-term periods of exposure.

2. The ambient air quality criteria chosen for the Kwinana Air Modelling Study are considered to be satisfactory indicators of air quality over a range of averaging periods. The 1979 World Health Organisation annual and 24-hour levels and the Victorian EPA 1-hour objectives are recommended to the Air Pollution Control Council as guidelines for sulphur dioxide.

3. Air quality considerations should be an integral part of the planning process in the Kwinana study area, particularly in the interim buffer zone. Planning should take account of the likely ambient air pollutant levels and the possibility of emission controls.

4. Without a major reduction in sulphur dioxide emissions at Kwinana, population density within the interim buffer zone should be minimised as should any commercial activities which might be affected adversely by air pollution.

5. It is recommended that the Department of Public Health arrange meetings with representatives of Kwinana industry to discuss the findings of the study and to explore ways of reducing air pollution during critical times.

6. The Department of Public Health and the three relevant local government authorities at Kwinana should promote and implement a progamme to make the public fully aware of the extent of the air pollution impact at Kwinana. In particular this programme should be directed at present residents and intending new residents of the area.

7. The extent of the air pollution impact well inland should be further investigated by monitoring short-term pollutant levels in the vicinity of Thompson Lake.

Chapter 1

INTRODUCTION

1.1 KWINANA: A BRIEF DESCRIPTION

The Kwinana industrial area (Figure 1.1) is situated on the coast of Cockburn Sound, some 30 km south of Perth and opposite Garden Island. Cockburn Sound is a natural harbour which has attracted light and heavy industry, urban development and a strategic naval base on Garden Island. There is potential for further industry including ship building and dock facilities. The industrial area is on the edge of a fairly featureless coastal plain which is bordered to the east by the Darling Scarp about 30 km inland. Current land use around the existing industrial area is predominantly rural, with some dormitory suburbs and land for parks and recreation.

Land use in the Perth metropolitan area is primarily controlled by the Metropolitan Region Scheme. Future growth of the region will be in the form of corridors as set out in the document *The Corridor Plan for Perth* (MRPA, 1970). Concept planning for the South West Corridor envisages a much higher urban density from Fremantle to Mandurah. Rockingham is identified as a sub-regional centre.

The effects of air pollution generated by industry at Kwinana are therefore an important consideration in the planning process for the region. Already approximately 50,000 people reside in areas adjacent to the industrial complex and a good understanding of the impact of air pollutants must be gained before further decisions concerning the growth of residential zones, in particular, are made.

In addition, due to its proximity to Perth, and because of the existing industry, the Kwinana area was an ideal location to undertake a major study of dispersion processes in a coastal location. The Kwinana Air Modelling Study (KAMS) is the first attempt in Western Australia at such a comprehensive study.

1.2 HISTORICAL BACKGROUND

1.2.1 The Growth of the Kwinana Industrial Complex

The development of Kwinana as Western Australia's first heavy industry complex began in the 1950s and has continued since that time. Initially, an oil refinery was established in 1955 followed by a steel rolling mill (1956), an alumina refinery (1964), a blast furnace (1968), a fertiliser plant (1968), a power station (1970) and a nickel refinery (1973). A cement works, north of the main industrial concentration, but of relevance to this study, began operations in 1955.

Air quality in the Kwinana environment is predominantly determined by the large industries already mentioned. However, other large operations, such as a bulk grain terminal, and many smaller support industries have also been established at Kwinana. In addition, this industrial activity has necessitated the installation of wharves, rock walls and groynes, and channels have been excavated in Cockburn Sound for shipping access.

About 5000 people are now employed by industries operating in the Kwinana area. Many of these reside in the dormitory zones of Medina to the south-east, Rockingham to the south, and Wattleup to the north-east. The study area encompasses portions of three local authorities, the Shire of Rockingham, the Town of Kwinana and the City of Cockburn. These authorities had populations of 23,000, 16,000 and 32,000 respectively in 1980, whilst the small but significant locality of Wattleup had a population of about 800.

1.2.2 The Coogee Air Pollution Study (CAPS)

The Kwinana Air Modelling Study had its genesis in the earlier pioneering Coogee Air Pollution Study. Investigations at Coogee were initiated following a proposal by the Industrial Lands Development Authority (ILDA) to rezone, for residential use, about 610 hectares of industrial land sited to the immediate north of the Kwinana industrial complex. This proposal was not accepted by the Air Pollution Control Council of WA, which recommended that the land should be retained as a buffer zone between industry and the residential development further north.

In 1972, State Cabinet directed that air pollution levels in the Coogee area be studied in detail so that the land use conflict could be resolved. The Coogee Air Pollution Study subsequently undertaken in 1973 and early 1974 was co-ordinated by the Department of Conservation and Environment.

Major components of the study included the monitoring of meteorological parameters, atmospheric sulphur dioxide concentrations, smoke and dust levels, and emissions of sulphur dioxide from industry. Based on these data, a simple atmospheric diffusion model was developed in an attempt to simulate the dispersion of pollutants.

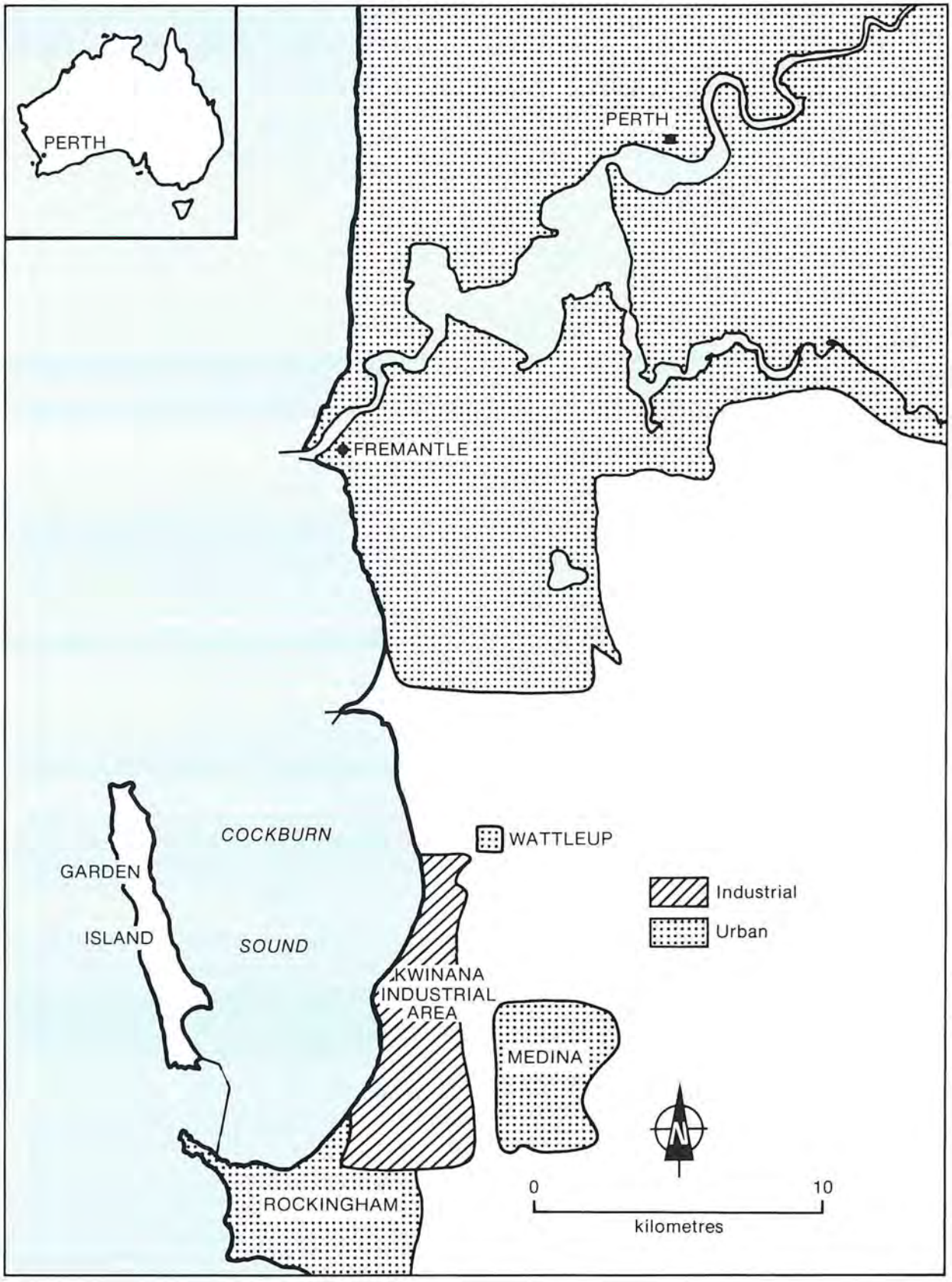


Figure 1.1. The location of the Kwinana region of Western Australia.

The mathematical modelling work gave good results for winter months, but consistently under-predicted ground level concentrations of sulphur dioxide in the summer sea breeze regime. Lack of knowledge of the vertical structure of the atmosphere constituted the main difficulty when modelling dispersion in these conditions.

On the basis of both the monitoring and modelling exercises, the CAPS report (Environmental Protection Authority, 1974) recommended that no residential development of the Coogee land take place. Subsequently, as part of an amendment to the Metropolitan Region Scheme, a substantial portion of the area in question was reserved for Parks and Recreation. The remainder was left zoned for light industry and is currently being developed by ILDA as a backup area for the Jervoise Bay ship building and offshore module construction facilities.

The Environmental Protection Authority further recommended that research be undertaken to define buffer zones around the Kwinana industrial area in general. Seen as central to this task was the development of mathematical models which, in particular, could better incorporate the contribution of the sea breeze to the dispersion process. The resulting, more detailed investigation became known as the Kwinana Air Modelling Study (KAMS).

1.3 KWINANA AIR MODELLING STUDY: OBJECTIVES AND METHODOLOGY

1.3.1 Goals and Objectives

The aim of most air quality management programmes is to minimise the effects of air pollution on health, vegetation and materials. These objectives can be achieved either by controlling the source of the emission or by keeping sensitive activities out of areas where air pollution will cause damage. Both methods involve costs and ultimately it is the community itself which must decide how much it is prepared to pay to safeguard air quality.

A decision on just what constitutes an appropriately clean atmosphere can only be made after consideration of those levels of pollutants which have adverse effects on particular aspects of the environment that are of concern. Unfortunately the vital relationship between emissions of pollutants and ambient concentrations is extremely complex, and mathematical models are often needed to help determine the most cost-effective management programme.

The development and use of mathematical models as air quality management tools was seen as the dominant aspect of the Kwinana Air Modelling Study, and this was reflected in the goals and objectives which were identified at an early stage. These were based in part on immediate aims, but were also directed to the wider benefits that would be gained from research into air pollutant dispersion.

(i) KAMS Goals

Primary.
To enable through the application of air dispersion modelling techniques an air quality management plan to be developed for the Kwinana industrial area.

Secondary.
To apply the knowledge gained through the Kwinana Air Modelling Study at other sites in Western Australia, so that optimum planning with respect to air quality may be carried out and implemented.

(ii) KAMS Objectives

The Experimental Study

- Purchase and/or develop a set of instruments to be used at Kwinana and, later, elsewhere in WA for atmospheric dispersion studies.
- Develop expertise in experimental procedure, especially in atmospheric remote sensing techniques.
- Measure, on a continuous basis, emissions from industry, meteorological conditions and ground level concentrations of pollutants, and create a data bank accessible to all interested parties.
- Design and conduct experiments to study particular aspects of the meteorology and dispersion processes, to provide physical descriptions suitable for computer modelling purposes.

The Modelling Study

- Quantify air dispersion processes in and around the Kwinana area to aid transportation and land use planning, including the capability to give practical advice on questions such as the nature and size of buffer zones and the capacity for industry to expand at Kwinana.

- Evaluate emissions and ambient air pollution standards in the Western Australian context, including the need for amended or supplementary legislation.
- Develop methodologies for reviewing the environmental impact of new and established air pollution sources.
- Develop and evaluate methods for the identification of sources of air pollution.

1.3.2 The Structure of the Study

(i) Organisation

The Kwinana Air Modelling Study was conceived as a co-operative exercise with contributions from Government agencies, academic institutions and Kwinana industry. To this end, an Air Pollution Prediction Policy Group was formed in 1976 with senior representatives from the Department of Public Health, the Commonwealth Bureau of Meteorology, the Department of Industrial Development, the State Energy Commission and the Department of Conservation and Environment. A representative from the Town Planning Department later joined the Policy Group. The overall aim of this body was to guide the development of expertise in WA by which practical air quality management of industrial areas could be undertaken on a routine basis.

The Policy Group set itself a charter which focused on the development and refinement of air dispersion modelling techniques at Kwinana and identifying those areas of the State where further work should take place.

In order to initiate the first part of this task, the development and validation of practical air dispersion models, the Policy Group set up a Technical Working Group (TWG) to plan the Kwinana Air Modelling Study. The KAMS Technical Working Group was made up of representatives from the Clean Air Section of the Department of Public Health, the Commonwealth Bureau of Meteorology, the Department of Conservation and Environment, the Department of Industrial Development (later the Department of Resources Development), the State Energy Commission, Murdoch University and the Western Australian Institute of Technology.

Day-to-day co-ordination and execution of the study was carried out by a Core Group consisting of a small number of staff from the Department of Conservation and Environment and the Department of Public Health. The work of this group was supplemented with contract work undertaken by the School of Physics and Geosciences at the Western Australian Institute of Technology and occasionally by the School of Environmental and Life Sciences at Murdoch University. The Technical Working Group was regularly informed of progress in the study and suggestions were discussed at TWG meetings. In practice, it was found that direct contact between participants was preferable and, after the first few years, formal TWG meetings were not needed until final compilation of the report.

(ii) Components

Activities in KAMS were concentrated in four main areas: aerometric data collection, industrial emissions data collection, data management and analysis and mathematical model development and validation (Figure 1.2). A comprehensive account of these activities is set out in later chapters and a brief description is given below.

Aerometric Measurements

Meteorological and pollutant parameters were measured continuously at a number of sites in the study area. In particular, two instrumented automatic base stations were operated for the duration of the study.

In addition, more detailed meteorological and pollutant dispersion data were obtained from four intensive field experiments conducted at Kwinana.

Emissions Inventory

Industry at Kwinana provided data from which a high quality sulphur dioxide emissions inventory was compiled. The excellence of these data enabled sulphur dioxide to be used in the validation of the mathematical models developed for the study.

Data Management and Analysis

Base station data were logged onto cassette tape, edited, reformatted and stored on a computer. All other data were recorded on paper charts which were digitised manually and also stored on computer. The data were then in a form suitable for analysis and for use in the mathematical models.

Mathematical Models

Two numerical models were developed to simulate pollutant dispersion in a wide range of atmospheric conditions. Specialist sub-models dealing with particular meteorological phenomena were developed separately and provided input to the major models.

Using the meteorological and emissions data, the models produced, for a range of averaging periods, sulphur dioxide concentration estimates for the study area. These estimates were then compared to the measured sulphur dioxide data to complete the validation process.

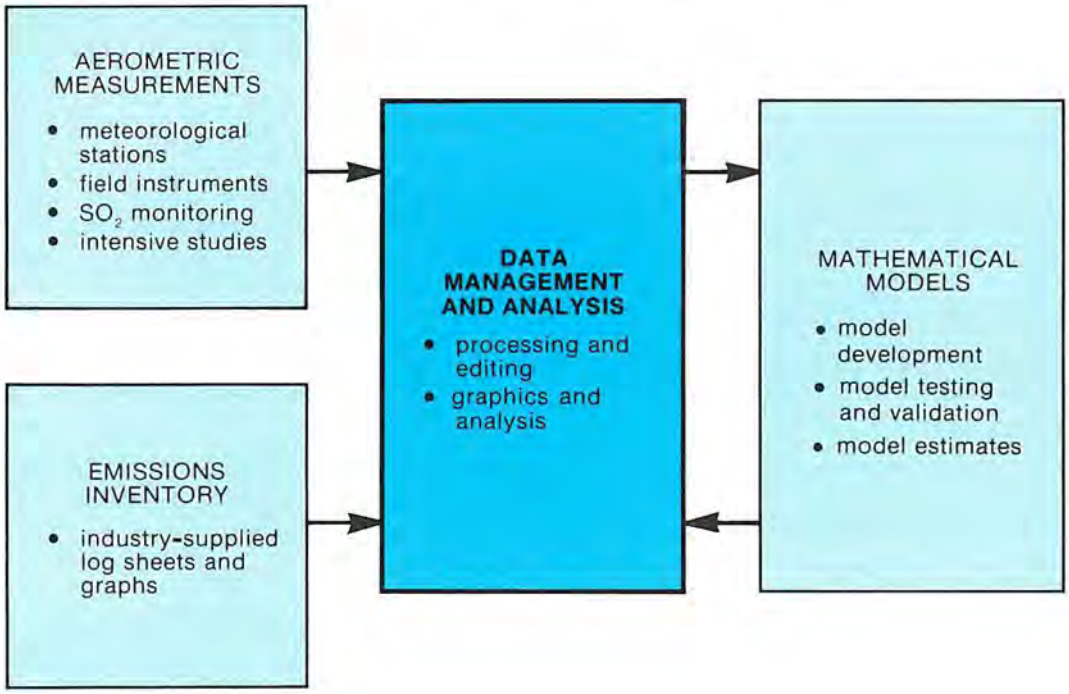


Figure 1.2. The major components of the Kwinana Air Modelling Study.

1.3.3 The Application of Study Results

The purpose of the Kwinana Air Modelling Study has been to allow the air pollution consequences of land use planning decisions to be determined and be updated as necessary. Specifically, modelling may be used to indicate both the present impact of air pollution, and the effect that changed circumstances, such as expansion of industry or alteration of fuel type, would have on the Kwinana environment.

However, the processes of air pollutant dispersion are essentially random and affected by factors which may be poorly understood and can often not be readily measured. This means that the definitive air pollutant dispersion model does not exist and all model estimates are made with a degree of uncertainty. Nevertheless, good quality modelling can provide planning authorities with valuable information on existing and future air pollution impact. Such information may then be integrated with other land use constraints to optimise planning decisions.

Even with the aid of mathematical models the task of the planner is not simple. In the first instance, model results based on a limited time period of measurements may not take account of rare but extreme conditions which lead to unacceptable pollution levels in the atmosphere. Secondly, there is little agreement on the health effects of pollutants, and consequently air pollution standards throughout the world vary widely. In addition, there may be cases where the chosen standard is not clearly violated. Decisions on the course of action required in places that experience pollutant levels near, but below, the standards are most difficult, and can involve consideration of factors which are loosely drawn together and termed 'quality of life'.

Chapter 2

AIR POLLUTION AND ITS MANAGEMENT

Inevitably, some air pollution is always present near industrial zones or large cities with motor vehicle traffic. Careful planning and sensitive use of controls can do much to safeguard against the adverse impact of air pollution on the surrounding environment.

Clearly, it is not possible in populated areas, that the atmosphere be completely unpolluted at no cost to anyone. The control of air pollution does involve costs to all members of the community, most often passed on in the cost of finished products and manufactured goods. Consequently, the control of air pollution must take into account the cost to the community and not be unreasonable when viewed in relation to any adverse impact.

The essential problems of air quality management are to determine what constitutes an appropriately clean atmosphere and what cost the community is prepared to pay to achieve or maintain such a state. The relationship between air pollutant exposure and adverse effects is also difficult to establish, especially in the area of human health.

In addition, the task of defining a 'clean atmosphere' is made more complex by a general community expectation that the atmosphere be not only healthy but inoffensive with good visibility.

This chapter considers the major elements of the air pollution problem. These elements include the nature of air pollution, the techniques used to quantify air pollution impact and the measures that may be taken to minimise its effects.

2.1 AIR POLLUTANTS AND THEIR EFFECTS

Air pollution may be defined as any atmospheric condition in which substances are present at high enough concentrations above their normal ambient levels to produce a measurable adverse effect on man, animals, vegetation or materials.

Prior to industrialisation, most of the common air contaminants were produced naturally by fires, volcanoes and vegetation. The advent of large population centres and heavy industry has now made air pollution a major environmental problem of industrialised nations.

2.1.1 Types of Air Pollution

Contaminating substances in the atmosphere occur in the form of gases, liquid droplets or solid particles and can be placed in two general categories: primary and secondary pollutants.

(i) Primary Pollutants

This class represents those air pollutants that are emitted directly from sources whether they be from industry, motor vehicles or domestic activities. A summary of the most common primary pollutants is given below.

Carbon Monoxide and Carbon Dioxide

Carbon monoxide (CO) and carbon dioxide (CO_2) are both products of the combustion of carbonaceous fuels. Carbon monoxide results from incomplete combustion and is an odourless and tasteless gas. More than 60% of the total world emission of CO comes from motor vehicle exhausts.

Carbon dioxide is not normally considered an air pollutant but in recent years the global background of CO_2 has been steadily increasing, giving rise to concern about its possible effect on large scale meteorology and the climate.

Oxides of Nitrogen

The most common oxides of nitrogen (NO_x) in the atmosphere are nitric oxide (NO) and nitrogen dioxide (NO_2). NO is a colourless, odourless gas while NO_2 is an orange-brown gas with a pungent odour.

Global natural emissions of NO_x far exceed man-made emissions. However, man-made emissions usually occur in high density industrial centres and cities, resulting from combustion processes in which temperatures are high enough to oxidise atmospheric nitrogen. Most NO_x emitted in combustion is in the form of NO but this is then oxidised in the atmosphere to form NO_2.

Sulphur Dioxide

Sulphur dioxide (SO_2) is a colourless, pungent, irritating gas. About 60% of SO_2 is emitted by natural sources such as volcanoes and the oxidation of hydrogen sulphide by bacteria. Man-made sources of SO_2 arise predominantly from the combustion of fossil fuels and from mineral processing. In addition, SO_2 reacts with moisture in the atmosphere to produce sulphuric acid, which may dissolve in cloud water droplets to produce the so-called 'acid rain'.

Suspended Particulates

The term suspended particulates refers to any substance, other than water, which exists as a liquid or solid in the atmosphere and remains in suspension because of its small size. Suspended particulates include such pollutants as dust from industrial stacks and stockpiles, smoke, fumes, particulate lead, pollen grains and sea salt.

Others

In addition to the common pollutants, many other substances are emitted into the atmosphere as a result of man's activity and during natural processes. These include such atmospheric pollutants as asbestos, mercury, benzene, fluorides and lead. Many of these, though present in the atmosphere in small concentrations, can have a marked effect on human health.

(ii) Secondary Pollutants

These pollutants are formed in the atmosphere by chemical interaction between primary pollutants and normal atmospheric constituents. Two of the most important classes of secondary pollutants are listed below.

Photochemical Oxidants

Photochemical oxidants are probably the most important group of secondary pollutants. They consist of ozone (O_3), formaldehyde, organic hydroperoxides, peroxyacetyl nitrate (PAN) and a number of other highly reactive chemical species. Ozone is, by far, the predominant oxidant and is used as the indicator of photochemical activity.

Ozone is formed from oxygen under natural conditions in the stratosphere, and this is mainly responsible for background levels observed in the lower atmosphere. Oxidants are produced by the action of sunlight on hydrocarbons and oxides of nitrogen. Man-made emissions of hydrocarbons are predominantly associated with the production and storage of petroleum products, motor fuels and solvents and with motor vehicle exhaust emissions.

Secondary Aerosols

These particulates are largely responsible for the haze which is normally associated with high concentrations of oxidants. Secondary aerosols are composed mainly of sulphates, nitrates and hydrocarbons arising from primary pollutants, the formation of which depends on chemical reactions and the absorption of gases and liquids onto suspended particles.

2.1.2 The Effects of Air Pollution

Substantial evidence has been accumulated in recent years to show that air pollution has an impact on public health, vegetation and materials as well as impairing visibility and generally interfering with the enjoyment of life and property. In addition, air pollution may influence climate on a regional and even a global scale.

Although some of the effects of air pollution are specific and measurable, others such as health effects on humans are difficult to quantify. The major effects of air pollution are listed below.

(i) Health Effects

Most air pollutants exert their influence on human health by an irritant stimulation of the eyes, nose, mouth, throat and bronchial tree. Others such as carbon monoxide and lead are directly absorbed into the body.

The respiratory system has an effective protective system against invasion by foreign material. Large particles are filtered from the airstream by hairs in the nasal passage and are trapped by the mucus layer lining the nasal cavity and the trachea. In addition, particles may be scavenged by fine hair-like cilia

which line the walls of the entire respiratory system. Most particles of sizes exceeding 5 micrometres (μm) are effectively removed in the upper respiratory system. Smaller particles, of radii less than a few micrometres, are able to penetrate deeply into the lungs.

Often several pollutants can be present at the same time and, as a result, observed effects may be attributable to the combined action of more than one pollutant. The overall physiological response to mixtures of pollutants may be additive, synergistic (greater than additive) or antagonistic (less than additive).

General health effects that can be attributed to some of the most common air pollutants are reviewed below.

Carbon Monoxide (CO)

The effect of exposure to carbon monoxide is reflected in a reduction of the oxygen-carrying capacity of the blood. It has been found experimentally that this leads to longer reaction times, a reduction of visual sensitivity in the dark and an impairment of the ability to estimate time intervals. From this it is suggested that exposure to CO can lead to increased incidences of traffic and other accidents.

Sulphur Dioxide (SO_2)

Sulphur dioxide is a highly water soluble gas and consequently is readily absorbed in the moist passages of the upper respiratory system. It acts as a direct irritant on the human bronchial system and can lead to an increased incidence of respiratory symptoms especially in elderly people, and in those already suffering from diseases such as asthma, chronic bronchitis and emphysema. The main effect is seen in the first minute or two of exposure with only a slight further increase up to 15 minutes.

High SO_2 levels are often associated with high particulate concentrations, though this is not the case at Kwinana. It is known that small aerosol particles can transport SO_2 deep into the lungs and since moisture is often absorbed by these particles, the SO_2 dissolves to form a fine mist of dilute sulphuric acid. As a consequence a three to four fold increase in the irritant response to SO_2 is commonly observed in the presence of particulate matter.

Nitrogen Dioxide (NO_2)

The health effects of nitrogen dioxide are comparable to those induced by sulphur dioxide in that the respiratory system is the main target. Young children, especially, living in areas with high NO_2 levels have been known to experience a significant reduction in ventilatory capacity and a high incidence of respiratory illness.

Ozone (O_3)

The primary health effect of ozone is associated with irritation of the eyes and the respiratory system. There is strong evidence to show that a marked deterioration in the respiratory function occurs in the presence of elevated levels of O_3, especially with exercise.

Suspended Particulates

Airborne particles in the size range less than 5 μm have a potential to cause respiratory problems in humans. Most particles emitted are larger than this and never reach the lower air passages. Particles that are smaller than 0.1 μm do not appear to be a major health concern.

Though there is little evidence to suggest that general airborne particulates constitute a major risk in their own right, they often carry contaminants such as sulphates and nitrates. These, when in contact with water, can form acids which are potentially more irritating than the original gaseous pollutant.

In addition there are a number of particulate substances such as silica and asbestos which by themselves are well recognised as able to contribute to serious disease, especially at high concentrations which may be found in poorly controlled occupational premises.

(ii) Vegetation Effects

All plants are, to some extent, affected by toxic air pollutants. Many species show obvious damage to foliage while plant growth or production is impaired in others. The major phytotoxic pollutants are sulphur dioxide and ozone.

Sulphur Dioxide (SO_2)

Though sulphur is an essential nutrient for plant growth, high levels of SO_2 in the atmosphere can severely damage trees and crops. This damage generally takes the form of necrosis to both upper and lower surfaces of the leaf. In addition the transformation of SO_2 to sulphuric acid mist can cause black spots on leaves and flowers.

Ozone (O_3)

Ozone is considered one of the air pollutants most damaging to plant life. Damage ranges from leaf injury to a reduction in growth and crop yield. Also, ozone appears to affect nitrogen fixation in some grasses and legumes. This has serious implications for fertiliser use.

Fluorides

Gaseous fluorides are particularly toxic to plants such as grape vines and some pastures. The gas enters the plants through openings in the leaves and is transported to the margins where it is accumulated. The major effects include reduced growth and injury or death to individual leaves or whole plants.

(iii) Other Effects

Materials Damage

Damage to materials is a considerable, though little recognised result of air pollution. The major effects include the deterioration of rubber due to high oxidant levels, the destruction of masonry and metals due to acid particles and the discoloration of fabrics and surfaces due to the action of oxides of nitrogen and particulates.

Global Effects

The effects of air pollutants are sometimes observed on an international and even global scale. Perhaps the most important examples are the increase in global carbon dioxide levels resulting from the burning of fossil fuels, and the precipitation of acid rain as a result of emissions of SO_2 from a distant source. A potentially more damaging phenomenon, however, is the depletion of the ozone layer of the atmosphere through reaction with fluorocarbons released by the use of aerosol pressure sprays and from industrial processes.

2.2 AIR POLLUTION METEOROLOGY

Pollutants, once released into the atmosphere, are influenced by complex physical and chemical processes which determine the level of concentrations experienced in the environment. In many cases, such as in KAMS, chemical processes, whilst present, are not significant and physical factors have the greatest effect on the dispersal of air pollutants.

The transport and dispersion of pollutants is primarily a function of the winds and turbulent mixing present in the atmosphere. 'Turbulent diffusion', the process produced by the rapid irregular motion of particles of air, serves to spread pollutants, and can be determined from a number of measurable atmospheric properties. Some important elements of meteorology are briefly described below to give the reader a conceptual understanding of the problems which must be addressed by air pollution models. A far more technical description of some meteorological elements is given in Chapter 6.

2.2.1 Winds

Wind is perhaps the most important factor in the dilution of pollutants since it provides a continually changing reservoir into which pollutants can be dispersed. During high winds, concentrations will be lower than in calm conditions, with a doubling of wind speed giving an approximate halving of the pollutant concentrations. Also, in regions with high variability of wind direction, pollutants will be dispersed much more widely, giving a lower maximum average concentration than would occur for a region with a clearly prevailing wind direction. Short-term peaks of concentrations (over 30 minutes, for example) may still be high however, depending on other meteorological factors.

The wind climate of a site is determined by both the large scale ('synoptic') winds due to high and low pressure systems, and local winds induced by topographic features. Local winds may be caused by mechanical or thermal influences. Examples of mechanically induced local wind effects are large eddies in the lee of mountain ranges, and reduced wind speeds at inland sites, attributable to the roughness of the land surface in

comparison to the sea. The most significant cases of thermal effects are the sea breeze/land breeze cycle experienced at coastlines and katabatic winds which flow down hill slopes at night.

While synoptic winds do not vary greatly between neighbouring localities, local winds can differ significantly over distances of a few kilometres. To detect local wind changes, air pollution studies include comprehensive monitoring of wind fields as a major component.

(i) Sea and Land Breezes

During the daytime in spring, summer and autumn, the air over the land is heated more rapidly as a result of solar radiation than it is over the sea. As the heated air rises and flows out over the cool sea air, the loss of inland air causes the inland air pressure to fall. The resulting sea-to-land pressure difference causes a return flow of air at low levels, which we identify as the sea breeze.

Initially, the high-level offshore/low-level onshore circulation (Figure 2.1(a)) is shallow and does not extend far inland or far offshore. But as the land warms, the 'sea breeze cell' grows and its leading edge, the sea breeze front, may move over 100 km inland by evening. The progressive deepening of the sea breeze is readily seen in coastal industrial areas, as the plumes of successively taller stacks change from an offshore to an onshore orientation.

After sunset, with the rapid cooling of the land surface, the sea breeze circulation may be reversed near the coast, producing the land breeze (Figure 2.1 (b)). In Perth, summer nocturnal conditions are dominated by synoptic-scale easterlies, so that the land breeze may be only a component of the total offshore wind. In winter, however, light land breezes of less than 100 m depth can occur.

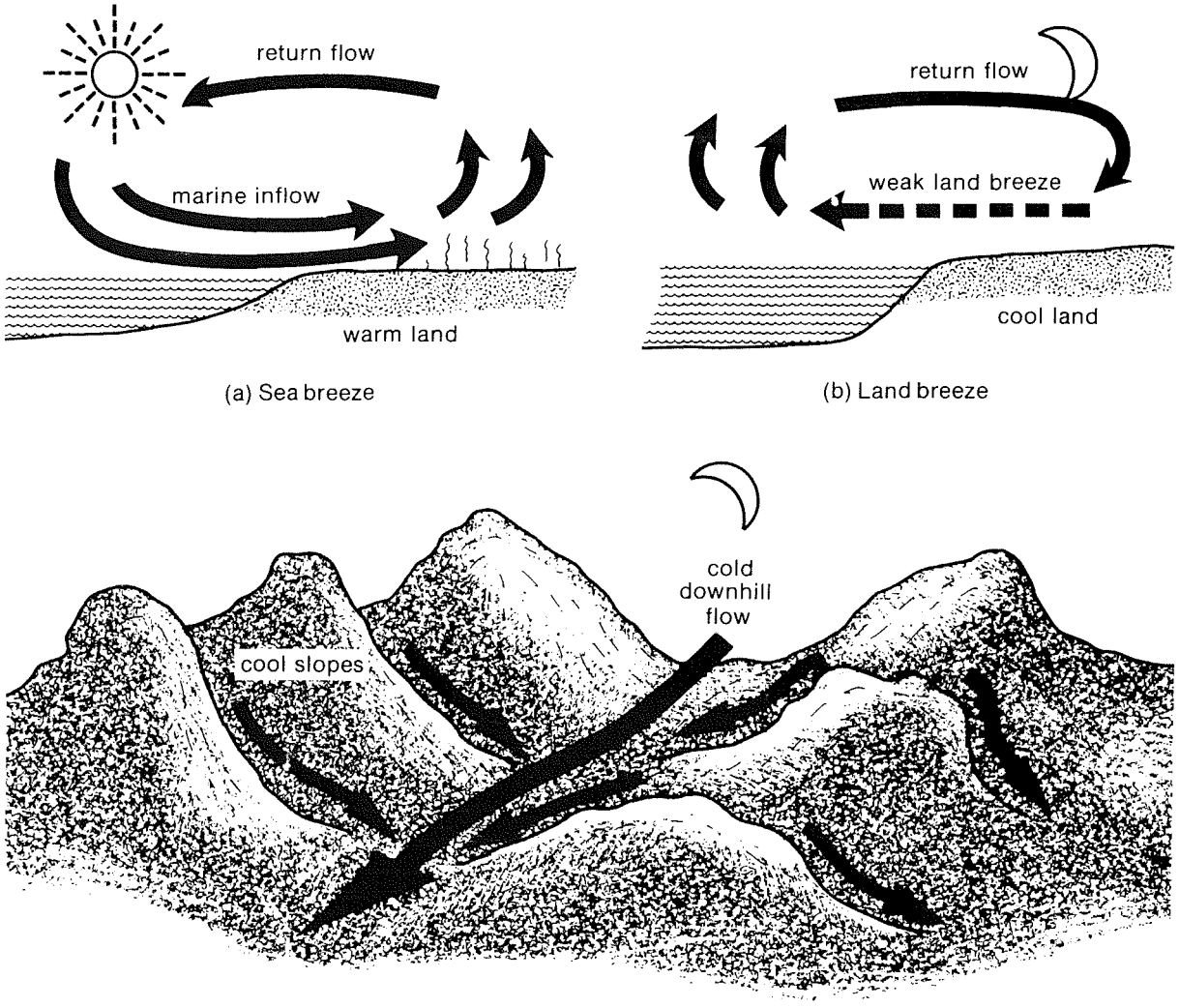


Figure 2.1. Local winds resulting from the differential heating of the atmosphere.

The significance of sea and land breezes in the air pollution climate of an area is twofold. Firstly, since they develop relative to the coastline, such breezes tend to have fairly fixed and steady direction, increasing the impact of an air pollutant source along that direction. Secondly, sea and land breezes generally involve shallow flows, and pollutants trapped within them tend not to mix with the lighter air above.

(ii) Katabatic Winds

Surface air cooled by the cold land surface at night becomes more dense than the air above. It therefore may be compared to a layer of water which is also denser than normal air, and behaves in a similar manner.

A katabatic wind is the downhill flow of this cool air. Such winds may be light but, like water, they tend to converge in valleys causing much more intense flows along the valley floor (Figure 2.1 (c)).

Like the land breeze, katabatic winds are often of regular direction and are quite shallow, causing significant modification to the air pollution climate of an area.

2.2.2 Turbulent Motions

The turbulent motions which disperse air pollutants are generated in two ways.

Firstly, the flow of wind over any ground or water surface causes turbulence to be generated in the layer of air near the surface. The amount of energy imparted to the turbulence is dependent on the roughness of the surface. Turbulent eddies formed by surface friction are typically small in size, although larger eddies may be formed around prominent topographic features.

Turbulence is also generated when the surface is heated to a temperature greater than that of the air mass above, causing thermals or bubbles of warmed air to rise from the surface. The turbulent eddies so formed (called convection) tend to be larger in scale than those formed by surface friction, and their buoyancy causes them to penetrate to a greater height in the atmosphere.

2.2.3 Atmospheric Stability

The turbulent dispersive capability of the atmosphere is determined by the energy and size of its turbulent motions. This capability is conveniently described by a property called 'atmospheric stability'.

The atmosphere is said to be very stable when there is little or no turbulent motion present. Such conditions frequently occur, for example, on calm cloudless nights when the ground and the adjacent air cool down. In cooling, the air becomes more dense and so is inhibited from mixing with the lighter air above. Continued cooling throughout the night will result in a stable layer of air several hundred metres deep. In such stable conditions, the temperature may increase with height (in contrast to its normal decrease during daytime hours) producing what is termed a 'temperature inversion'. The particular case above is also termed a 'radiation inversion'.

An unstable atmosphere is found to exist on hot sunny days where several hours of sunshine has heated the ground to a temperature much higher than that of the general air mass. The air immediately adjacent to the ground becomes warmer and less dense than that above and so rises in the form of discrete thermals. These thermals are matched by much larger and less vigorous cool downdrafts. In this way, the air above the ground is continually mixed up to heights of several hundreds or thousands of metres.

Neutral atmospheric conditions, the intermediate case between stable and unstable, occur when the heating or cooling of the ground is relatively weak and when medium to strong winds obliterate any temperature variations throughout the air layer.

The behaviour of chimney plumes under the three atmospheric conditions described above is shown in Figure 2.2. Under stable conditions the plume disperses very slowly and ground level concentrations may not be registered within a distance of 5 km or more from the source.

Under neutral conditions plumes disperse at a moderate rate such that the maximum concentration at ground level will be registered a few kilometres downwind of a tall stack.

The behaviour of plumes in unstable conditions is very erratic and, whilst overall dispersion is rapid, high short-term concentrations may be produced at ground level within a few hundred metres of a tall stack.

2.2.4 Mixing Depth

In its undisturbed state the atmosphere up to a height of about 10 km is moderately stable, so that vertical

motion is inhibited. Hence, the turbulence generated near the ground does not penetrate upwards indefinitely but is limited in height to what is called the 'planetary boundary layer' or 'mixed layer'. As a consequence, the dispersion of pollutants from ground level is also limited to this layer, the depth of which is appropriately called the 'mixing depth'. Low mixing depths are cause for concern since air pollutants released near the ground will produce high ground level concentrations.

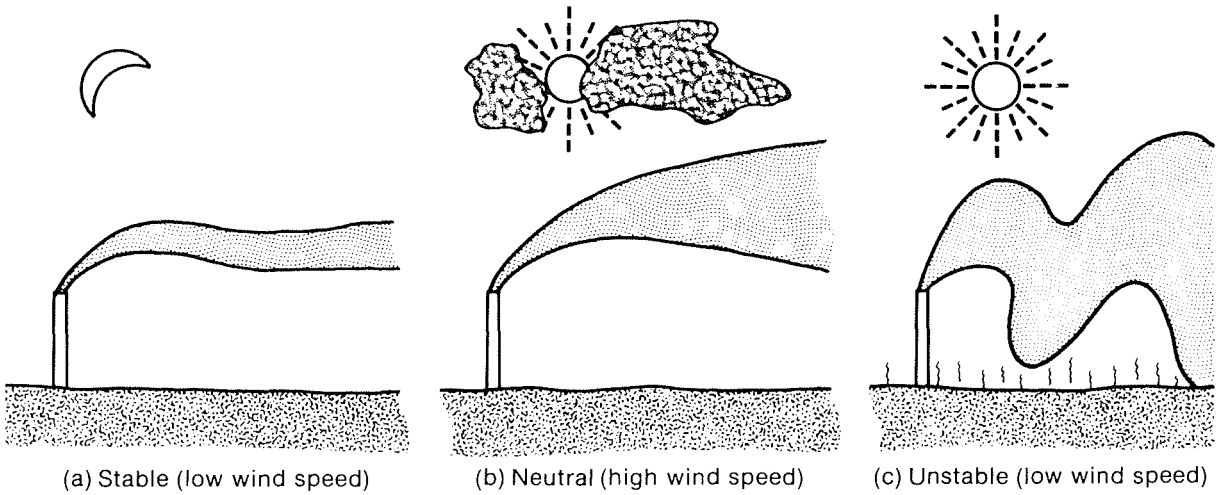


Figure 2.2. Typical plume behaviour under various conditions of atmospheric stability.

At the upper limit of shallow planetary boundary layers, there frequently exists a thin very stable layer or elevated temperature inversion which, due to its stability, acts as a 'lid' on the boundary layer. As well as limiting the rise of well dispersed airborne pollutants, this lid also prevents the rise of buoyant chimney plumes which would otherwise rise into the stable air above. Only very hot chimney plumes may retain enough buoyancy to penetrate such low level lids.

A number of meteorological phenomena which lead to shallow planetary boundary layers (low mixing depths) with strong 'lids' are described below.

The formation of stable temperature inversions on calm cloudless nights was described in the previous section. Following sunrise, incoming solar radiation begins to heat the ground, leading to the formation of a shallow mixed layer which deepens as the thermal mixing intensifies. For a few hours after sunrise the mixing depth is relatively low and the 'lid' above the mixed layer is strong.

Figure 2.3 illustrates the behaviour of plumes as a radiation inversion is eroded in the early morning. In Figure 2.3(a), one stack is tall enough (200 m high for example) to extend right through the shallow mixed layer so that its plume does not reach ground level. The second stack, although below the 'lid', has a hot plume which is buoyant enough to penetrate the lid. The plume from the third and smallest stack is trapped within the mixed layer and disperses much more rapidly than the other two.

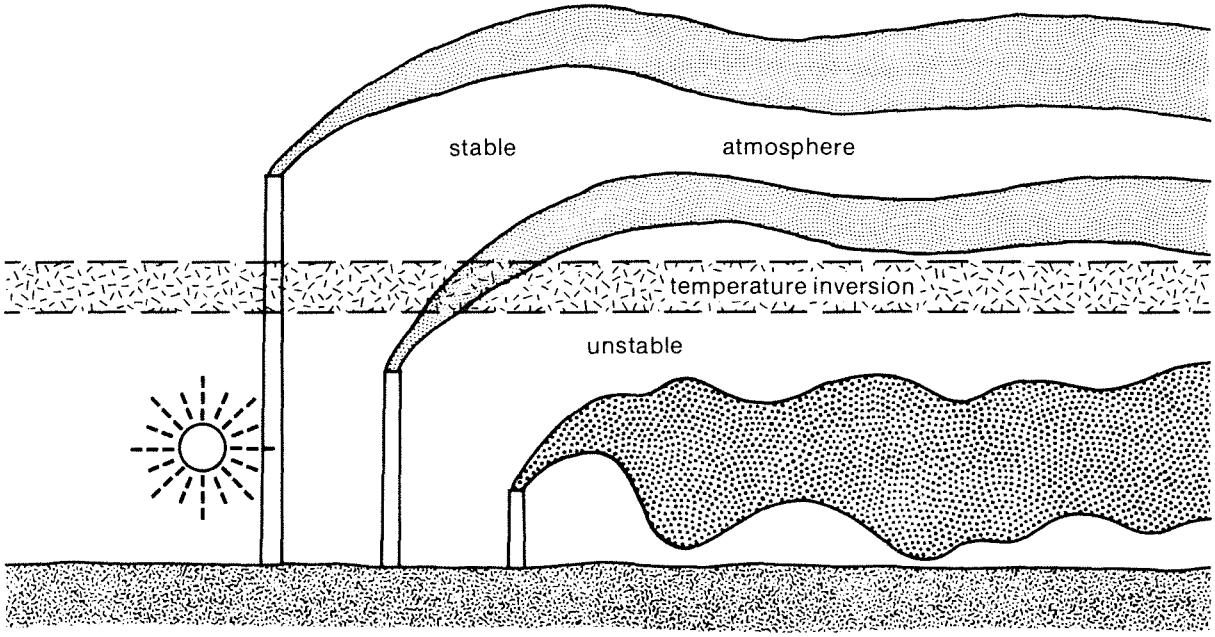
Figure 2.3(b) shows the situation 3 hours later when the mixing depth has doubled and where all of the plumes are now trapped within the mixed layer.

Elevated temperature inversions may also be formed by the subsidence of stable air masses. In areas dominated by high pressure systems, such subsidence may bring warmer air from above closer to the surface, increasing atmospheric stability at lower levels and creating a 'subsidence inversion'. The latitude of Perth corresponds closely to that of the global pressure belt called the Sub-Tropical High, so that this type of inversion is frequently detected.

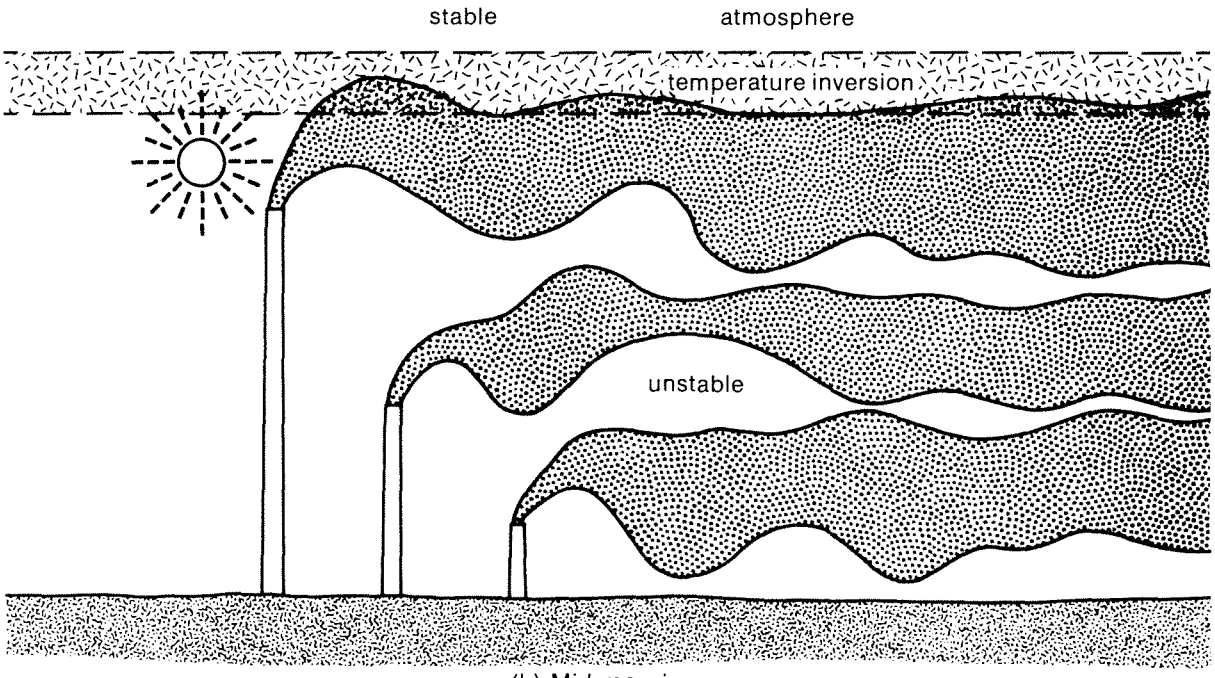
Since subsidence inversions generally occur at an altitude of 1-2 km, they do not affect greatly the impact of industrial air pollution sources. However, they tend to persist for periods of a day or more, and over wide areas, so that plumes from large sources such as bushfires may be detected over many kilometres, trapped beneath a subsidence inversion.

Of particular importance at near-coastal sites is the limited mixing depth associated with sea breezes. These flows are typically 200 to 500 m deep near the coast on hot days and there is a strong temperature inversion between the cool sea breeze flow and the synoptic flow aloft. Once the sea breeze is well established, there are few plumes hot enough to penetrate such an inversion.

The motion of chimney plumes observed immediately after the onset of the sea breeze may be very complex (Figure 2.4), due to the shallow flow and the relatively weak inversion formed at this stage. Plumes from short



(a) Early morning



(b) Mid-morning

Figure 2.3. The effect of temperature inversion erosion on pollutants released from different levels.

stacks may be trapped within the sea breeze flow while plumes from tall stacks are influenced only by the synoptic flow. Those from stacks of intermediate height are affected by both the sea breeze and the synoptic flow. This complex situation is generally short-lived.

2.2.5 Coastal Influences

When an onshore flow such as the sea breeze or a synoptic wind crosses a coastline it is modified by the change in surface roughness and surface heat transfer of the ground. A boundary layer is formed inland from the coast within which the turbulent mixing is stronger than in the marine air, especially on hot days when thermal mixing over the land is vigorous. The behaviour of plumes from industrial chimneys will depend on where they are released in relation to the boundary layer.

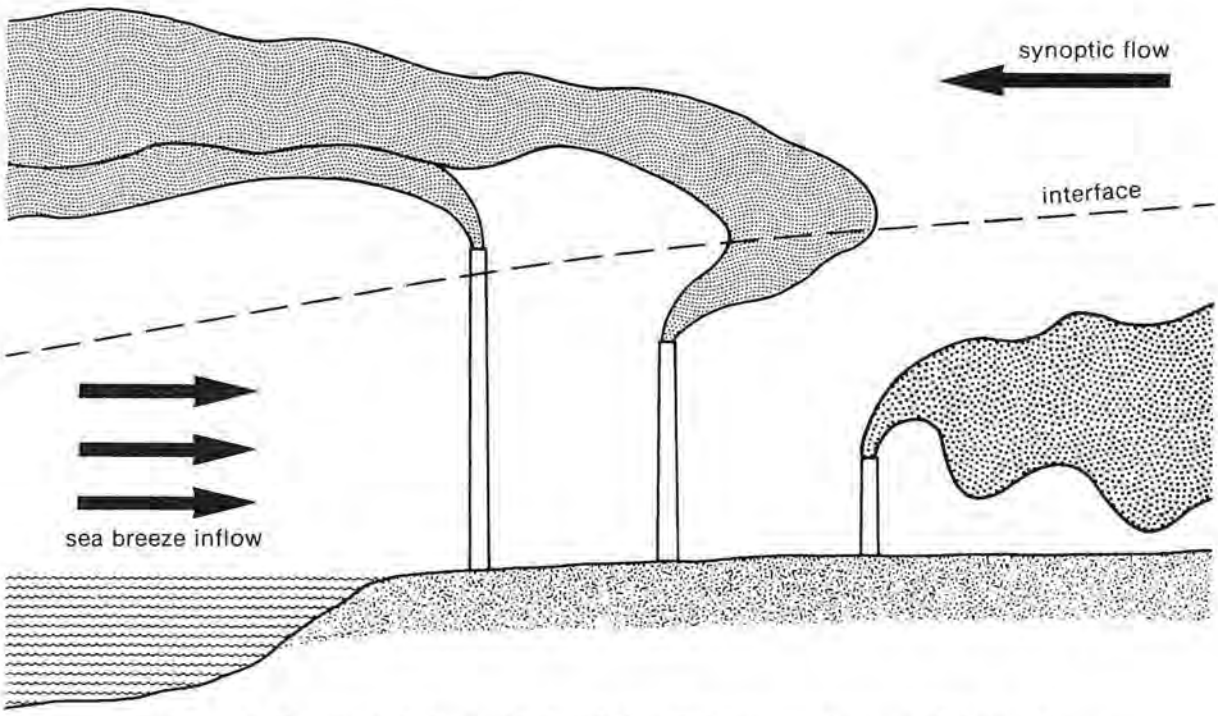


Figure 2.4. An illustration of the complexity of plume behaviour at the onset of the sea breeze.

Figure 2.5 shows that a plume released within the boundary layer will be rapidly dispersed, while a plume from a tall stack at the coast may rise and disperse very slowly in the marine flow until it intersects and is mixed into the growing boundary layer several kilometres downwind of the stack. Due to this complicated plume behaviour, high ground level concentrations may be registered at much greater distances from the source than in the case of the low plume first described. This phenomenon is commonly known as 'shoreline fumigation'.

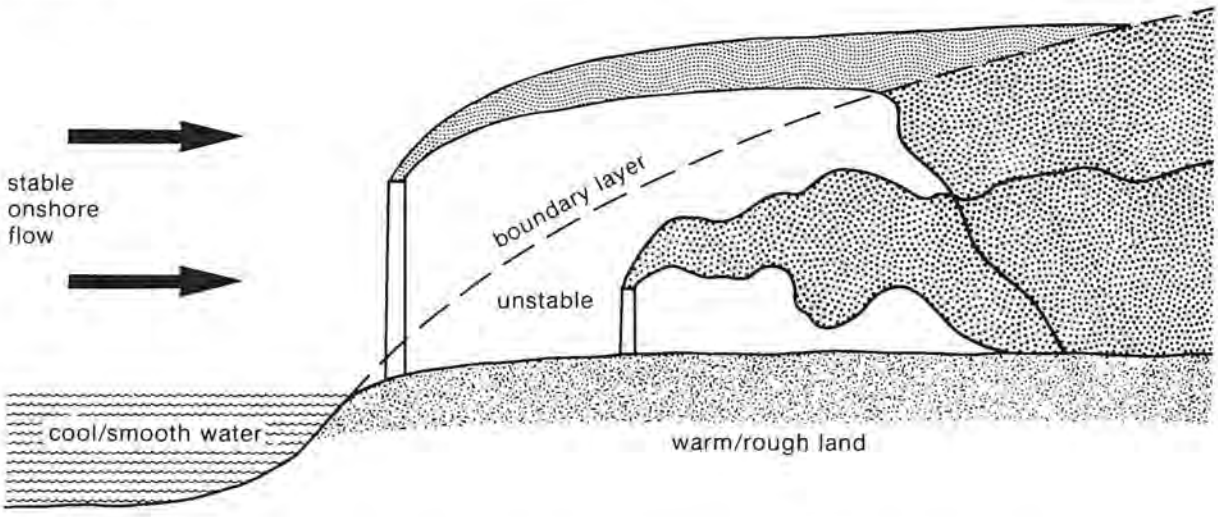


Figure 2.5. The fumigation process due to the presence of a coastal boundary layer.

2.3 MONITORING AIR QUALITY

The acceptability of air quality is most usually determined from the results of monitoring ambient pollutant concentrations with reference to a set of air quality objectives designed to protect health, welfare or vegetation. Ambient monitoring data are also required to validate mathematical dispersion models.

Ambient pollutant monitoring programmes vary considerably depending on the pollutant to be monitored,

the area of concern, the use to which the data are to be put and the resources available. These factors, in turn, affect the density and siting of the monitoring network and the frequency with which measured variables are recorded.

Pollutant levels in the atmosphere are most commonly monitored to determine their impact on the human population or sensitive vegetation. The programmes needed for this type of surveillance are related to the manner in which the pollutant adversely affects its subject. Where damage results from cumulative long-term doses of a pollutant, an instrument which measures long-term average concentrations and is located in a region of maximum impact might adequately indicate the nature of the problem and any need for remedial action. A knowledge of the meteorology of the area and an inventory of pollutant sources would aid initial siting of the monitor.

Where there are many pollutant sources spread over a large area, monitoring long-term average concentrations is relatively simple since these concentrations often do not vary greatly over the area. Thus, the annual average sulphur dioxide concentration representative of a large city such as London, for example, may be quite accurately determined from a single monitoring site in the city.

This is not the case, however, in a region such as Kwinana where pollutant sources are located quite closely together. Since atmospheric dispersive characteristics vary with direction, long-term pollution impact is direction-dependent, and a function of distance from the main sources. The annual average concentrations experienced in urban pockets such as Medina (south-east of the sources), Rockingham (south) and Wattleup (north-east) therefore have to be determined separately. Thus, accurate determination of even long-term average concentrations over the KAMS study area using an ambient pollutant monitoring programme may require a network of possibly 10-12 instruments to register the spatial variability of the long-term impact.

In the case where high, short-term pollutant concentrations are of concern, instruments which monitor continuously are most profitably deployed. These sorts of instruments have a response time often of only a few seconds and can measure the short-term variability of pollutant concentration levels. The data produced can be processed directly using electronic data logging equipment or by computer to give average concentrations for any chosen period. Short-term averages most commonly range from 3 minutes to 3 hours.

Short-term, high pollutant concentrations are often far more variable over an area of study than is the long-term average concentration. This may be due to topographic features such as hills and valleys or to dispersive mechanisms such as shoreline fumigation (Section 2.2.5). The monitoring programme generally required to illustrate such variations in the Kwinana area, for example, would consist of a large number of continuous monitors located as closely as 1 km apart. Clearly, in most cases limitations of resources and manpower could prevent the implementation of such a programme.

Alternatively, it is possible to create mathematical representations of the pollutant transport processes – 'models' – to provide insights into the pollution climate of an area. However, pollutant dispersion models can be of value in air quality management only if they have been properly validated. Most often validation requires the mathematical model to reproduce to an acceptable accuracy a set of ambient monitoring data obtained at a few sites. In KAMS for example, sulphur dioxide was measured continuously at two sites and a data set of 10-minute, 1-hour, 3-hour, 24-hour, monthly and annual average concentrations generated for comparison with the model output. Where long-term averages only are produced by a model, it is not necessary to have continuous monitoring and instruments with a coarser time resolution may be used.

In addition to ambient monitoring, an inventory of actual pollutant emission levels from industrial or other sources is often included in an air quality management programme. This may be undertaken to determine compliance with emission regulations, or to provide input for mathematical dispersion models.

Emission levels may be determined directly using chemical techniques to analyse flue gases or indirectly from plant operation information such as fuel composition and usage. Chemical methods are most often used to determine compliance with emission limits set by air quality management agencies.

The modelling of the existing air pollution impact of a region requires an accurate inventory of pollutant emissions as a model input. Where there are a large number of sources the emission levels are obtained most efficiently by consideration of plant operation and processes. For KAMS, emission levels averaged over periods from 30 minutes to 8 hours of some 50 sources of sulphur dioxide were estimated from fuel composition and consumption rates during the study period. There are disadvantages, however, in using such a technique when a flue gas scrubbing system is in operation or fuel consumption data are provided at irregular or large time intervals. In both cases flue gas composition variability may not be reflected in the emissions data and this will affect estimates of ground level concentrations.

2.4 MODELLING AIR QUALITY

Air quality models provide the type of information which monitoring generally cannot, namely a description of pollutant distributions over a wide area, with fine resolution if required. Models are often conveniently considered to be a 'black box' into which data is fed and from which the required results are produced. Nevertheless, it is important to realise that the quality of the results is critically dependent on the contents of the 'box'. Furthermore, a model developed and validated for one locality may be quite inappropriate for another locality. It is important, therefore, that the persons responsible for using a model developed elsewhere are completely familiar with its capabilities and limitations.

An air quality model in its developed form is a computer program which employs mathematical descriptions of the physical phenomena known to be important in determining the transport and dispersion of air pollutants. The model accepts input data describing either time sequences or statistical distributions of important meteorological parameters and emissions of pollutants from industrial or other sources. The computer uses these data in a succession of calculations which ultimately yield an estimate of ambient pollutant concentrations. Long-term average concentrations or short-term peak concentrations may be obtained from the appropriate data.

The successful use of computer models reflects the state of sophistication of modern computers. Computers which execute around one billion operations per second have revolutionised the techniques available to scientists for solving complicated mathematical problems such as turbulent dispersion. In addition the development of data logging equipment which produces computer-compatible data on magnetic tape or various other storage media has facilitated the handling of massive quantities of data. The three million values of meteorological parameters recorded during KAMS are easily stored on one magnetic tape and may be transferred in seconds.

A detailed discussion of the models developed in KAMS is given in Chapter 6. The remainder of this section briefly describes the important components of an air quality model. These components relate closely to the important meteorological phenomena described in Section 2.2 above.

To model a region such as the Kwinana area it is most convenient to describe the region by map grid co-ordinates, with grid points about one kilometre or less apart. Important features such as the coastline and industrial sources of pollutants are fixed within the grid. The model should ultimately produce estimates of concentrations at each grid point, allowing contours of concentrations to be mapped.

The transport of pollutants over the grid is influenced primarily by wind speed and direction which must be specified in the model. These parameters are routinely measured and form part of the input data file. Data from a network of anemometers may be required if the wind changes speed or direction significantly over the region.

Pollutants may come from an area source such as an urban district or a point source in the case of an industrial chimney. The rise of hot chimney plumes may be calculated by the model from emissions data supplied by the industry. The distribution or shape of plume gases may be either specified directly (using the Gaussian plume model of Section 6.4.1(iii) for example) or computed using other techniques such as the eddy diffusion model (Section 6.4.1(ii)). In either case the contribution of the plume to the ground level concentration at any grid point can be calculated.

As described in Section 2.2 the rate and vertical extent of plume spread is strongly dependent on the atmospheric stability and mixing depth. Accurate determination of these two parameters is a central part of air pollution modelling. The various methods in use all utilise meteorological parameters measured near the ground (and sometimes aloft) to estimate the mixing energy (or lack of it) in the planetary boundary layer. Mixing depths are sometimes measured directly by an acoustic sounder, or inferred from radiosonde records.

Finally, there are features specific to given locations which require specialised model components to be developed. In KAMS, the feature requiring special attention was the internal boundary layer described in Section 2.2.5. Mathematical descriptions of the boundary layer growth and plume mixing in this layer have been developed and incorporated into the KAMS models. In some areas, the effect of topography on dispersion must be included in the formulation of a mathematical model.

2.5 AIR QUALITY OBJECTIVES

Modern air quality management normally involves the establishment of air quality objectives (or standards) and a control programme to achieve or maintain such objectives. The objectives may specify acceptable pollutant concentrations in the atmosphere, scientifically defined to safeguard the environment and, in particular, the health and welfare of human beings.

Ambient air quality objectives are based on the assumption that there exists a pollutant 'threshold concentration' which represents conditions to which the environment can be repeatedly exposed without adverse effect. There are currently in existence a large number of such objectives, often referred to as guidelines, target values, goals, acceptable levels and detrimental levels. They vary with regard to severity, timescale and degree of accounting for particulate matter present in the air. Traditionally, standards have been specified as a limiting average concentration over periods ranging from 24 hours to a full year. In more recent times there has been more concern with short-term air pollution episodes ranging from 30 minutes or less to a few hours. Corresponding short-term standards have been produced in several countries.

The most significant air pollutant, in an historical sense, to come under the scrutiny of control agencies has been sulphur dioxide; it is also a pollutant of particular importance at Kwinana (Section 3.2). As a result of a number of severe air pollution episodes involving sulphur dioxide in Britain, Europe and the United States (Gilpin, 1978), there have been attempts to markedly reduce ambient concentrations of this pollutant in large cities and industrial areas. The acceptability of the resulting concentrations was necessarily related, in the first instance, to the adverse effects of sulphur dioxide on health.

Though it is generally accepted that air pollution affects human health, studies aimed at determining the degree of effect have not been unanimous in their findings. Interpretation of the results is made more difficult by the variation of such factors as the time and frequency of exposure, age and medical history of the subjects, the extent of cigarette smoking and the effect of simultaneous exposure to other pollutants. Indoor pollution from sources such as tobacco smoke, indoor fires and cooking may reach higher levels than those experienced outdoors.

These epidemiological studies have been used to indicate the lowest concentration of sulphur dioxide at which adverse health effects, such as increases in respiratory symptoms or respiratory disease incidence in the general population, might be expected. Standards have then been set below the levels indicated in the studies. A useful summary of the effects of sulphur dioxide is given in a World Health Organisation (WHO) document *Sulphur Oxides and Suspended Particulate Matter*, Environmental Health Criteria 8 (WHO, 1979). The essential aspects of this summary are also given here.

Inhalation studies carried out under controlled short-term exposure conditions show that sulphur dioxide alone, at a concentration of 2100 $\mu g/m^3$, slightly affects respiratory function, while sulphuric acid mist affects respiratory function at levels as low as 1000 $\mu g/m^3$. Effects in pulmonary function have been reported from joint exposure to SO_2 and hydrogen peroxide, as well as to SO_2 and ozone.

In morbidity studies on short-term exposure to a combination of SO_2 and total particulates, the lowest daily-average concentrations at which adverse effects occurred were 200 $\mu g/m^3$ and 150 $\mu g/m^3$ respectively. For long-term joint exposure studies, effects were noted at annual mean concentrations of 60-140 $\mu g/m^3$ for SO_2 and 100-200 $\mu g/m^3$ for total suspended particulates. There were, however, reservations expressed as to the validity of some of these studies.

Based on evaluation of the literature, WHO has developed guidelines for the protection of public health. These are set in terms of 24-hour values (100-150 $\mu g/m^3$ for SO_2 and for smoke) and in terms of annual means (40-60 $\mu g/m^3$ for sulphur dioxide and for smoke).

The World Health Organisation guidelines are based on observations among populations in communities exposed to a mixture of sulphur dioxide and smoke or total suspended particulates. It is recommended, however, that the levels of each pollutant should be below the values stated: that is, 100-150 $\mu g/m^3$ and 40-60 $\mu g/m^3$ for 24-hour and annual average sulphur dioxide concentrations respectively.

In addition, as is pointed out in the document, there remains much uncertainty about the minimum levels associated with demonstrable effects. Where populations exposed to different levels of pollution had been compared, it could not necessarily be assumed that even those who were exposed to a level lower than the known lowest effect level would be unaffected by it. Where effects were demonstrable, it was difficult to determine whether these effects were related to extended exposures at the average levels or more particularly to shorter-term high pollution episodes within the period.

Many standards for sulphur dioxide, including the WHO guidelines, have been based largely on the experience in highly industrialised cities of the northern hemisphere. This experience is one of relatively high 'background levels' due to a multitude of sources with some high short-term episodes resulting from adverse emission and meteorological conditions.

As a consequence, most standards have focused on annual mean concentrations, adding a 24-hour average value that should not be exceeded more than a certain number of times per year. Table 2.1 shows a range of sulphur dioxide standards that have been established in recent years, in addition to the WHO values.

The United States EPA has set both 'primary' and 'secondary' standards. The primary standards are designed to protect public health, while the secondary standards are to protect aesthetics, property and vegetation. The secondary standard is more stringent than the primary for the annual mean while 24-hour standard has been replaced by a short-term, 3-hour standard.

Table 2.1. A range of ambient sulphur dioxide levels established by various organisations. The levels given in 3, 4 and 5 have been converted from parts per million and rounded upwards.

1. UNITED STATES (USEPA, 1977)

Primary Standard (to protect public health)

Annual average:	80 $\mu g/m^3$
24-hour average:	365 $\mu g/m^3$ exceeded not more than once per year

Secondary Standard (to protect public welfare)

Annual average:	60 $\mu g/m^3$
3-hour average:	1300 $\mu g/m^3$ exceeded not more than once per year

2. WORLD HEALTH ORGANISATION (World Health Organisation, 1979)

Guidelines

Annual average:	40-60 $\mu g/m^3$
24-hour average:	100-150 $\mu g/m^3$

3. VICTORIA (Victoria Government Gazette No. 63, 1981)

Acceptable Level

1-hour average:	500 $\mu g/m^3$ exceeded on no more than 3 days per year
24-hour average:	170 $\mu g/m^3$ exceeded for no more than 3 days per year

Detrimental Level

1-hour average:	1000 $\mu g/m^3$ not to be exceeded
24-hour average:	310 $\mu g/m^3$ not to be exceeded

Alert Level

1-hour average:	1400 $\mu g/m^3$

4. JAPAN (Werner and Stern, 1974)

Environmental Objectives

Maximum 1-hour average:	300 $\mu g/m^3$ not to be exceeded
24-hour average:	120 $\mu g/m^3$ not to be exceeded

5. SWEDEN (Werner and Stern, 1974)

Guidelines

30-minute average:	750 $\mu g/m^3$ exceeded not more than 15 times per month
24-hour average:	300 $\mu g/m^3$ exceeded not more than once per month
1-month average:	150 $\mu g/m^3$ not to be exceeded.

Sweden has a 30-minute, 24-hour and 1-month standard while the Japanese have introduced a 1-hour and 24-hour standard.

The Victorian EPA objectives, the only sulphur dioxide standards in Australia with a statutory basis, have a three-level structure. An 'acceptable level' is defined as a concentration above which sensitive persons may experience some ill effect (Environmental Protection Authority of Victoria, 1979). At concentrations above the 'detrimental level', it is claimed that ". . . a substantial portion of the exposed population may be adversely affected, or significant changes are likely to be caused to some segments of the environment" (Victorian Government Gazette, 1981). An additional 'alert level' has also been specified.

Prior to 1981, the National Health and Medical Research Council of Australia (NHMRC) recommended that the earlier, less stringent, WHO long-term goals of 60 $\mu g/m^3$ for the annual mean and 98% of 24-hour average observations below 200 $\mu g/m^3$ be adopted as guidelines (WHO, 1972). Although without statutory backing, both figures were used as guidelines in WA.

Following a meeting in October 1981, the NHMRC recommended as an air quality goal, a maximum permissible annual mean level in the urban environment of 60 $\mu g/m^3$ for sulphur dioxide. No goal has yet been set for 24-hour or lesser averaging periods. The Council did, however, recommend that ". . . sulphur dioxide and particulates in the urban environment are not allowed to rise above existing levels" (National Health and Medical Research Council, 1981).

Up until the present, high level short-term air pollution episodes have not been seriously considered for planning or control purposes in Western Australia. Although the effects of chronic exposure to brief high levels of sulphur dioxide are not certain, they cannot be neglected (Anderson et al., 1974). In addition, the effects of these episodes on individuals who already suffer from respiratory disease, who are cigarette smokers or who are exposed simultaneously to other contaminants may be more severe than for a healthy population.

The problem of defining appropriate air pollution health standards, though a difficult one, should not be considered intractable. Bates (1972) asserts that some medical authorities have been inclined to discount epidemiological data which show adverse effects on health due to air pollution, on the grounds that convincing evidence of pathogenic mechanisms has not been advanced. As a consequence it is sometimes maintained that unless some clinical condition can be shown to be directly caused by air pollution, then it is without effect. Bates believes that this is a simplistic view of disease.

It is quite apparent that more work could be done to devise, for local conditions, appropriate ambient air quality standards. In Australia, this applies, in particular, to an evaluation of the place of long- and short-term standards. The question also remains as to whether the standards used in the northern hemisphere, where the atmosphere is often already heavily polluted, are appropriate to the relatively clean atmospheric environment found in Australia. Furthermore, there should be consideration of wider aspects of air pollution including welfare and annoyance. As documented by WHO (1979) ". . . it may be that effects such as annoyance reactions will, in the future, be the critical effects on which criteria, as regards the protection of public health, will be based".

For the purpose of this study, the sulphur dioxide standards against which modelled and measured concentrations were evaluated are presented in Chapter 8. Recommendations in respect to standards are made in Chapter 9.

2.6 AIR QUALITY MANAGEMENT PROCEDURES

Air quality management has been defined (Stern, 1977) as ". . . the regulation of the amount, location and time of pollutant emissions to achieve some clearly defined set of ambient air quality standards or goals." In order to achieve this, an air pollution control authority must have at its disposal:

- A set of air quality objectives related to the short-term and long-term effects of pollutant concentrations on health, vegetation and so on,
- An inventory of existing or proposed pollutant sources in the particular area of concern,
- Monitoring data to determine existing pollutant concentrations,
- Predictive methodology to relate emissions to ground level atmospheric concentrations,
- Viable emission control options which can be used to meet objectives.

Air quality management programmes are devised taking into account community values, the state of technology and economic conditions. The implementation and design of such programmes also has regard for the particular circumstances of various industry types or groupings and can also include strategies for controlling emissions from mobile sources such as motor vehicles.

These programmes often incorporate a number of measures to control the effects of air pollution, including optimum siting of industry in respect to atmospheric dispersion, stack design, the prohibition of highly polluting fuels and processes and the application of emission controls. In addition, 'buffer distances' are used to protect the welfare (as opposed to health) of individuals near industrial activities.

In areas where ambient air quality objectives are not being achieved, stringent controls may be applied to new sources. Existing industry, however, is often given a reasonable period of time (based on economic and social factors and the impact of existing air quality levels) to reduce emissions.

The formulation of a coherent strategy for air pollution management is hampered by the difficulty in clearly demonstrating the relationship between pollutant emissions and measured atmospheric concentrations. Mathematical models are increasingly used to investigate the relationship and determine the time, place and rate of emission needed to meet the chosen ambient air quality objectives.

A brief description of the major elements of modern air quality management is given below.

2.6.1 Siting of Industry

The location of industry can have a marked effect on the dispersion of pollutants emitted, and consequently, on the constraints imposed by the industry on adjacent land uses. While primary control of ground level

concentrations is achieved by stack design and emission limits, a regional air quality plan should seek to site industry in the most favourable location having regard to the physical features which influence dispersion and the existing and projected land use patterns.

In particular, heavy industry and urban or other sensitive activities should be sufficiently separated. Whilst stack design and emission controls are generally used to protect health, a 'buffer zone' can be used to protect welfare, or against nuisances such as dust and noise.

It is not intended, however, that a sterile zone should exist between industrial sources and sensitive land uses. Less sensitive activities can be accommodated in the area around industry so that the welfare or amenity of individuals in urban areas, for example, is protected.

2.6.2 Controlling Ground Level Concentrations

(i) Stack Height

Under most meteorological conditions maximum ground level concentrations resulting from a given source will be decreased by increasing the stack height. Consequently, tall stacks long have been considered as a valuable air quality management tactic, especially in the United Kingdom (Department of the Environment, Scottish Development Department, Welsh Office, 1956). In Australia industrial stacks up to 300 m have been constructed in an effort to achieve acceptable ground level concentrations.

While the use of the tall stack is clearly of benefit for an isolated source, there are potential problems for industries located near built-up areas and near the coast. Since the maximum ground level concentration from a tall stack is attained at a considerable distance from the stack, it may contribute significantly to pollution levels in an area that has already an air pollution problem of its own. In addition, plumes from stacks on the coast may interact with the boundary layer formed there and produce the shoreline fumigation phenomenon (Section 2.2.5). In such cases it may be that a shorter stack is a preferable option, depending on the effects of the consequent higher near-source concentrations thereby produced.

(ii) Emission Controls

The fundamental concept of emission limits or standards is that there is some maximum possible, or practical, degree of emission control which it is reasonable to ask all members of a specific class of industry or source to achieve.

Emission limits are generally specified as a mass emission rate per unit time, production, distance (in the case of mobile sources) or fuel used. Due to later developments in emission control technology, there may be a differential between existing and proposed new sources, with new sources subject to a greater degree of control.

In addition to limits on emissions from individual plants, total emissions for a region may have to be controlled. When pollutant concentrations approach or exceed ambient air quality objectives, lower emission limits may have to be applied. In the United States, for example, if a new industry wants to locate in such an area, it may only do so if there is a reduction in emissions elsewhere in the airshed. The industry may therefore be required to install appropriate controls on an existing source.

Regulations for emission control may specify emission rates, appropriate control technology or prohibited activities and a description of the methods used to determine compliance. If new technology makes it possible to set a more stringent standard, this can readily be applied to all new sources.

Uniform application of emission limits is not always the most cost-effective way to manage air quality. Stringent application of a limit in a remote locality may necessitate a large expenditure for a small reduction in air pollution effects. Conversely, if the standard is too flexible, industrial emissions may not be controlled to the degree necessary to preclude adverse effects or the alienation of land adjacent to industry. Thus, a distinction between emission limits set for country and metropolitan regions may be acceptable.

A number of different approaches can be applied to the control of emissions from industrial sources:

Best Available Control Technology (BACT)

With this approach, each industry is required to employ the best technology currently available for controlling emissions and to keep the control equipment in good operating order. Emission limits based on the 'best technology' can be imposed though actual emission limits need not be specified; the operator who installs and maintains appropriate equipment may be deemed to be complying with the regulations.

Economic considerations are to some degree built into the BACT philosophy. Just what constitutes the best available control technology is determined taking into account the additional cost that will be imposed on the industry. BACT is normally only applied to new sources of emissions.

Best Practicable Means (BPM)

The 'best practicable means' approach to emission control has regard to factors such as local conditions, the state of technical knowledge and the economic climate (even of an individual company). Consequently, this means of control is more flexible than BACT since the degree of control could change from year to year or between industries of the same type.

In Western Australia, the control of emissions from new sources is regulated by the Air Pollution Control Council under the Clean Air Act. The Act specifies that ". . . all practicable means . . . " should be used to control emissions. No emission limits (except for dark smoke) have been specified under the Clean Air Act. However, the National Health and Medical Research Council emission standards normally are applied as guidelines for new sources.

2.6.3 The Role of Models in Air Quality Management

While ambient pollutant monitoring indicates pollutant concentrations under existing conditions, it is often necessary to estimate concentration distributions likely to result from changes in emission levels, stack configurations or meteorological conditions.

An ambient air quality model is a tool by which atmospheric pollutant concentrations can be estimated for any emission levels under varying meteorological conditions. As a result, many important aspects of air quality management are best addressed by the use of models. This does not mean, however, that models always provide an accurate simulation of the pollutant dispersion process. Consequently, even with the aid of mathematical models, the management of air quality is a difficult task.

Some uses of mathematical models in air quality management, particularly with reference to Sections 2.6.1 and 2.6.2, are described below.

(i) The Determination of Existing Pollutant Levels

The air pollution impact from industry already existing in an area can be estimated using a mathematical model properly validated at only a few points. Long-term average concentrations and the frequency of short-term, high concentration episodes can be compared with chosen health or vegetation standards, to indicate any need for emission controls or the protection of sensitive activities.

In the United States, for example, standard mathematical models are specified to determine compliance with the Ambient Air Quality Standards (AAQS) which have been set for a number of pollutants. For a given location, the evaluation process begins with measurement of the ambient air quality. If the measured value is less than the AAQS, then the situation is acceptable. If mathematical modelling shows that the AAQS would be exceeded at some future date (due to industrial growth or change in fuel type), then an appropriate control programme can be devised in an attempt to prevent the predicted violation.

When measured values are above the AAQS, emission controls can be applied to bring them into compliance with the standards.

(ii) Planning the Location of New Industry

If the pollutant emissions of a proposed industrial activity can be estimated with reasonable accuracy, mathematical models may be used to determine likely pollutant impact, and locate the industry so that it has the minimum adverse affect on adjacent land uses. This is especially important in planning for competing land uses near urban areas.

On the Perth coastal strip, for example, modelling has shown that pollution impact is generally at a minimum to the south-east of a pollutant source. It is therefore preferable that such sources be located to the north-west of urban areas when this option is available. The spatial separation of the land uses would, of course, require detailed modelling, taking into account the location and height of sources, emission levels, and the time of emission.

(iii) Stack Design

Mathematical models are commonly used to determine the stack height needed to ensure acceptable ambient pollutant concentrations in the vicinity of a proposed industrial source. For a given emission, a

stack height is chosen and the model is run to produce estimates of the ground level atmospheric concentrations that could be expected. If the concentrations do not satisfy the design criteria or ambient air quality objectives used for comparison, another stack height is chosen and further concentration estimates generated. The procedure is repeated until the design criteria are met.

The meteorological data used in the modelling process can be that of a typical year or may involve the detailed study of the 'worst-case' conditions which produce the highest concentrations.

(iv) The Evaluation of Emission Control Strategies

Mathematical models can also be used to estimate the contribution to atmospheric pollutant concentrations of each pollutant source in a particular airshed. Consequently, the impact of various air quality management options such as fuel changes, the installation of control equipment or selective shut-down can be evaluated for cost-effectiveness.

In addition, 'real-time' models are used to simulate air dispersion processes virtually as they occur in order to predict when pollutant concentrations become unacceptable. In Los Angeles for example, complex models are used to simulate the build-up of photochemical pollutants. On the basis of the modelling information measures can be taken to alleviate the problem. These may include shutting down certain stationary pollutant sources or banning motor vehicles from the city area.

Chapter 3

THE KWINANA ENVIRONMENT

3.1 LAND USES IN THE KWINANA REGION

Land uses within the KAMS study area are subject to control by the Metropolitan Region Planning Authority (MRPA) which has statutory responsibility for planning in the whole of the Perth metropolitan region. Local authority planning schemes provide the detail necessary to implement the objectives of the Metropolitan Region Scheme (MRS). Figure 3.1 shows the zoning of the current Metropolitan Region Scheme and the principal industries that are of relevance to the modelling study.

The study area can be considered to be divided by the proposed controlled access highway (CAH). To the west of the CAH lie the major heavy industry complexes while to the east rural land uses predominate with large residential areas to the south-east and south-west of the study area. Some areas of land reserved as Parks and Recreation in the MRS also serve to buffer the residential areas from the effects of industrial activities.

3.1.1 Heavy Industry

Most of the land to the west of the CAH is zoned industrial. Activities in this area include the refining of oil, the refining or processing of iron, steel, alumina and nickel and the production of various chemicals and fertilisers. In addition, the State Energy Commission operates a large power station at Kwinana which supplies power to the Perth metropolitan region.

The Cockburn Cement Company has a plant to the north of the study area between Thompson Lake and the coast. Land on which the plant is sited has not been designated for industrial use under the Metropolitan Region Scheme but has been zoned for industry under the local authority town planning scheme which prevails in this instance.

3.1.2 Residential

There are two major residential areas of relevance to the study. To the south-east of the major heavy industries lies an urban area encompassing the suburbs of Medina, Orelia, Calista and Parmelia. Future residential expansion is planned to extend southwards of the existing development. The large regional centre of Rockingham to the south-west includes the suburbs of Shoalwater, Safety Bay and Hillman.

The smaller residential enclave of Wattleup lies to the north-east of the major heavy industries. However, of the area zoned urban, only the portion to the west of the railway line at Wattleup has been developed.

3.1.3 Agriculture

Land to the east of the CAH is mostly zoned for rural activities. Much of this land is used for market gardening, small scale mixed farming and hobby farming. Large areas to the east of the SEC power station and the Alcoa alumina refinery, however, are used to store the caustic waste products generated by the alumina refining process.

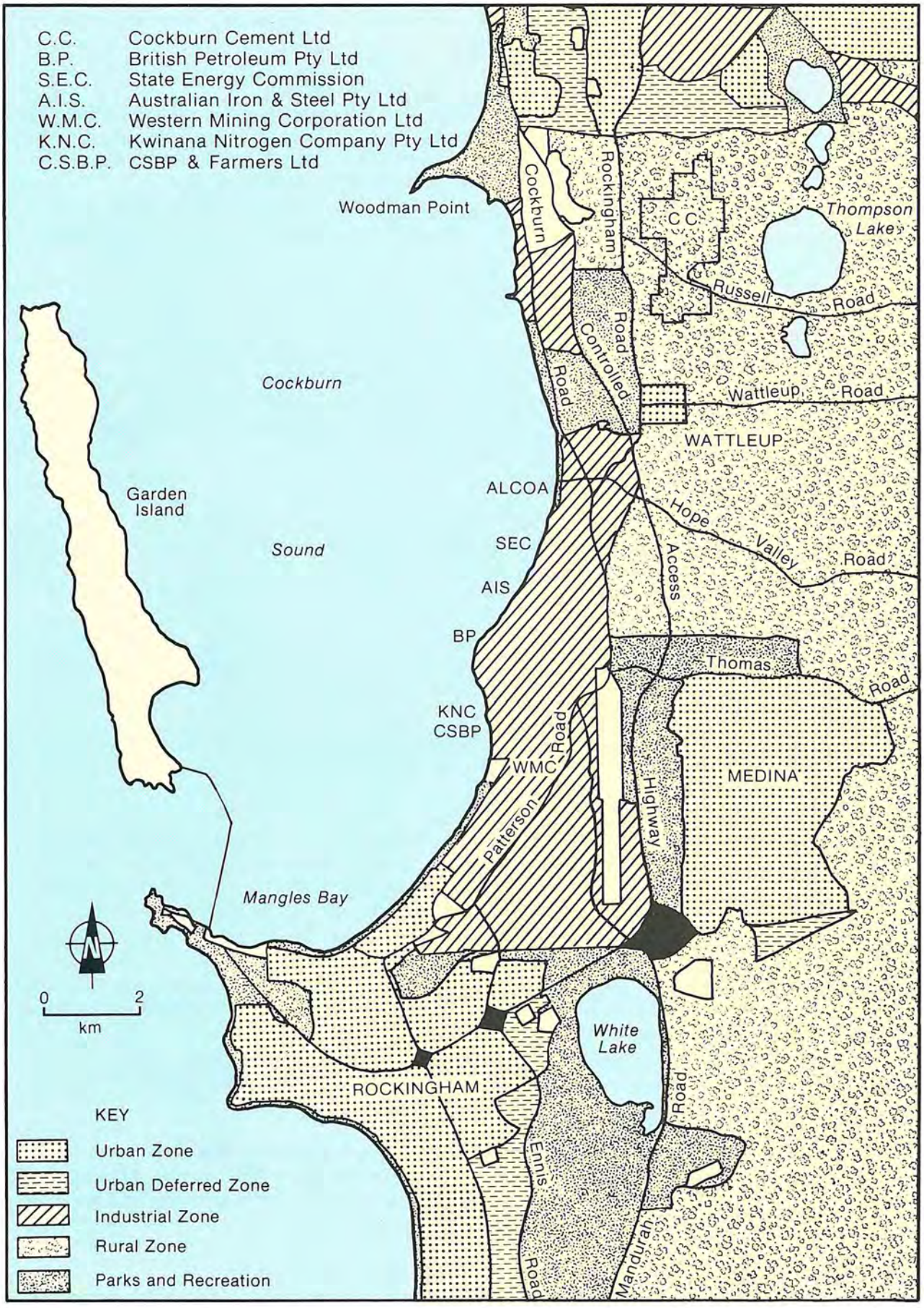


Figure 3.1. Details of the Metropolitan Region Scheme (October 1981) in the KAMS study area showing the location of the major industries.

A small rural wedge is also located to the west of the CAH covering portions of Naval Base and Hope Valley. At Hope Valley subdivision into half-hectare lots has occurred and as a consequence the population density here is higher than elsewhere within the rural zone.

3.1.4 Port Facilities

Large scale port facilities have been provided at Kwinana to service the heavy industry located adjacent to Cockburn Sound. Nine cargo berths exist at present, including one at the alumina refinery (Alcoa), two at the steelworks (AIS) and three at the oil refinery (BP). Two other berths are provided by the Fremantle Port Authority and another by Cooperative Bulk Handling Pty Ltd, for the loading of grain.

Provision has also been made in the Metropolitan Region Scheme for the development of an additional 17 berths in the Mangles Bay area and a number of berths offshore to accommodate future growth in demand for port facilities.

3.1.5 Recreation

Cockburn Sound and its associated mainland beaches form an important recreational resource for the population of the Perth metropolitan region. There are three main beaches and three public boat launching ramps on the eastern shores of Cockburn Sound. The area is heavily used for water-based recreation (Feilman Planning Consultants, 1978). In addition, there are six holiday camps, two Education Department camps and assorted caravan parks, rented cottages and camping sites which are used extensively, particularly during the summer months.

3.1.6 Open Space

Large areas of region open space exist to the north and west of Medina and to the west of Wattleup. Land use in the open space is limited and this ensures that conflict between the industrial activities to the west and residential land is minimised.

3.2 INDUSTRIAL ACTIVITY

The Kwinana industrial area is the most important heavy industry complex in WA. There are eight large industrial installations at Kwinana which are of significance for the Kwinana Air Modelling Study. All eight discharge a variety of air pollutants but sulphur dioxide is the predominant emission. Consequently, sulphur dioxide has been used to validate the mathematical models developed for the area.

The following is a brief description of the processes involved in each industry. More detailed information, particularly in regard to the emission of SO_2, is given in Martin and Rosher (1982).

3.2.1 Alcoa of Australia Ltd (Alcoa)

The alumina industry in Western Australia was established under an agreement between the State and Alcoa of Australia Ltd in 1961. The first unit of 200,000 tonnes/annum capacity was completed by 1964 and a further five units were subsequently added bringing the capacity of the refinery to 1.25 million tonnes/annum by 1970. Because of site limitations, this is the maximum capacity possible at the Kwinana plant.

The refinery has four major stacks which are fed from eight boilers in the powerhouse. Two calcination units feed each of three stacks but the major sulphur dioxide emissions from the plant can be attributed to the power generating process. Both powerhouse and calciners are operated at a steady rate giving uniform emissions of SO_2 throughout each day. The refinery is responsible for about 38% of the annual sulphur dioxide emission into the atmosphere at Kwinana.

Fuel oil with an average sulphur content of 3.3% is used throughout the refinery but the possibility exists that natural gas may replace oil. In such an event the SO_2 emissions would be greatly reduced from current levels.

3.2.2 The State Energy Commission (SEC)

The Kwinana power station is a major base load station and was originally intended to operate on oil. By 1973, four 120 MW oil fired units had been installed and the first of two 200 MW oil fired units was completed by 1976. Because of sharp increases in the price of oil by this time, it was decided to modify both of the 200 MW units so that coal could also be used for firing. The actual generating capacity on coal was reduced from 200 MW to 120 MW per unit. These conversions were completed by 1979 and the 200 MW units are currently used for base load generation on coal and for peak load with oil supplement.

Work is proceeding on the conversion of two of the 120 MW oil fired units to coal firing. This work will be completed by 1983 giving the station an overall capacity of 680 MW on a coal/oil mixture or 880 MW on oil alone.

The main air pollutants discharged from the station are sulphur dioxide and oxides of nitrogen from the combustion of fossil fuels. The gases are emitted into the atmosphere by means of three large stacks and the contribution from the power station to annual sulphur dioxide emissions for the region is about 20%. The amount of sulphur dioxide emitted varies quite markedly on a short-term basis due to large variations in electricity demand.

Future emission levels of sulphur dioxide from the Kwinana power station will depend on the nature of power generation adopted (base, intermediate or peak load) and the sulphur content of the fuel used. With the present load, the exclusive use of coal would result in some reduction in emissions whilst the use of natural gas would eliminate almost entirely the sulphur dioxide emitted from the power station.

3.2.3 Australian Iron and Steel Pty Ltd (AIS)

Two large plants were operated by the Broken Hill Proprietary Company (BHP) at Kwinana during the study period. A steel rolling mill was involved in the production of steel products for local supply and a sinter plant and blast furnace produced pig iron for export. A subsidiary company, Australian Iron and Steel Pty Ltd (AIS), controls the operation at Kwinana.

The rolling mill was commissioned in 1956 with an initial capacity of 50,000 tonnes/annum. The present capacity of the mill is 200,000 tonnes/annum though production at this time is only about 75,000 tonnes/annum of rolled products.

A blast furnace of 450,000 tonnes/annum capacity was commissioned in 1968 and was later upgraded to 900,000 tonnes/annum capacity. Since completion of the study, the blast furnace has been shut down as a result of a severe downturn in the market for pig iron product.

Power for the steelmaking and rolling processes is drawn from an on-site power station operated by AIS. The whole operation discharges sulphur dioxide to the atmosphere through five main stacks but these contributed only about 1.5% of the total annual SO_2 emission from the Kwinana industrial complex during the main study period. Therefore, the reduction in total SO_2 emissions due to closure of the blast furnace will not have a significant effect on present air pollution levels at Kwinana.

3.2.4 BP Refinery (Kwinana) Pty Ltd

The BP refinery was the first major industry to be established in the Kwinana industrial area with initial production taking place in 1955. The total capacity of the refinery is 5.2 million tonnes/annum and present crude oil usage is about 4.5 million tonnes/annum.

There are a number of complex processes in operation at the refinery and 25 stacks emit sulphur dioxide. The stacks are, in the main, low level sources and the refinery contributes about 39% of the annual sulphur dioxide loading in the area. Short-term variations in emissions are quite common and are due predominantly to the flaring off of large quantities of excess gas over short periods.

Additional air pollutants from the plant include hydrocarbons from storage facilities and oxides of nitrogen from combustion.

3.2.5 Kwinana Nitrogen Company (KNC)

A chemical plant jointly owned by BP and CSBP has been in operation at Kwinana since 1968. The present capacity of the plant is 100,000 tonnes/annum of ammonia, 83,000 tonnes/annum of nitric acid and 140,000 tonnes/annum of ammonium nitrate.

Refinery gas from BP is used as feedstock for the KNC plant and consequently emissions of sulphur dioxide are negligible, being somewhat less than 1% of all emissions from the industrial area. Pollutants such as oxides of nitrogen, ammonia and acid fumes are also discharged in varying amounts during operations.

3.2.6 CSBP and Farmers Ltd (CSBP)

Under an agreement with the State Government in 1964, CSBP has constructed a concentrated fertiliser manufacturing complex at Kwinana. Superphosphate is manufactured at the works at the rate of 500,000 tonnes/annum at the present time. Phosphoric acid, ammonium nitrate and compound fertilisers are also produced.

Power is generated internally from the manufacturing process and this ensures that discharges of sulphur dioxide to the atmosphere are not significant. Other air pollutants of some significance include fluorides, oxides of nitrogen and dust from stockpiles.

3.2.7 Western Mining Corporation Ltd (WMC)

Production from the WMC plant at Kwinana commenced in 1973. The refinery produces nickel (21,000 tonnes in 1978-79), and ammonium sulphate (98,000 tonnes in 1978-79). Power is generated within the plant using fuel oil and some natural gas and the standard products of combustion, sulphur dioxide and oxides of nitrogen, are produced. The sulphur dioxide discharged makes up about 3% of the total emission at Kwinana.

3.2.8 Cockburn Cement Ltd (CC)

The Cockburn Cement Ltd works at Kwinana has the capacity to produce about 800,000 tonnes/annum of cement clinker and approximately 350,000 tonnes/annum of quicklime.

Kilns used for processing are fired by pulverised coal or oil as a back-up. Oxides of sulphur and nitrogen are produced during the firing of the kilns but the level of discharge of these gases is not at all significant in relation to the whole of the regional output. The emission of particulates is, however, a more important problem.

3.3 AIR POLLUTION CLIMATE

The term 'air pollution climate' refers to the seasonal variations of the impact of air pollutant emissions within a region. It may be taken as the net effect of changes through the year of wind, mixing depth and atmospheric stability.

At Kwinana, the synoptic-scale winds are generally easterlies (Bureau of Meteorology, 1969). With major industry located near the coast, this factor results in a decrease of air pollution impact inland. The large daytime mixing depths which develop over the land surface to the east, and the strong convective motions which develop within the mixed layer, also help reduce pollution impact during periods of easterly wind.

At night, the rapid cooling of the inland regions results in the formation of radiation inversions (Section 2.2.3) during times of light wind. The reduced dispersion of near-surface pollutants under these conditions creates increased pollution potential for low level sources. Plumes from the major high level sources may remain above the inversion, however, reducing their effect, but after sunrise the rise of mixing depth can produce short periods of high ground level concentration, when the growing mixed layer extends above their level. Such 'fumigation' periods are a component of the air pollution climte which is difficult to predict without detailed study.

Times of onshore flow occur in all seasons, the winter season seeing periods of westerly winds associated with the passage of cold fronts. Pollution impact due to the winter westerlies is reduced, however, by their strength and depth, both factors which tend to keep mixing depths large.

In summer, the easterlies are disrupted by two main phenomena. The sea breeze (Section 2.2.1(i)) is the better known. The other, known as the 'west coast trough', is produced as air, carried by the easterlies, moves out over the ocean and cools. The pressure changes which result turn the winds to a more southerly direction, producing a clockwise circulation about a low pressure trough aligned along the coast. The trough moves inland frequently, and is largely responsible for the cool changes experienced on the coast in summer.

The sea breeze and west coast trough may cause limited mixing depths, although these are not as low as for nocturnal inversions. They reduce the upward dispersal of pollutants, while permitting emissions from elevated sources to disperse to ground level. For this reason, the summer period is that of greatest air pollution impact in the Kwinana region.

Chapter 4

FIELD MONITORING

An extensive field monitoring programme carried out over a number of years formed the basis of the Kwinana Air Modelling Study. The programme provided both meteorological data and ambient sulphur dioxide concentrations over the study area and the level of sulphur dioxide emissions from major industry at Kwinana. Meteorological information and industrial emissions formed the input to the mathematical dispersion models whilst ambient sulphur dioxide measurements were required for model validation.

Two instrumented base stations were operated throughout the study. Base Station 1 was located in the Wattleup residential area and Base Station 2 further south at Kwinana. Following the acquisition of additional equipment, Base Station 2 was relocated in late 1979 to a site at Hope Valley (Base Station 3).

Other continuous monitoring included the use of Woelfle field anemometers, 24-hour sulphur dioxide sequential samplers and an acoustic sounder. The location of all monitoring equipment is illustrated in Figure 4.1. A more detailed account of the field monitoring equipment and methods used in the study is given by Rosher, Rayner, Raich and Martin (1982).

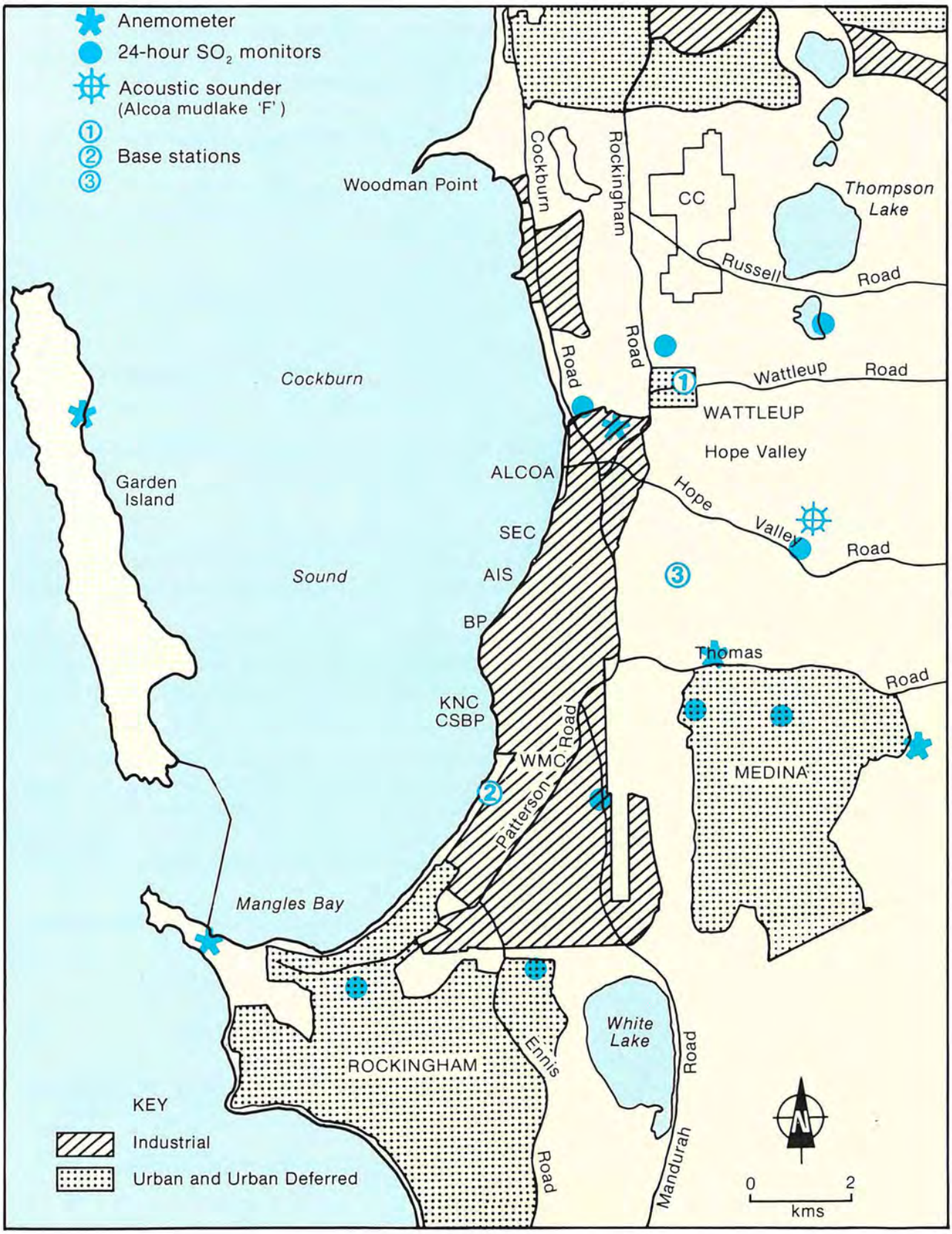


Figure 4.1. The KAMS study area showing the location of monitoring instruments.

4.1 DESCRIPTION OF EQUIPMENT

4.1.1 Base Stations 1 and 2

Each consisted of an instrumented 10 m tower and an airconditioned van housing electronic signal conditioning equipment, a continuous sulphur dioxide monitor and data logging equipment. The vans and sulphur dioxide monitors were supplied by the Clean Air Section of the Department of Public Health.

A brief description of each of the meteorological sensors used at the two base stations follows:

- Wind Speed (10 metres): MRI model 1074 cup anemometer, consisting of a light bulb-photocell assembly, a light chopper disc and a tachometer to compute wind speed.
  Range 0 to 35 m/sec, Accuracy 0.1 m/sec.
- Wind Direction (10 metres): MRI model 1074, consisting of a ganged two-section potentiometer and a resistance-to-voltage conversion circuit.
  Range 0 to 540 degrees, Accuracy 3 degrees.
- Air Temperature (10 metres): MRI model 842, consisting of an aspirated dual thermistor and resistor network with a resistance-to-voltage conversion circuit.
  Range -30 to 50 degrees C, Accuracy 0.15 degrees.
- Dew Point (10 metres): MRI model 892, consisting of an aspirated lithium chloride sensor with bifilar wire electrodes.
  Range -50 to 50 degrees C, Accuracy 1.5 degrees.
- Solar Radiation: MRI model 860, consists of Eppley Black and White Pyranometer with a high precision amplifier.
  Range 0 to 1400 W/m^2, Accuracy 2.5%.
- Sigma Theta (10 metres): MRI circuit 1431200 provides a continuous real-time standard deviation measurement of the wind direction from its mean over a 3-minute period.
  Range 0 to 45 degrees, Accuracy 2.5%.

Continuous air sampling and analysis for sulphur dioxide was carried out using a TRACOR 270HA atmospheric sulphur analyser. In the TRACOR, sulphur dioxide concentrations are determined by using an automatic gas chromatograph to separate the sulphur dioxide from other gases, and then passing it through a flame photometric detector.

EDAS 16 data loggers manufactured by Digital Electronics were used to record 10-minute averages of all parameters. The units utilize voltage-to-frequency converters and high speed counters to provide accurate scalar averages of the input signals, thus, avoiding the aliasing errors inherent in many other logging systems.

4.1.2 Base Station 3

Analysis of the meteorological data from the Kwinana base station showed that the site was less than ideal for the purposes of model development and validation. A new site at Hope Valley subsequently was chosen as more representative of the whole of the study area. The base station was relocated in late 1979.

The opportunity was also taken to significantly upgrade the base station. A 27 m tower was installed with wind and temperature being measured at two levels. Some additional parameters were also measured. A brief description of additional sensors installed at Hope Valley follows:

- Wind Speed, Wind Direction, Air Temperature and Sigma Theta at 27 metres all have the same specifications as their counterparts at 10 metres located at Base Station 1.
- Net Radiation: Middleton Instruments Net Pyradiometer with precision amplifier.
  Range -700 to 800 W/m^2, Accuracy 3%.
- Relative Humidity at 10 metres: Vaisala Humidity meter with precision amplifier.
  Range 0 to 100%, Accuracy 5%.
- Soil Temperature at 0.5 cm: Analog Devices, Two Terminal IC Temperature Transducer with associated circuitry for current to voltage conversion.
  Range 0 to 90 degrees C, Accuracy 0.1 degrees.
- Soil Heat flux at 1 cm: Middleton Instruments Heat Flux Plate with precision amplifier.
  Range -150 to 200 W/m^2, Accuracy 5%.

4.1.3 Acoustic Sounding

Acoustic sounders make use of the fact that sound waves propagating through the atmosphere undergo weak reflections where a change in refractive index is encountered. Such changes can arise from turbulence-

induced inhomogeneities in the temperature structure, and, to a lesser extent, the humidity of the atmosphere.

A sounder transmits pulses of sound vertically into the atmosphere and records on a paper chart the weak signals backscattered from these density inhomogeneities. Strong signals are registered throughout a convective mixed layer and at the interface with an inversion where entrainment of the warmer air from above is occurring.

Acoustic sounding in KAMS was performed in two modes:

- Continuous operation of a sounder (constructed by the University of Melbourne) operated by Murdoch University at a site near the Alcoa mudlake 'F' (Figure 4.1).
- Operation for shorter periods (during experiments) of a mobile acoustic sounder, designed and constructed by the WAIT School of Physics and Geosciences. This instrument was generally sited at Base Stations 2 or 3.

4.1.4 Sulphur Dioxide Monitoring (24-hour samplers)

In addition to continuous sulphur dioxide monitoring at the base station sites, air sampling for the determination of 24-hour average sulphur dioxide concentrations at Kwinana was carried out using a sequential sampler developed by the Clean Air Section of the Department of Public Health. Monitoring was undertaken at nine sites (Figure 4.1).

The sampler is designed so that air is passed through a Whatman No. 1 filter and then through a 50 mL sample of potassium tetrachloromercurate (TMC) absorbing solution contained in glass Dreschel bottles with flow-matched sintered glass bubblers. Eight bottles are available in each instrument (changed automatically at midnight) which allows samples to be collected weekly.

The analytical technique used in this work is a modified version of the pararosanaline method (West and Gaeke, 1956). Adjustments are made for the temperature-dependent decay rate of the absorbing complex for the computation of 24-hour average sulphur dioxide concentrations.

4.1.5 Woelfle Anemometers

Five continuously recording Woelfle-type Lambrecht anemometers were located in the study area to determine the wind field of the region. The instruments were mounted on wooden posts at a height of approximately 10 metres above the ground at sites shown on the location map.

The Woefle anemometer records, onto a continuous strip chart, the wind direction and the wind travel (wind run). The wind run is converted to an average speed over one hour by an analyst using a special scale overlay. Wind speed can be resolved to about 0.1 metre/second (m/s). At very low wind speed the anemometer characteristics determine the recording accuracy, and each anemometer has a particular wind speed below which it stalls, indicating calm air. At wind speeds above 10 m/s the reading accuracy is reduced.

The anemometer records showed that the wind field over the study area was fairly uniform under most conditions with differences being due to the local topography at each site and the reduction in wind speed inland due to frictional effects.

4.2 DATA PROCESSING AND ANALYSIS

Cassettes produced by the data loggers operating at the two base stations contained all the 10-minute average information from the meteorological and pollutant monitoring instruments. Additional information relating to instrument calibration, maintenance and general operation of the base station was entered into a free-format log book.

The digital cassettes were read under program control to temporary magnetic cartridge storage on a mini-computer. This transfer allowed for the deletion or modification of records which were known to be of doubtful quality. The raw data were then plotted by the mini-computer to reveal any data errors or anomalies which had not been indicated in the log books, following which appropriate adjustments were made.

The corrected data were transferred to the central computer for final processing involving the application of predetermined calibration expressions to produce a time series of 10-minute average parameter values.

During the two and a half years of base station operation over 2 million 10-minute averages were recorded and processed. An example of data presentation is shown in Figure 4.2 (a), (b), (c) where daily averaged wind speed, daily maximum and minimum air temperatures and daily solar radiation are graphed as a time series for a period of one year. Figure 4.3 shows the wind speed and direction histogram for the period July 1979 to June 1980, the year over which the models were run. An alternative presentation of this information is given in the wind/speed direction percentage occurrence matrix of Table 4.1.

Photography—Shepherd Baker Studios

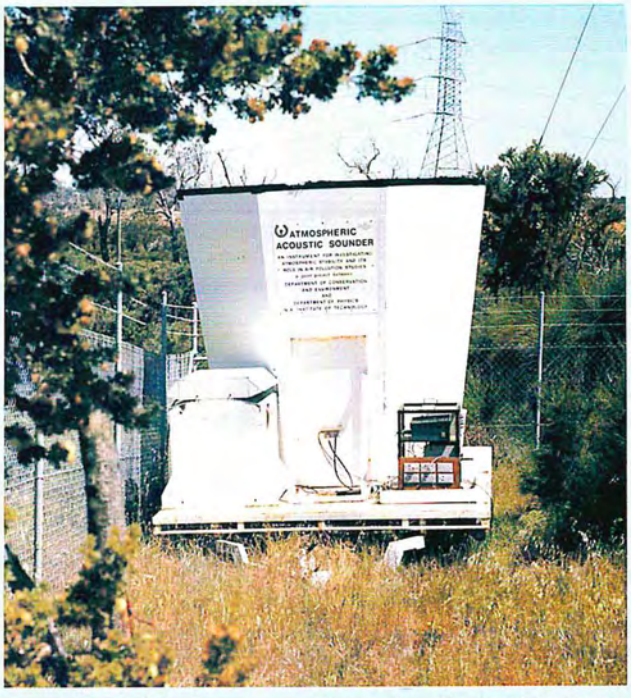
Plate 1. Wattleup base station.

Photography—Ken Rayner

Plate 2. Hope Valley base station.

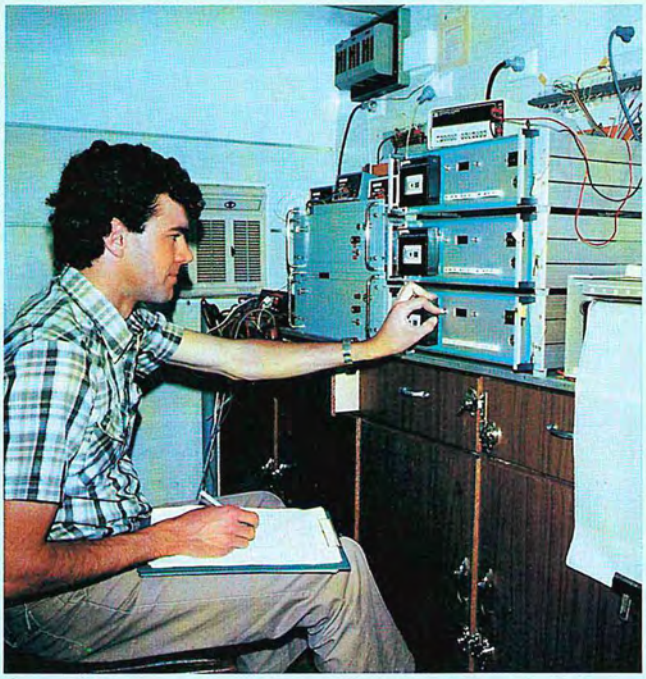
Photography—John Rosher

Plate 3. A Woelfle anemometer on 10 m pole.



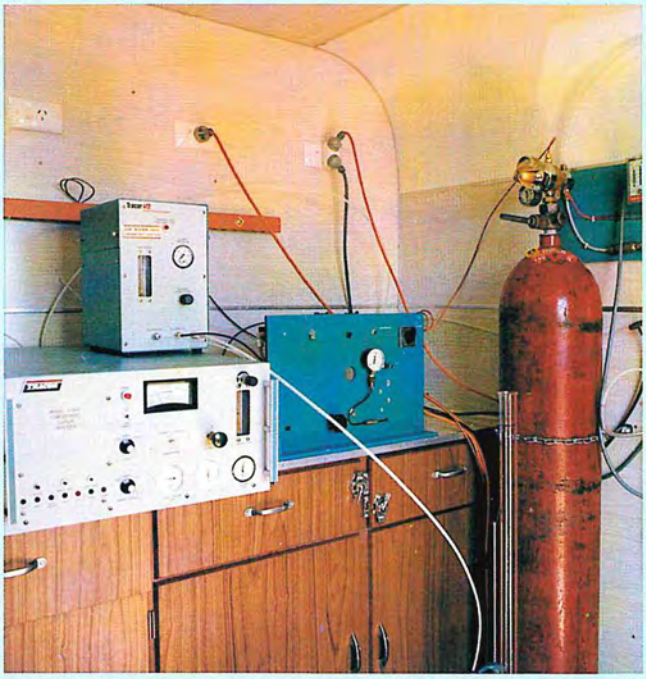
Photography—Shepherd Baker Studios

Plate 4. The WAIT-DCE mobile acoustic sounder.



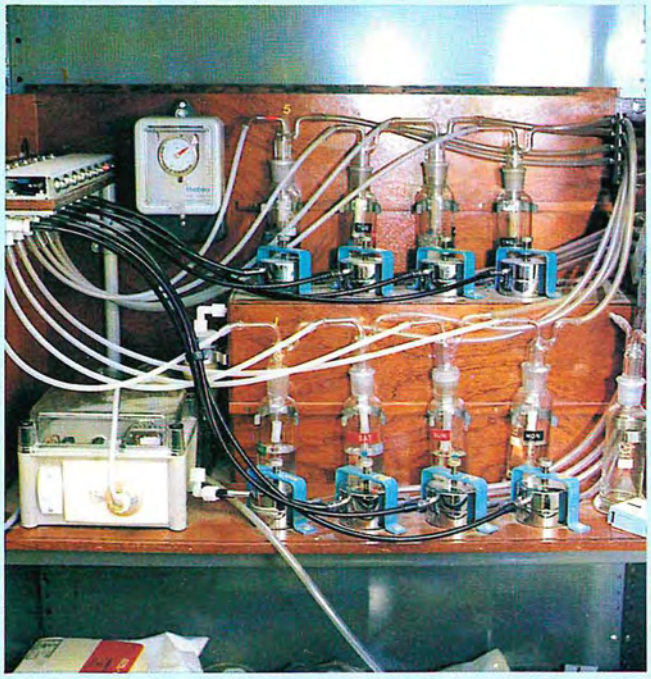
Photography—Ken Rayner

Plate 5. Cassette data loggers and paper chart printer.



Photography—Shepherd Baker Studios

Plate 6. A TRACOR continuous sulphur dioxide monitor.



Photography—Shepherd Baker Studios

Plate 7. A 24-hour sequential sulphur dioxide sampler.

Photography—Shepherd Baker Studios

Plate 8. Computing facilities used for the study.

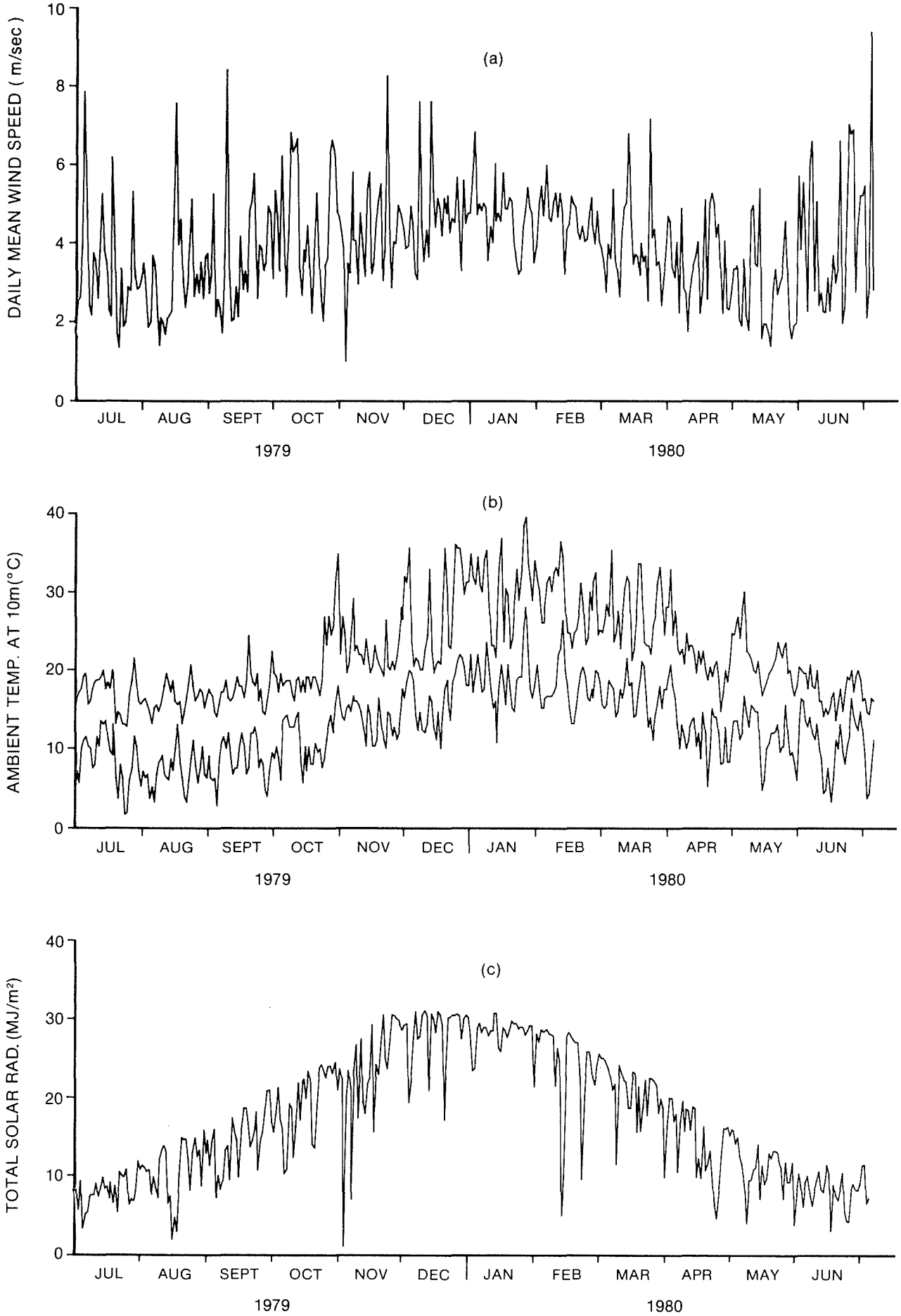


Figure 4.2. Meteorological data measured at Wattleup base station from July 1979 to June 1980 showing (a) daily mean wind speed, (b) daily maximum and minimum temperature and (c) daily total solar radiation.

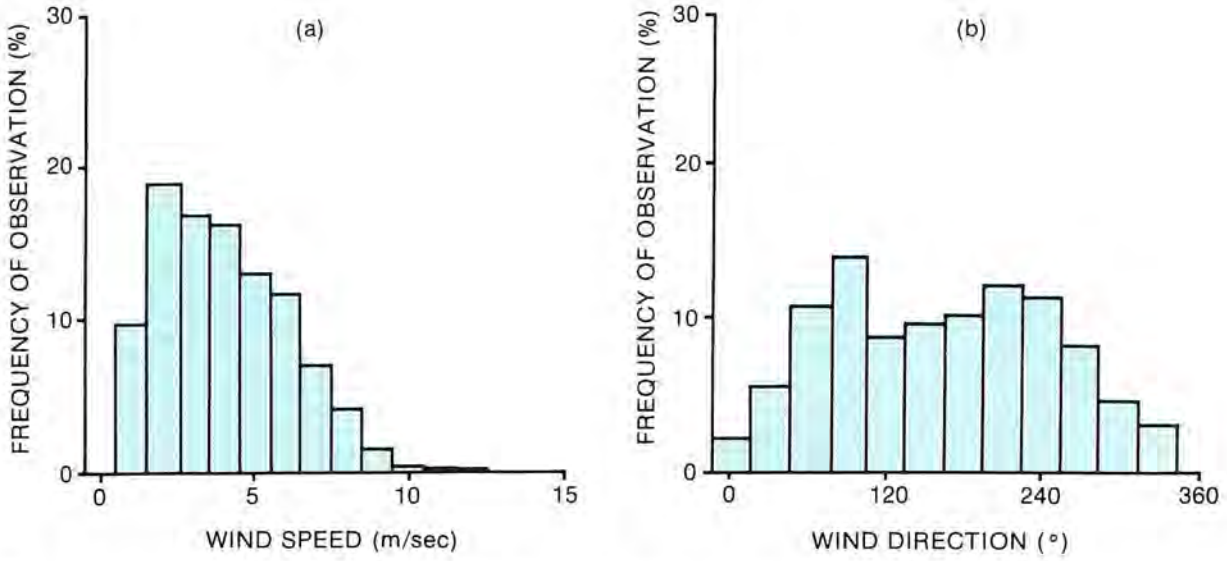


Figure 4.3. (a) Wind speed and (b) wind direction frequency distributions for Wattleup base station data for the period July 1979 to June 1980.

Table 4.1. Wind speed/wind direction frequency matrix for wind data measured at the Wattleup base station from July 1979 to June 1980.

Speed (m/sec)	Direction (degrees from North)											
	0	30	60	90	120	150	180	210	240	270	300	330
1	.3	.6	1.7	1.9	1.3	1.3	.9	.5	.2	.3	.3	.3
2	.3	1.0	3.4	3.1	1.7	3.3	3.0	.8	.5	.9	.6	.4
3	.4	1.0	1.7	2.0	2.1	2.6	2.8	1.0	.8	1.3	.7	.4
4	.3	1.0	1.3	2.2	2.0	1.5	1.9	1.5	1.6	1.5	.9	.6
5	.3	.6	.9	1.8	.9	.6	.9	1.9	2.2	1.4	.9	.5
6	.2	.6	.9	1.5	.4	.2	.5	2.5	2.6	1.2	.7	.4
7	.1	.3	.5	.8	.2	.1	.2	2.0	1.6	.7	.3	.3
8	.1	.2	.3	.4	.1			1.2	1.0	.5	.2	.2
9		.1	.1	.1				.5	.5	.2		.1
10								.1	.2	.1		
11									.1	.1		
12									.1			

4.3 INDUSTRIAL EMISSIONS DATA COLLECTION AND PROCESSING

Within the study area eight major industries existed from which emissions data were required (Section 3.2). Data were received in differing type, format and frequency of recording from each industry and hence data processing methods varied. In all cases sufficient information was supplied to determine for each source in each industry the following parameters:

- Mass and volume flux of emitted gases
- Mean temperature of gases emitted
- Sulphur dioxide content of gases emitted
- Moisture content of gases emitted.

The processing procedure involved the keying of the log sheet information or the values read from supplied graphs onto a mini-computer. Checking and editing of the data on the mini-computer took place before transfer of the data to the mainframe computer where the data were processed to provide gas emission rates. Data files produced from the processing of each month's data were then collated into a single file containing all information from the industries for the period of the study. This file was used for all further analysis of the emissions data and it formed the emissions data base for the atmospheric dispersion models.

Further details of this procedure are given in Martin and Rosher (1982) and the total daily sulphur dioxide emission from Kwinana industry is shown in Figure 4.4.

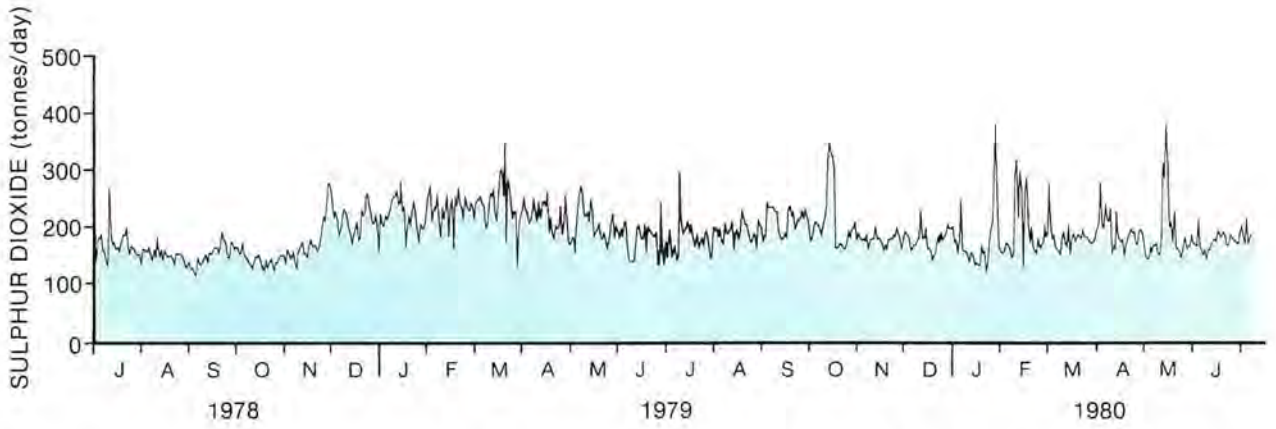


Figure 4.4. The total daily output of sulphur dioxide from all major industries at Kwinana for the period July 1978 to June 1980.

4.4 THE EFFECTIVENESS OF THE FIELD MONITORING PROGRAMME

Through KAMS, changes were made to the field monitoring programme to make the most efficient use of the equipment available. The most significant of these was the re-siting of Base Station 2 from the Kwinana residential area to Hope Valley and the subsequent measurement of wind and temperature at two levels.

The move to Hope Valley was important in two ways. The site was far more exposed than the Kwinana or Wattleup sites and consequently better represented the meteorology over the study area. In addition, since Hope Valley was east of the main north-south industrial strip at Kwinana, measurements of sulphur dioxide were able to indicate unambiguously the pollutant source. This was not the case at Wattleup where all the major industries contributed to pollution episodes during south-westerly winds. Unfortunately, full use of this capacity at Hope Valley was not made due to a major malfunction in the sulphur dioxide monitor for a period of 5 months.

Data recovery from the instrumentation at the Wattleup base station for the period of operation from 16 June 1978 to 2 February 1981 is shown in Table 4.2. Recovery rates improved steadily throughout the study. In particular, towards the end of the study the sulphur dioxide monitor was achieving nearly 100% recovery.

From the analysis of the 5 years of data from the Woelfle field anemometers it is apparent that 2 years of continuous data would adequately specify the wind field at Kwinana. The Woelfle anemometer, though relatively maintenance free, does require monthly chart changes and subsequent digitising of the chart which is a manpower-intensive exercise. In view of the coarse 10 degree resolution of wind direction the effort spent in obtaining data beyond 2 years could have been spent more profitably on other aspects of the study.

Because of the limitations of the method used for measurement (Section 7.2.2), data from the nine 24-hour sequential samplers were not of a suitable accuracy to be used in validating the mathematical dispersion models developed for KAMS. Consequently, much reliance was placed on the results of sulphur dioxide measurements made using the continuous monitors at the two base stations. The validation procedure would have been improved by the availability of additional continuous measurements of sulphur dioxide, particularly from the vicinity of Thompson Lake.

Table 4.2. Data recovery from Wattleup base station for the period 16 June 1978 to 2 February 1981.

INSTRUMENT	PERCENTAGE RECOVERY
Wind speed	86.2
Wind direction	96.2
Sigma Theta	96.2
Air temperature	97.3
Solar radiation	97.3
Dew point*	98.8
Sulphur dioxide	79.5
Data logger	97.3

* installed 25.4.79.

Chapter 5

INTENSIVE FIELD EXPERIMENTS

5.1 PHILOSOPHY

The success of any air dispersion modelling study depends to a large extent on the information obtained from the continuous long-term monitoring of basic meteorological and air pollution parameters. Often, however, additional data on meteorological phenomena of particular interest are required, but limitations on manpower and finance dictate that these cannot be obtained on a continuous basis. However, intensive field experiments over short periods can be conducted to obtain a comprehensive set of data.

For the Kwinana Air Modelling Study, two major intensive field experiments were undertaken in order to gain an understanding of plume rise and pollutant dispersion in the sea breeze at Kwinana. The effects of topographic features and shoreline fumigation were of particular interest and the study of these mechanisms was a necessary part of the mathematical model development process. The first of these experiments was conducted on 2 March 1978 and the second study on 31 January 1980 was designed to extend the knowledge obtained from the first.

The other major field experiment conducted during KAMS on 29 October 1980 was designed to investigate the formation and erosion of nocturnal radiation inversions.

An outline of the experimental techniques used and the results of the intensive experiments are given below.

5.2 THE 2 MARCH 1978 FIELD EXPERIMENT

5.2.1 The Components

The primary aim of the first field experiment conducted for KAMS was to determine, quantitatively, plume rise and dispersion of pollutants released from tall chimneys into the sea breeze at Kwinana. It was expected that this preliminary work would indicate the most important phenomena influencing the dispersion of pollutants from the Kwinana industrial complex.

The March 1978 experiment was structured around two activities: the release from a stack and subsequent sampling of an inert tracer gas and the emission of black smoke to facilitate plume photography. Mathematical models were then used to compare measured plume rise and dispersion against calculated values. A description of the major components of the study is given below. The data from the study were compiled into a report and their analysis presented at a subsequent workshop (Department of Conservation and Environment, 1978a, b).

(i) Tracer Release

Two gases, sulphur hexafluoride (SF_6) and Freon 11 ($CFCl_3$), were released at known rates from the 114 m SEC stack at Kwinana during a sea breeze. Five separate air samples were then collected at each of 21 predetermined sites downwind of the stack, out to about 8 kilometres. The samples were analysed at the University of WA and concentration contours plotted for each tracer. The methodology for the tracer experiment is described in a working paper prepared for KAMS (Glossop and Hamilton, 1977).

(ii) Photography

To obtain a visual image of a typical plume at Kwinana, the SEC released a number of short puffs of black smoke. The puffs were photographed from the ground and from the air. The ground level photographs were analysed to measure plume rise as a function of downwind distance, and the aerial photographs fixed the plume direction accurately.

(iii) Radiosonde Releases

Officers from the Bureau of Meteorology released a number of radiosondes throughout the day of the experiment. Vertical profiles of wind speed, wind direction and temperature were obtained for use in the modelling of plume rise and dispersion.

(iv) Acoustic Sounding

Two acoustic sounders were used to determine the atmospheric mixing depth of the sea breeze. One was stationed on the coast and the other about 4 km inland (Figure 4.1).

(v) Continuous Monitoring

During the experiment, the normal continuous monitoring network for KAMS was in operation. This included the five Woelfle anemometers and two automatic base stations at Wattleup and Kwinana providing 10-minute averages of wind speed, wind direction, temperature, solar radiation and the standard deviation of wind direction.

5.2.2 Summary of Findings

The field exercise of 2 March 1978 was carried out in a relatively weak sea breeze. The thermal internal boundary layer set up over the land was thus able to grow rapidly and was intersected by the plume containing the tracer at a short distance from the source. Ensuing fumigation resulted in the highest concentrations of both tracers being located in the vicinity of Wattleup (Figure 5.1).

The experiment showed that under certain conditions, high concentrations of pollutants can be experienced in a particularly localised area, both in width and downwind extent. This has important implications for residential settlements such as Wattleup under sea breeze conditions.

The dispersion of the tracer gases released during the experiment was simulated using the standard Gaussian dispersion formula with plume rise calculated using a model developed by Rayner (1974). Cross-wind and vertical plume spread parameters were determined by the stability category method of Turner (1970) and atmospheric mixing depth obtained from the radiosonde and acoustic sounder records.

The position and magnitude of the maximum ground level concentration of the tracer gases were estimated reasonably well using Turner stability Class C. There were, however, no sound criteria for choosing Class C. Selection of a stability class appropriate to the marine air or the inland surface layer would have yielded categories D and B respectively and the dispersion patterns for either class were vastly different from that measured.

It was therefore clearly recognised, following the 2 March 1978 experiment, that a model based on specification of discrete atmospheric stability categories would inadequately represent dispersion at a coastal location. In addition, modelling would be required to include the mechanism of shoreline fumigation produced by the interaction of industrial plumes with the internal boundary layer which occurs during the sea breeze.

5.3 THE 31 JANUARY 1980 FIELD EXPERIMENT

5.3.1 The Components

With the experience and knowledge gained from the March 1978 experiment, it was evident that additional data were required to gain a better understanding of the dispersion process within the sea breeze. To this end the January 1980 field experiment was far better designed than that of March 1978 with a number of additional meteorological measurements being undertaken.

In particular, the availability of the 27 m tower at the new Hope Valley base station enabled vertical profiles of wind speed and air temperature to be determined. The profiles were used to calculate heat and momentum transfer near the surface which determine the atmospheric stability and mixing depth (Chapter 6).

As in the first experiment, tracer gases were released from the SEC stack and gas sampling carried out downwind to determine the extent of plume dispersion. The release rate of Freon 11 was, however, increased in an attempt to minimise the impact of background concentrations on the measured levels.

The WAIT mobile acoustic sounder was deployed at the Hope Valley base station in addition to the permanent sounder located at Alcoa mudlake 'F'. An attempt was also made to obtain shoreline vertical temperature profiles but due to instrument malfunction, this was not successful.

5.3.2 Summary of Findings

The sea breeze experienced at Kwinana on 31 January 1980 was significantly different to the sea breeze of the earlier experiment. Inflow temperatures were lower and the strength of the breeze greater. These facts had important consequences in relation to the rate of growth of the internal boundary layer and the resulting fumigation process.

Maximum concentrations for both tracer gases were located some 6 km downwind of the stack (Figure 5.1). Calculations verified that the plume was indeed intersecting the slowly growing boundary layer at a distance of about 6 kilometres from the source. The plume, which had largely retained its integrity in the stable inflow air, was then quickly mixed to ground, causing the high concentrations measured in the vicinity of Thompson Lake.

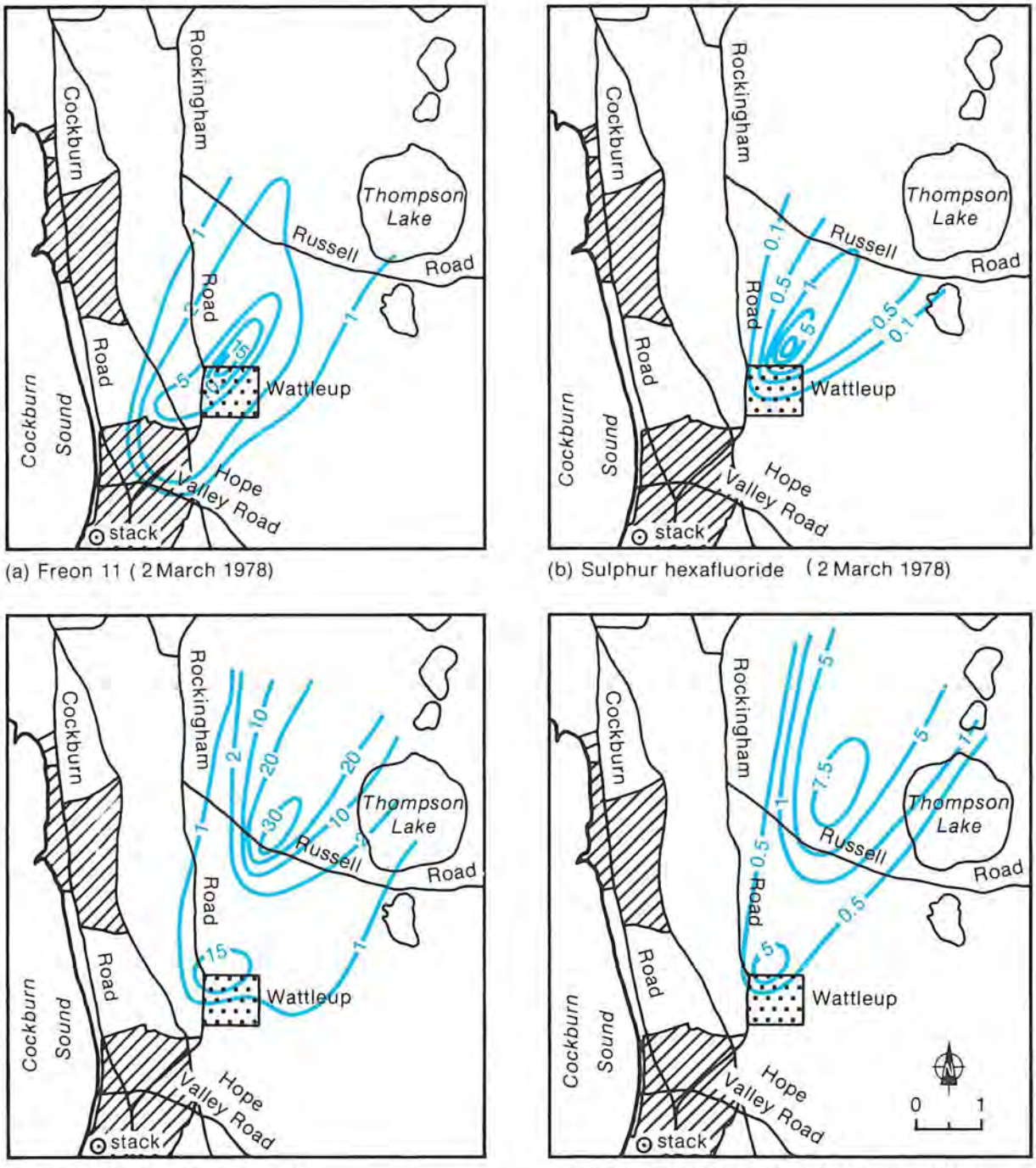


Figure 5.1. Ground level tracer concentrations contours ($\mu g/m^3$) interpreted from data obtained during KAMS field experiments. The outer contours in (c) and (d) have been plotted from limited data.

The additional data available from the upgraded base station at Hope Valley enabled the use of a three dimensional grid model to represent tracer gas dispersion on the study day. The model performed creditably and demonstrated clearly the importance of the shoreline fumigation process in producing large ground level concentrations several kilometres downwind of the source. Later improvements in the resolution of the model and the mixing depth and dispersion parameterisation (Rye, 1982) resulted in an even better simulation of dispersion (Chapter 7).

In addition, a Gaussian model was developed to include the effects of the thermal internal boundary layer and a continuous stability scheme. This model was also able to accurately estimate the position and magnitude of the maximum ground level concentrations. A description of this work is given by Rosher, Rayner and Paparo (1982) and results presented in Chapter 7.

Data from the field experiment and an analysis of the data presented at a workshop are given in two reports (Department of Conservation and Environment, 1980a, b).

5.4 THE 29 OCTOBER 1980 FIELD EXPERIMENT

5.4.1 The Components

The 29 October 1980 field experiment was designed to provide data by which the stability and mixing depth models developed for the study (Chapter 6) could be further refined and validated. Much of the required data were already being recorded routinely at the Hope Valley base station. Hence the experiment involved the inclusion of additional sensors into the monitoring network and the running of a number of special programmes. A brief description of the experiment components is given below:

(i) Radiosonde Releases

Hourly slow-ascent radiosonde releases with dual theodolite tracking provided vertical profiles of wind and temperature throughout the day. The profiles gave estimates of the evolution of the mixing depth and the strength of the temperature inversion. An acoustic sounder operating at Hope Valley during the experimental period provided an alternative method to determine the mixing depth.

(ii) Turbulent Fluxes

Surface layer stresses and heat fluxes were determined from the two-level measurements of wind and temperature at the Hope Valley base station. Additional measurements of relative humidity, net radiation, ground heat flux, ground temperature and rainfall were also necessary as input to the Rayner (1981a) surface layer energy budget model (Chapter 6) which produced turbulent flux estimates for comparison with tower estimates and for subsequent use in the mixing depth model.

(iii) Plume Photography

The major industrial plumes at Kwinana were photographed periodically throughout the experiment to provide qualitative information on plume behaviour as the temperature inversion was eroded.

5.4.2 Summary of Findings

The validation of the energy budget and mixing depth models (Rayner, 1981b) using data from the October 1980 experiment showed that continuous estimates of mixing depth and atmospheric stability could be derived from the routine measurement of meteorological parameters at either of the base stations.

As a consequence, the coarse stability category approach (Turner, 1970), traditionally used for Gaussian dispersion calculations, was replaced by a more sensitive scheme to estimate dispersion parameters from the calculated atmospheric stability. In addition, the calculated mixing depth was used for both the Gaussian model (Section 7.1.1) and the finite difference model (Section 7.1.2) both of which were run continuously for an extended period.

The experiment also demonstrated that wind shear above the temperature inversion has an impact on acoustic sounder trace, making interpretation of these records subject to error. It is expected that the current generation doppler acoustic sounders will allow wind shear to be continuously measured providing a more reliable interpretation of mixing depth from the sounder.

Data from the experiment are presented in Rayner and Rosher (1981) and analyses and simulation exercises presented in Rayner (1981b).

5.5 THE EFFECTIVENESS OF THE KAMS FIELD EXPERIMENT PROGRAMME

Both of the first two major experiments carried out as part of KAMS were designed to achieve an understanding of the dispersion process in the sea breeze at Kwinana. The second experiment (31 January 1980), built upon, and sought to extend, the knowledge gained in the first (2 March 1978). The third experiment (29 October 1980) provided valuable model validation data, giving confidence to the prediction of atmospheric stability and mixing depth.

The intensive studies demonstrated the critical importance of the stability of the sea breeze inflow in determining the location of the major pollutant impact at Kwinana. The failure of the January 1980 experiment to determine the vertical wind and temperature structure at the coast limited the value of this experiment in the model validation procedure. It is important that vertical structure be measured both at the coast and well inland during any future studies of dispersion in the sea breeze.

In conclusion, the KAMS field experiments enabled the major mechanisms influencing air pollutant dispersion at Kwinana to be identified and high quality validation data to be produced. Consequently, various approaches to the modelling of atmospheric processes were evaluated, and practical schemes applicable to the available long-term data were derived.

Chapter 6

DISPERSION OF AIR POLLUTANTS IN THE LOWER ATMOSPHERE

The air pollutants which most directly influence man are those which are emitted near the earth's surface and disperse into the planetary boundary layer. This boundary layer is typically 0.2 to 2 kilometres thick and is that layer within which the turbulence induced by surface heating or surface friction is contained. The upper limit of the planetary boundary layer is defined by the existence of an overlying stable air mass which limits the vertical transfer of air pollutants.

Dispersion of air pollutants within the planetary boundary layer is directly determined by turbulent motions which range in scale from minute rapid fluctuations through to large eddies associated with topographic features. As well as being dispersed by turbulent motions, air pollutants are transported across a region by winds associated with mesoscale or synoptic pressure systems.

Prediction of air pollutant dispersal is therefore largely dependent upon estimation of the mean turbulent motions in the planetary boundary layer. This, in turn, requires model prediction or measurement of surface heating and friction, boundary layer height and inversion strength as a function of time, mesoscale flow (such as sea breezes and katabatic winds) and other locally important meteorological phenomena. In practice, these components or sub-models may either be incorporated into one complex computer program or may be independent programs which successively develop an input data file for a compact dispersion computation.

This chapter describes, in some detail, several of the sub-models which are used in the KAMS dispersion models described in Chapter 7. As such, this chapter will be of interest to the scientist, but may be beyond the scope of the layman. A working knowledge of atmospheric science is assumed. The discussion and presentation of mathematical expressions is specific to the models developed. For more detailed discussion on the derivation of results, the reader is referred to the technical reports cited.

6.1 PLUME BEHAVIOUR

Plumes from industrial chimneys are most often thermally buoyant and highly turbulent. Their initial behaviour, after leaving the stack, is dominated by their own buoyancy and momentum and hence they rise in a fairly coherent manner. During this initial rise, ambient air is entrained by the plume and serves to dilute plume heat and momentum, thereby bending it over.

As a plume travels downwind, its turbulent energy level decays until it has reached that of the ambient air. At this stage, the turbulent motions in the atmosphere become the dominant mechanism for dispersing the plume.

Compared to some of the uncertainties associated with the actual dispersion of a plume, plume rise is relatively well understood and documented. An outline of the approach taken in the study to determine plume rise under specific conditions is given below.

6.1.1 Initial Plume Rise

The initial phase of plume rise typically lasts for a few hundred metres downwind of the stack, depending on the intensity of atmospheric turbulence.

Briggs (1975) derives the plume conservation equations for mass, buoyancy, momentum and energy in integral form, which may be solved numerically if so desired. He shows, however, that for the special case of a neutral atmosphere, plume rise may be adequately described by the analytical solution.

$$\Delta H = 1.6\, F^{1/3}\, u^{-1} x^{2/3} \qquad (6.1)$$

where $F = g \dfrac{(T_o - T_a)}{T_o} w_o\, b_o^2$

and where x is downwind distance
u is wind speed
w_o is efflux velocity
b_o is stack exit radius

T_o is efflux temperature (°K)
T_a is ambient temperature (°K)
g is gravitational acceleration

The parameter F represents the initial buoyancy flux of the plume. Initial vertical momentum is shown by Briggs to be relatively unimportant.

6.1.2 Plume Rise into Stable Air

For a plume rising into a stable constant density gradient, Briggs (1975) gives the final height of rise as

$$\Delta H = C_2 \left(\frac{F}{us} \right)^{1/3} \tag{6.2}$$

where C_2 is a constant (approximately ≈ 2.6) and where s is a measure of the atmospheric stability defined as

$$s = \frac{g}{T_a} \frac{\partial \theta_a}{\partial z} \tag{6.3}$$

The parameter θ_a is the virtual potential temperature of ambient air. When $\partial\theta_a/\partial z$ is positive (stable atmosphere), the buoyancy flux of the rising plume decreases to zero at the level ΔH above the stack and the plume subsequently undergoes damped oscillations about this level as it moves downwind (Figure 6.1).

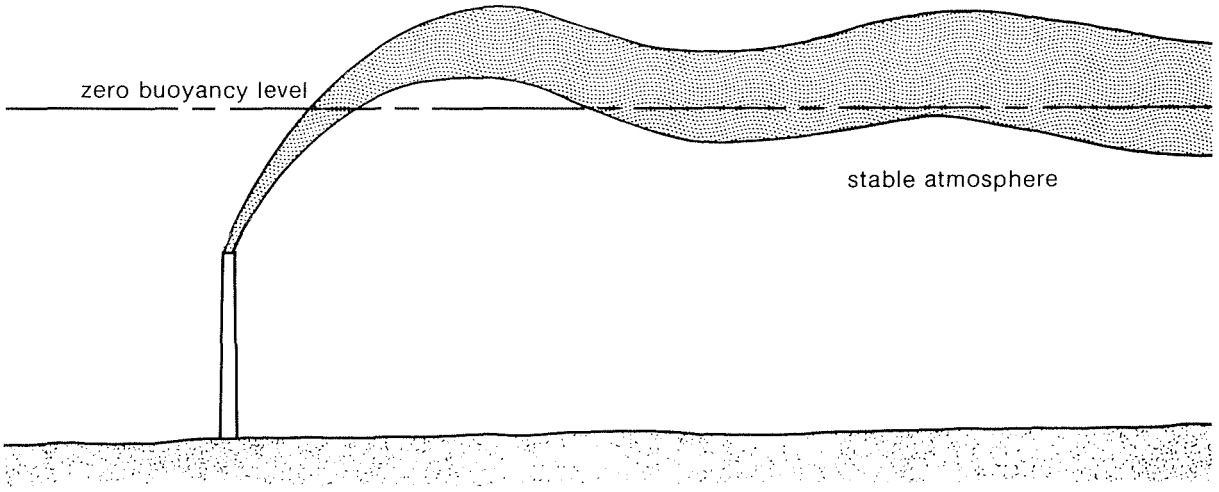


Figure 6.1. Plume oscillation about the zero buoyancy level in a stable atmosphere.

6.1.3 Plume Levelling in Neutral/Unstable Air

Perhaps the most widely accepted formula for the calculation of maximum plume rise in neutral/unstable conditions is the extension of Equation (6.1), proposed by Briggs (1975):

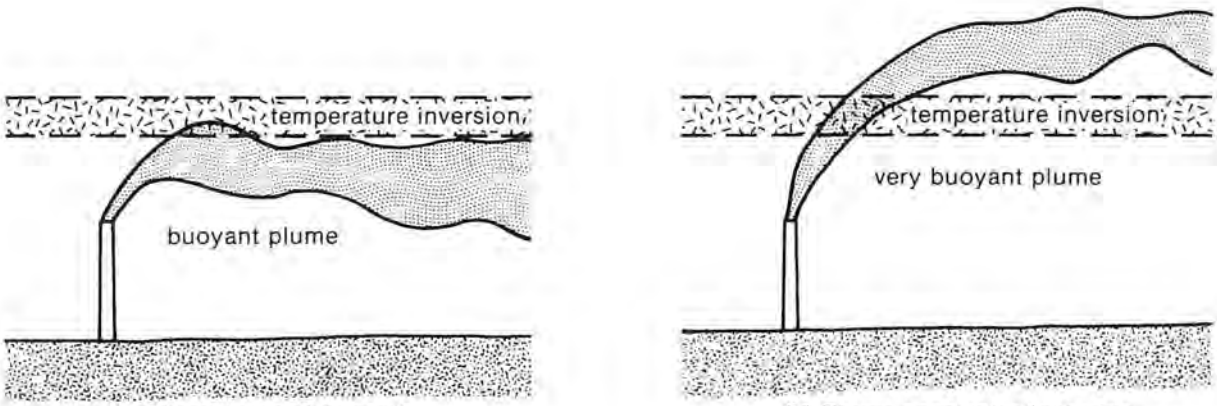
$$\Delta H = 1.6\, F^{1/3} (3.5\, x^*)^{2/3}\, u^{-1} \tag{6.4}$$

where $x^* = 14\, F^{5/8}$ for $F < 55\ m^4\ sec^{-1}$
$x^* = 34\, F^{2/5}$ for $F > 55\ m^4\ sec^{-1}$

The levelling is assumed to occur downwind of the distance 3.5 x*, with Equation (6.1) applying at shorter ranges. However, as can be seen from the formula, the levelling height is determined solely from the buoyancy of the plume, with no reference to the intensity of atmospheric turbulence which is responsible for the transition of the plume to its levelled state. This shortcoming has been addressed by Briggs who proposed two formulae for the cases of mechanically and thermally dominated atmospheric turbulence. These formulae have been discussed by Rosher, Rayner and Paparo (1982) but require further verification before they can be used with confidence.

6.1.4 Plume Penetration of an Elevated Inversion

Pollutants are often released into a well-mixed layer of air which is capped above by warmer air. In many cases, plumes may rise to the level of the elevated inversion base but have insufficient buoyancy to penetrate it. If a plume has sufficient buoyancy to penetrate the inversion, it is likely to be transported away and have little or no impact on ground level concentrations in the vicinity of the source. Both cases are illustrated in Figure 6.2.



(a) Plume trapped beneath inversion.

(b) Plume penetrates inversion and is trapped aloft.

Figure 6.2. Some common plume-inversion interactions.

Manins (1979) gives the following formula to predict the fraction FR of plume materials which will be trapped under an elevated lid:

$$FR = \frac{0.08}{P} - (P - 0.08) \qquad (0<FR<1) \tag{6.5}$$

where $P = F / \frac{(ug\Delta\theta\Delta h^2)}{T_a}$ and

$\Delta\theta$ is the strength of the temperature rise through the inversion, and Δh is the distance from the top of the stack to the inversion.

6.2 INFLUENCE OF THE EARTH'S SURFACE

As previously indicated, the transfer of momentum, heat and vapour between the earth's surface and the lower atmosphere largely determines the turbulent state of the planetary boundary layer and hence its dispersive capability. Any model of the planetary boundary will therefore require specification of these transfers.

There are now well established theoretical and experimental procedures that may be used to estimate turbulent transfers or fluxes from meteorological measurements within the lowest fifty or so metres of the atmosphere, the so-called surface layer. The relevant theory and the procedures adopted in KAMS are summarised below. A detailed discussion of this work is given by Rayner (1981a).

6.2.1 Theory of Surface Layer Transfers

The parameters which are required for input to a dispersion model are the friction velocity u_* and the virtual heat flux H_v. The friction velocity is derived from the stress (or momentum flux) τ by the equation

$$u = \left(\frac{\tau}{\rho_a}\right)^{1/2} \tag{6.6}$$

where ρ_a is the density of air.

The virtual heat flux H_v accounts for the buoyancy contribution of both the sensible heat flux H_s and the water vapour flux E, so

$$H_v = H_s + 0.61\, C_p T_a E \tag{6.7}$$

where C_p is the specific heat of air. On hot dry days, $H_v \approx H_s$.

The fundamental measure of atmospheric stability in the surface layer is the Monin-Obukhov length L, defined as

$$L = \frac{-\rho_a C_p u_*^3 T_v}{kg H_v} \tag{6.8}$$

where T_v is the virtual air temperature in Kelvin (analogous to H_v) and k is the von Karman constant (approximately 0.41).

Mean flow variables (velocity, temperature, humidity) may be expressed as functions of z/L. For example, for velocity u

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz}\,\phi_m\left(\frac{z}{L}\right) \tag{6.9}$$

where the function ϕ_m has been evaluated by experiment. In integral form, the mean flow parameters take the form

$$u = \frac{u_*}{k}\left(\ell n\left(\frac{z}{z_o}\right) - \psi_m\left(\frac{z}{L}\right)\right) \tag{6.10}$$

where ψ_m is an integral function of ϕ_m and z_o is the roughness length.

A conventional way of expressing the turbulent fluxes is in the bulk aerodynamic form:

$$\tau = \rho_a\, C_D\, u^2 \tag{6.11}$$

$$H_S = -\rho_a\, C_p\, C_H\, u\,(\theta - \theta_s) \tag{6.12}$$

$$E = -\rho_a\, C_W\, u\,(q - q_s) \tag{6.13}$$

where the subscript s indicates surface values and where C_p, C_H and C_W are bulk transfer coefficients which are strong functions of height z, stability z/L and surface characteristics z_o, z_H or z_W. Garratt (1978) has established useful relationships between z_o, z_H (and consequently z_W) over land.

Hence, the turbulent fluxes may be evaluated from Equations (6.11) to (6.13) if measurements of u, θ and q are available at an elevated level (10 metres) and at the surface (where u = 0). Alternatively, the fluxes may be evaluated from gradient relationships of the form of Equation (6.9) if the gradients can be measured.

6.2.2 Use of Multi-Level Tower Measurements

A standard means of obtaining data to estimate gradients of u, θ and q is to instrument a tower or mast at two or more levels above the ground, within the atmospheric surface layer. The tower erected for this purpose in KAMS is described in Section 4.1.2.

To obtain accurate long-term continuous estimates of fluxes from tower measurements, the instruments must maintain an extremely high degree of accuracy and stability. Temperature sensors, for example, which are separated by only a few metres must be consistently accurate to better than 0.1°C. Many standard instruments for wind, temperature and, in particular, humidity have calibration and drift inaccuracies that preclude their use for this type of work.

Equipment and manpower costs render the method unsuitable for many situations where dispersion estimates are required fairly promptly. Tower measurements may be most valuable during intensive field experiments however, when frequent calibration checks are feasible. The Hope Valley tower (Base Station 3) was utilised principally for this purpose in KAMS. Turbulent flux calibrations from the tower data were subsequently used to validate the other methods described later.

An initial experiment, involving three sensitive anemometers at heights up to 28 metres on the tower, allowed the determination of z_o based on the method proposed by Paulson (1970). This parameter, and the related parameters z_H, allowed C_D and C_H to be defined for neutral conditions.

The method of flux computation using estimates of velocity and temperature gradients is described by Rayner (1981a) and will not be discussed here. However, having evaluated z_o, an alternative scheme for flux computation can be derived which requires temperature measurement at two levels and velocity measurement at only one level. The equations for the method take the form

$$\tau = \rho_a\, C_D\, u_2^2 \tag{6.14}$$

$$H_S = -\rho_a\, C_p\, C_H'\, u_2\,(\theta_2 - \theta_1) \tag{6.15}$$

where subscripts 1 and 2 represent the lower and upper levels respectively and where C_H' is a modified heat transfer coefficient as defined by Rayner (1981a).

This method is attractive since only one anemometer is required, removing the possible error involved in estimating wind speed difference between the two levels. Whilst the equations are similar in form to the bulk aerodynamic relations (Equations (6.11) to 6.13)), the difficult problem of measuring the temperature θ_s right at the soil/air surface is avoided.

6.2.3 Modelling Surface Layer Turbulent Fluxes

For reasons previously described, construction and maintenance of a meteorological tower is not a viable

option in many situations where continuous data are required. Routinely available continuous data most often come in the form of single height measurements of wind speed and direction, temperature and humidity. Solar radiation and rainfall data are also usually available within a given region of interest. It is desirable to use this type of data for dispersion modelling purposes.

Consequently, a numerical model was developed using the above-mentioned data to predict H_v and u_* from a description of the surface layer and moisture budgets combined with the surface layer relations presented in Section 6.2.1.

Conservation of heat energy at the surface provides a constraint which may be incorporated into the computation of turbulent fluxes. Taking all fluxes to be positive when directed away from the surface, the conservation equation may be written as

$$G + R + H_s + H_L = 0 \tag{6.16}$$

where G is the ground heat flux, R is net (short-wave plus long-wave) radiation and H_L is latent heat, given by

$$H_L = L_e E \tag{6.17}$$

L_e is the latent heat of vaporisation. G may be calculated from Equation (6.16) if R, H_s and H_L are known. H_s is dependent on T_g, the ground temperature, which must itself be related to ground heating G. Similarly, H_L is dependent on the surface specific humidity q_g, which is itself related to the ground moisture content as determined by the recent history of precipitation and evaporation. Hence there are a variety of implicit relationships from which estimates of the turbulent fluxes may be extracted. A full description of the model and results is given by Rayner (1981a). The important components of the model are briefly described below.

(i) Ground Temperature Simulation and Sensible Heat Transfer

The ground temperature T_g may be described by the equation:

$$\frac{\partial T_g}{\partial t} = \frac{2}{C_s} G - \Omega \left(T_g - T_d \right) \tag{6.18}$$

where Ω is the earth's angular frequency ($7.27 \times 10^{-5}\ s^{-1}$) and T_d is a deep soil temperature. C_s is defined as

$$C_s = \left(2\ \rho_s c_s \lambda_s / \Omega \right)^{1/2}$$

where ρ_s is soil density, c_s is soil specific heat and λ_s is soil heat conductivity. Equation (6.18) is called a force-restore equation: the right hand first term represents the forced heating/cooling, while the second term tends to restore the surface temperature to that of the soil at depth, T_d. The term T_d may be estimated from an integral formulation based on the penetration depth of the annual thermal wave,

$$\frac{d\ T_d}{dt} = \frac{G}{C_d} \tag{6.19}$$

where $C_d = \left(2\pi.365 \right)^{1/2} C_s$

Sensible heat is calculated using Equation (6.12) where θ_s is a combination of soil, grass and leaf temperatures. It is necessary to assume that the effective surface temperature deviation is proportional to the ground surface temperature deviation, that is

$$(\theta_s - \theta) = \beta' \ (T_g - \theta) \tag{6.20}$$

The single coefficient β' accounts for patchy shading of the soil and for the limited heat transfer from vegetation.

(ii) Ground Moisture Simulation and Evaporation

The moisture content of surface soil may vary between dry and saturated states and may change very quickly under the influence of evaporation and precipitation. As a consequence, latent heat loss associated with evaporation may vary from an insignificant contribution to the heat budget (dry surface conditions), to being a dominant cooling mechanism (moist surface condition). The volume fraction of soil moisture, w, may be described by relations similar to those for the surface temperature:

$$\frac{\partial w_g}{\partial t} = -C_1 \frac{(E - P)}{\rho_w d_1} - \frac{C_2\ \Omega}{2\pi} (w_g - w_d) \qquad 0 \leqslant w_g \leqslant w_{max} \tag{6.21}$$

$$\frac{\partial w_d}{\partial t} = -\frac{(E - P)}{\rho_w\ d_2} \tag{6.22}$$

where P is the precipitation rate and ρ_w is the density of water. The parameters d_1 and d_2 represent the depth to which the diurnal and annual moisture cycles respectively extend, with w_d being the average moisture content over the depth d_2. The coefficients C_1 and C_2, together with d_1 and d_2, need to be evaluated for a particular soil type. The term w_{max} is the maximum possible soil moisture content, above which run off occurs.

To preclude erroneous 'negative evaporation' effects when q_g is less than the air humidity q, the bulk aerodynamic formula (Equation 6.13) is rewritten as:

$$E = \rho C_w u \alpha \ (q_{sat}(T_g) - q) \tag{6.23}$$

where $\alpha = \min [\ 1,\ w_g/W_k\ ]$ and q_{sat} is specific humidity for saturated soil at temperature T_g. W_k is that value, less than w_{max}, at which the soil surface may be considered saturated. The model is therefore limited to situations where the effects of evapotranspiration, canopy heat storage and shielding of the ground from radiative transfers are relatively small.

(iii) Radiative Transfers

Net radiation R is the remaining heat transfer to be specified in the heat budget of Equation (6.16). Single-site measurement of this parameter over land is of limited use due to the often varying surface characteristics of a region. Furthermore, it is necessary to calculate surface-emitted radiation within the model to ensure the stability of the soil temperature computation. Hence, all components of radiation must be evaluated separately.

In practice, this involves measuring global short-wave radiation, estimating surface albedo and emissivity, and measuring or calculating downward long-wave radiation from the atmosphere. The last parameter represents the greatest difficulty. Atmospheric long-wave radiation was not measured in KAMS as its importance had not previously been recognised. Instead, it was calculated from Swinbank's (1963) formula:

$$Q_{LI} = 5.31 \times 10^{-14} (1 + 0.17\, C^2)\, T_a^6 \quad mW/cm^2 \tag{6.24}$$

where C is the amount of cloud cover. Cloud data were obtained from the Bureau of Meteorology observations at Perth Airport.

(iv) Numerical Simulation

The numerical simulation procedure for the above heat budget model is fully described by Rayner (1981a). This involves numerical integration of the soil temperature and moisture differential equations coupled with a computation of the stability-dependent turbulent fluxes and the heat budget from Equation (6.16). The model input data required are wind speed, air temperature, humidity, short-wave radiation, rainfall and cloud cover. Output includes the required parameters u_* and H_v.

(v) Results

The model results have been compared with results of computations using the two-level tower data with generally good agreement.

However, whilst the model uses relatively simple data and has relatively low data accuracy requirements, it does require specification of a variety of parameters such as C_s and C_d. These may not be readily available for a given locality, necessitating separate investigation.

The model produces credible results when simulating periods of rainfall which cause the atmosphere to become stable. This is in contrast to the stability categorisation scheme of Turner (1970) and similar implicit heat budget approaches which take no account of rainfall effects or variation in any of the surface features described in the foregoing equations.

Wattleup base station data were used to run the heat budget model for a 12-month period. It proved to be very efficient, taking about 3 CP seconds per day of simulation on a Cyber 172 computer. The output data file included all data from the base station necessary for subsequent dispersion modelling.

6.3 MIXING DEPTH

The term 'mixing depth' is commonly used to describe the depth of the turbulent planetary boundary layer within which air pollutants disperse. The vertical extent of dispersion is limited to the mixing depth due to the presence of a stable air mass above. Lower mixing depths lead to more concentrated levels of air pollutants at ground level. There is frequently a temperature inversion at the base of the stable layer which acts as a barrier

to chimney plumes with insufficient buoyancy (Section 6.1.4). It is clearly necessary for the purposes of air pollution modelling to be able to determine the depth of the mixed layer and the strength of the inversion lid.

In practice, it is most important to specify mixing depths accurately when they are low, since large mixing depths have little effect on the rise and dispersion of plumes. At Kwinana, limited mixing depths are associated with the following meteorological phenomena:

- Stable nocturnal boundary layers,
- Erosion of a radiation inversion during morning hours,
- Stable onshore flow, including sea breezes and the passage of the west coast trough.

During daylight hours the formation of a thermal internal boundary layer within onshore flows has a significant impact on the dispersion of chimney plumes. A theoretical description of each phenomena is given below.

6.3.1 Nocturnal Boundary Layers

On cloudless nights, the upward radiation of heat from the ground exceeds the downward radiation from the air mass and so the ground becomes colder than the air. The resulting temperature difference produces a downward turbulent flux of heat in the air above the ground, generating a stable temperature gradient known as a radiation inversion.

The density gradient causes damping of the turbulence in the planetary boundary layer to the extent that, under near-calm conditions, the turbulence in the air near the ground may decay completely. Under these conditions the air aloft becomes decoupled from the air near the ground, sometimes producing marked variations in wind speed and direction with height. Pollutants from an elevated source will disperse very slowly as dispersion is limited to molecular processes together with the effect of any residual turbulence. Under these conditions the mixed layer, as normally observed, does not exist.

If a radiation inversion has formed but there is still appreciable wind at ground level, turbulence will continue to be generated, by surface friction, within a layer known as the nocturnal boundary layer. The depth of this layer may be considered as the mixing depth, although the layer will be stably stratified and so dispersion will be relatively slow. Venkatram (1980) analysed the data from three major field experiments to produce a simple relationship:

$$h = 2400\ u_*^{2/3} \tag{6.25}$$

from which the depth of the layer, h, may be determined.

This formula has obvious limitations, such as its lack of recognition of the effect of cloud cover, but it is well behaved over the full range of nocturnal stabilities. Limited comparison of this formula with acoustic sounder data has shown agreement within a factor of 2.

In the absence of more definite results from research in this area, Venkatram's formula was adopted for use in KAMS.

6.3.2 Growth of the Daytime Mixed Layer

Following sunrise, solar heating of the ground generates thermal turbulence which combines with the mechanical turbulence to mix thoroughly the nocturnal boundary layer. The continuing input of solar energy causes the mixing height to grow in two ways:

- The heat is mixed upward, 'replacing' the heat lost to the ground during the formation of the nocturnal inversion;
- The turbulent kinetic energy produced by the buoyancy effects of solar heating, plus the continuous wind stirring at the surface, actively entrains the stable air aloft and distributes it throughout the mixed layer. This entrainment process causes a sharp temperature inversion at the top of the mixed layer.

Rayner (1981b) describes a model of the process by which an inversion is eroded. The model is based on a one-dimensional prescription of the temperature and velocity profiles, as shown schematically in Figure 6.3. Potential temperature θ_m and velocity components u_m and v_m are taken as being constant throughout the well-mixed layer (consistent with observation). These variables are further assumed to exhibit sharp changes across the thin inversion. Surface inputs of sensible and latent heat, H_s and H_L and stress τ are shown.

The core of this model is a description of the turbulent kinetic energy budget within the well-mixed layer, expressed in the form:

$$\frac{dh}{dt} = C_K\, q^{3} \left(C_T\, q_*^{2} + \frac{gh\Delta\theta}{T_a} - C_s\,(\Delta u^2 + \Delta v^2) \right)^{-1} \tag{6.26}$$

where $q_*^3 = w_*^3 + c_N^3 u_*^3$

and where $w_* = (gh H_v/\rho_a C_p T_a)^{1/3}$ is the buoyancy velocity scale, shown later to play a key role in dispersion under convective conditions. The constants C_K, C_T, C_s and C_N have been evaluated from experimental data and have values of 0.18, 0.8, 0.2 and 1.33 respectively.

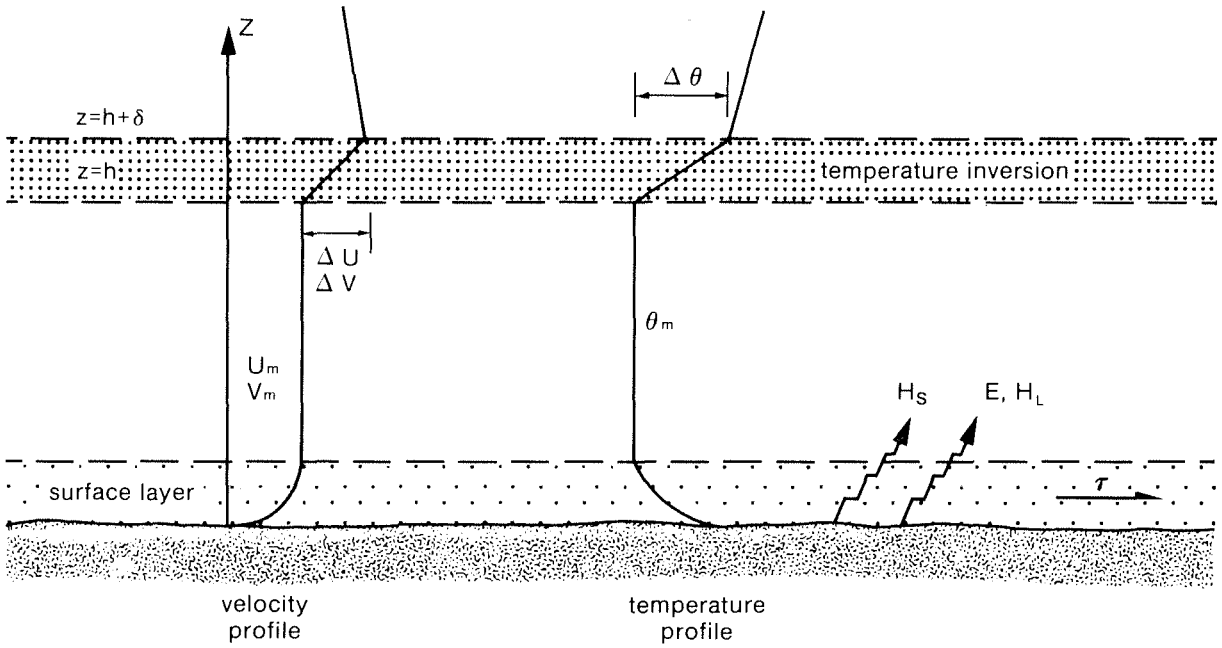


Figure 6.3. Well-mixed layer parameters.

Equation (6.26) may be solved together with equations of heat and momentum conservation for the layer to predict the layer depth, temperature and velocity. However, the momentum equation requires specification of the geostrophic velocity as a function of height and time, information which is not routinely available. Fortunately, the shear contribution to well-mixed layer deepening appears to be of little importance in normally encountered convective conditions. The final term in Equation (6.26) was therefore neglected in KAMS, but this aspect warrants further investigation.

To meet the requirements of the dispersion models, a numerical model was developed to produce a continuous data file of mixing depths based on the nocturnal boundary layer formula (Equation (6.25)) and the inversion erosion model described above. Coastal mixing depth effects were subsequently superimposed over these data within the dispersion model itself. The main input for the mixing depth model is the output data file from the energy budget model which includes values of u_* and H_v. The model also requires an initial morning temperature profile, obtained for the study from the 0700 LST radiosonde release data from Perth Airport. These data were modified to suit the model requirements, as described by Rayner and Watson (1981).

The model computes nocturnal mixing height at each time step using Equation (6.25) until, following sunrise, there is sufficient input of turbulent kinetic energy at the surface to commence erosion of the stable temperature profile (q_*^3 is positive). Following this time, mixing height is computed by the numerical solution of Equation (6.26) until the turbulent energy input decays to zero after sunset.

The model was tested against the results of the 29 October 1980 field experiment (Rayner and Rosher, 1981) and was clearly capable of simulating the essential features of inversion erosion on this day. It compared favourably with the record from an acoustic sounder operated during the experiment.

The mixing depth model executes very quickly (about 3 CP seconds per day on a Cyber 172) and so can be run quite cheaply for long periods. Both dispersion models applied in KAMS used output from this type of mixing depth model as the available acoustic sounder data did not provide a completely reliable data sequence. The scheme as described here was applied exactly for the Gaussian model (Section 7.1.1) with a simplified form used for the finite difference model (Section 7.1.2).

6.3.3 The Sea Breeze

The sea breeze provides an example of the most fundamental of mesoscale atmospheric processes, that of motion due to differential heating. This phenomenon is important in pollutant dispersion at coastal sites since

vertical mixing is generally limited to the layer of air defined by the cool marine inflow.

To allow a more detailed understanding of the way in which the sea breeze affects pollution dispersal at Kwinana, a meteorological computer model was developed to produce high-resolution simulations of Perth's sea breeze (Rye, 1980). The model was a valuable tool for investigating the broad features of the sea breeze. The sea breeze model was not intended for use in routine dispersion calculations, but rather provided the means of analysing a number of factors which were difficult to measure directly.

The approach involved the representation, on a two-dimensional grid aligned vertically and perpendicular to the coast, of wind velocity $\underline{v}$, temperature T, pressure p, and density ρ. These variables were interrelated through the equations representing the conservation of momentum, mass and energy:

$$\frac{d\underline{v}}{dt} = -\frac{1}{\rho}\nabla p - f\ \underline{k}x\underline{v} + \underline{F} \tag{6.27}$$

$$p = \rho RT \tag{6.28}$$

$$\frac{\partial p}{\partial t} = \nabla.(\rho\underline{v}) \tag{6.29}$$

$$\text{and } dT = \left(\frac{\gamma - 1}{\gamma}\right) T\frac{dp}{p} + \frac{dQ}{C_p} \tag{6.30}$$

where f is the Coriolis factor, $\underline{k}$ the unit normal vector, F represents friction, R the universal gas constant, γ the ratio of specific heats of air, C_p the specific heat at constant pressure and Q the heat input.

With the pressure, density and velocity gradients evaluated by differences between adjacent grid points, and a mathematical transformation of the above equations, the evolution of each variable was computed starting at sunrise. The resolution used, about 100 m vertically (in the lowest few hundred metres) and 3 km horizontally, allowed observation of the most significant features of any day's sea breeze.

Model tests showed that estimated winds, temperatures and mixing depths agreed favourably with measurements available (Rye, 1980). The model also demonstrated rapid growth of mixing depth inland from the coast and wind shear effects, both of which could change air pollution estimates considerably. Some wind-field plots generated using the sea breeze model are shown in Figures 6.4 and 6.5.

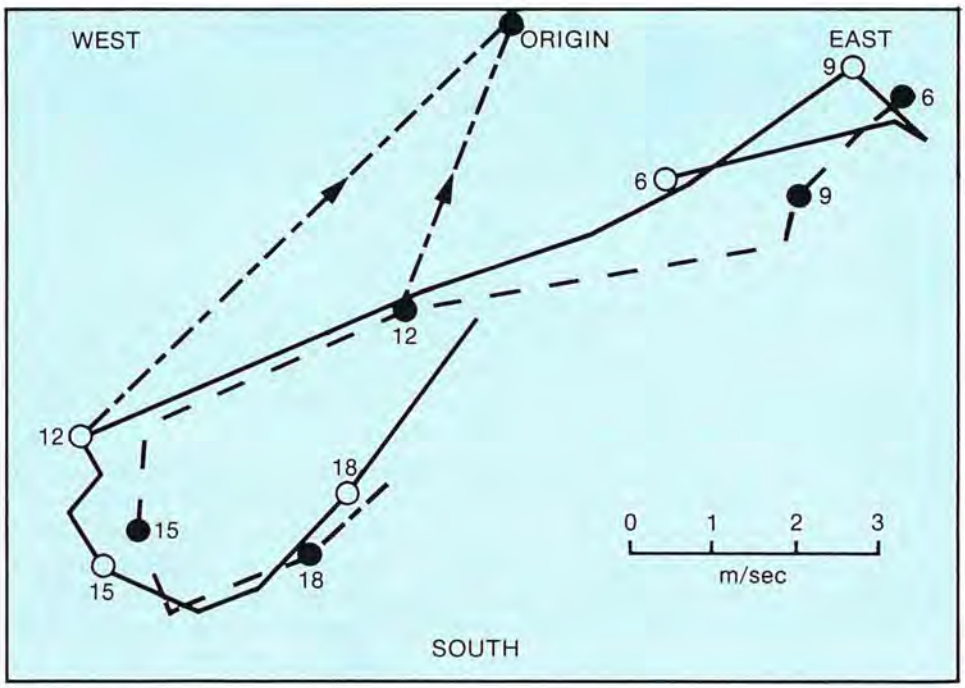


Figure 6.4. Representation of measured (——) and modelled (– – –) winds as a function of western standard time for Wattleup on 31 January 1980. The arrowed lines illustrate the meaning of the diagram, showing the measured and modelled wind vectors at 12 hours WST.

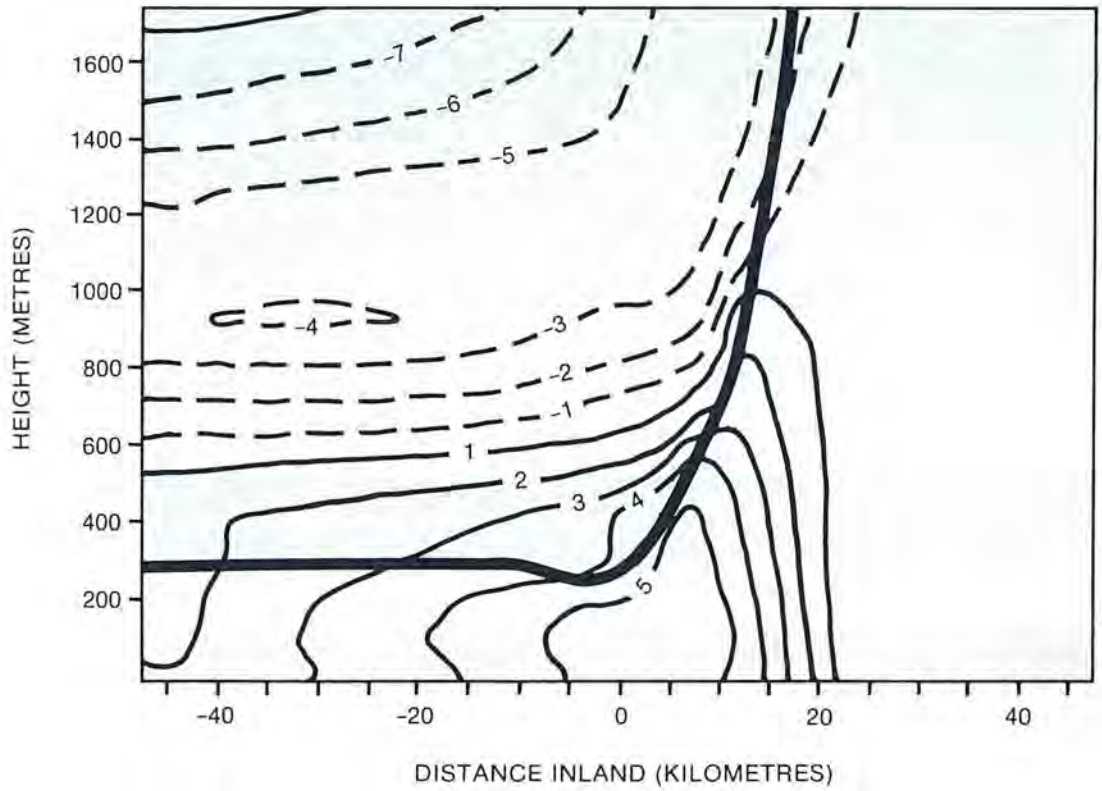


Figure 6.5. Estimated on-shore wind velocity as a function of height for 3.20 p.m. on 31 January 1980. The contour values are in m/sec and negative contours (broken lines) represent off-shore winds. The calculated mixing depth (heavy line) is also illustrated.

The use of the sea breeze model calculations of wind speed, stability and mixing depth as input data to the finite difference dispersion model confirmed the importance of accurate representation of these parameters. In particular, data from the model were used for the tracer study simulation activities in KAMS (Chapter 5).

The absence of any evidence of 'recycling' of pollutants at Kwinana was also explained by the sea breeze model. The return circulation above the south-westerly marine inflow was generally found to have a southerly component. As a consequence, any recycling would have occurred well to the north of Kwinana.

On the rare occasion when pollutants may have been recycled, mixing depths at the time of arrival of the sea breeze were large. Since ascent velocities and general atmospheric turbulence were also large at this time, pollutant dispersion would have been so rapid that concentrations experienced at ground level would have been low.

6.3.4 Internal Boundary Layers

When a moving air mass encounters a change in surface roughness or temperature, the flow near the surface is modified by the sudden change in stress and heat flux. The effects of the surface change penetrate upwards at a rate governed by the turbulent diffusion of momentum and heat, and so an internal boundary layer is formed. An example which is of particular concern to air pollution agencies occurs in shoreline environments during onshore winds, as shown schematically in Figure 2.5.

In the case of onshore flow, the air mass may be stably stratified after flowing for long distances over water and hence any industrial plumes emitted from tall stacks near the shoreline will disperse quite slowly, with little or no mixing induced by ambient turbulence. The thermal internal boundary layer (TIBL) which forms over the relatively hot ground is well mixed by convective turbulence, so any ground level releases are rapidly dispersed. Elevated plumes will remain intact until they impinge on the growing TIBL, at which distance they will be mixed rapidly to ground level, resulting in the phenomenon termed 'shoreline fumigation'. The importance of this phenomenon is readily apparent; it provides a mechanism whereby short-term high ground level concentrations of pollutants may be experienced at distances of several kilometres from the stacks. It is important therefore to understand the growth of TIBLs and to include their effect in dispersion models.

Turbulence is also generated at the ground by friction, but its effect on internal boundary layer growth is usually small compared to thermal turbulence. Only when surface heating is very small is it necessary to consider the effect of a mechanical internal boundary layer (MIBL).

A variety of models have appeared in the literature over the past decade describing the modification of fluid flow over changes in surface characteristics. Perhaps the most recognised work dealing specifically with the problem of shoreline internal boundary layers is that of Venkatram (1977). He applies the formulation of a mixed layer model (Tennekes, 1973) in a Lagrangian framework, so predicting the growth of a well-mixed column of air which is being advected downstream.

Numerical solution of the equations of momentum, heat and turbulent kinetic energy enables the internal boundary layer height h(x) to be determined in terms of the parameters defined in Figure 6.6. However, for the purposes of dispersion modelling, the calculation of h(x) at each time or distance interval is not feasible and so a simple analytical formula must be sought.

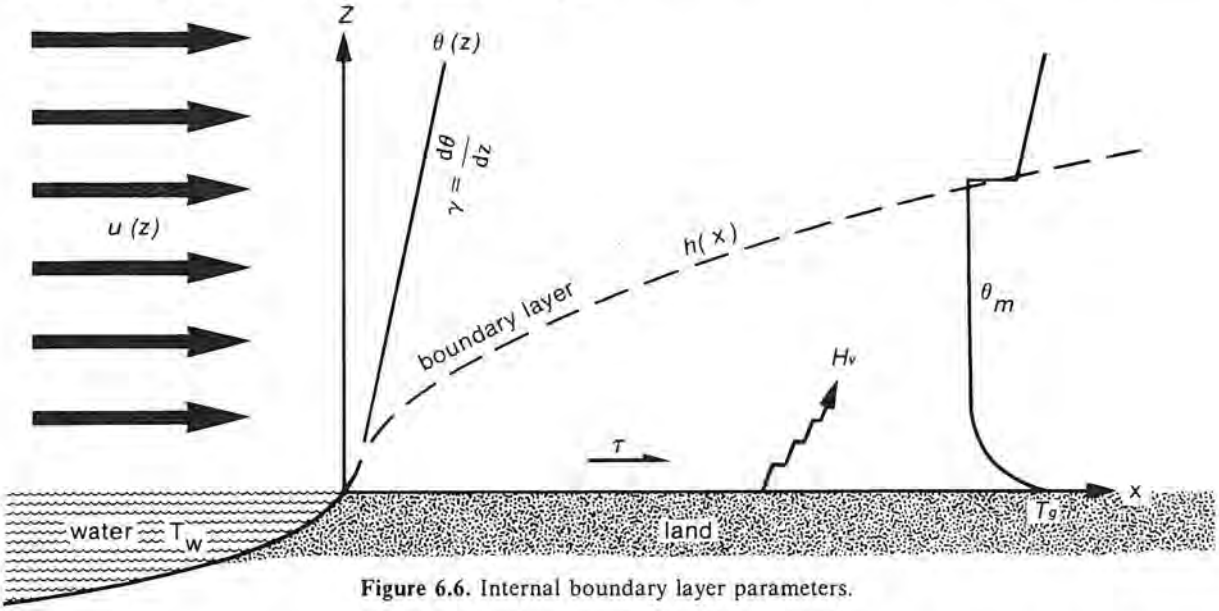


Figure 6.6. Internal boundary layer parameters.

Following Tennekes (1973), it is possible to obtain an analytical expressions for h(x) for two limiting cases; where convective turbulence is dominant (TIBL),

$$h(x) = \left(\frac{2.72\ H_v\ x}{\rho_a\ C_p\ \gamma\ u_m} \right)^{1/2} \tag{6.31}$$

and if mechanical turbulence determines the growth of the boundary layer (MIBL),

$$h(x) = \left(\frac{2.5\ u_*^3\ T\ x}{g \gamma\ u_m} \right)^{1/3} \tag{6.32}$$

An analytical expression for h(x) in which both mechanical and convective contributions are represented has not been derived. The application of these formulae to dispersion modelling is indicated in Rayner (1981b) and Rosher, Rayner and Paparo (1982).

6.4 DISPERSION IN THE PLANETARY BOUNDARY LAYER

Because turbulent motions in the atmosphere are essentially random, it is not possible to predict with certainty the instantaneous distribution on the concentration of a pollutant released from a given source. Basic equations describing turbulence do exist but because of their complexity, no single solution, or model, can effectively describe the diffusion process over the wide range of conditions that can be found in the atmosphere.

The central elements of turbulence relevant to the representation of average plume behaviour have been analysed by various researchers, however, producing a statistical model to give some insight into these random processes. From this work a number of approximate theories have evolved which allow the application of measured dispersion parameters in practical modelling exercises.

6.4.1 Methods of Modelling Dispersion

Four main theoretical methods for modelling dispersion from an elevated point source have emerged, namely statistical theory, eddy diffusion or K-theory, probability distribution (the Gaussian plume, for example) method and the mixed-layer scaling method. Each of these methods is outlined below.

(i) Statistical Theory

The origins of the statistical treatment of turbulent diffusion lie in the mathematical analysis of continuously varying quantities carried out by Taylor (1921). In this work, Taylor considered the velocity fluctuations of individual particles of fluid in homogeneous, stationary turbulence. Under these conditions, the statistics of the motion of a typical particle provide an estimate of the behaviour of all particles.

Taylor showed that the spread of an ensemble of particles may be represented as

$$\sigma_{y,z}^2 = 2\,\sigma_{v,w}^2 \int_0^T \int_0^t R(\xi)\,d\xi\,dt \tag{6.33}$$

where T is the travel time of a particle, σ_y and σ_z are the standard deviations of the concentration distribution in the lateral and vertical directions respectively, σ_v and σ_w are the standard deviation of the horizontal and vertical wind speed components respectively, and $R(\xi)$ is the Lagrangian autocorrelation function which represents the degree of correlation in the motion of a particle at two separate instants of time.

Equation (6.33) cannot be directly evaluated since the form of $R(\xi)$ cannot be specified for the atmosphere with any reasonable certainty. However, two limiting results can be obtained. For zero separation time ($\xi = 0$), $R(\xi) = 1$ so that Equation (6.33) becomes:

$$\sigma_{y,z} = \sigma_{v,w} T \tag{6.34}$$

For large separation times ($\xi \to \infty$), $R(\xi) = 0$ and Equation (6.33) becomes

$$\sigma_{y,z} = \sigma_{v,w}\,(2\,\tau_L T)^{1/2} \tag{6.35}$$

where $\tau_L = \int_0^\infty R(t)\,dt$ is the Lagrangian timescale which represents the extent of correlation over all values of time lag ξ. These limiting results indicate that the spread starts off with a linear form (proportional to time T) and ultimately tends to a parabolic form (proportional to $T^{1/2}$).

The solution to Equation (6.33) may be written in the generalised form

$$\sigma_{y,z} = \sigma_{v,w}\,T\,F\left(\frac{T}{\tau_L}\right) \tag{6.36}$$

where the function F must obey the two limiting results given by Equations (6.34) and (6.35). This equation may be transformed to spatial coordinates giving

$$\sigma_{y,z} = \sigma_{\theta,\phi}\,x\,F_{y,z}(x) \tag{6.37}$$

where σ_θ and σ_ϕ are the standard deviations of wind direction in the azimuth and elevation respectively, x is downwind distance and the function $F_{y,z}(x)$ is to be determined from experiment.

Pasquill (1976) has proposed a functional form for F_y, which is expressed analytically by

$$\begin{aligned} F_y(x) &= (1 + 0.0308\,x^{0.4548})^{-1}, \quad x \leqslant 10\ \text{km} \\ F_y(x) &= 0.333\left(\frac{10000}{x}\right)^{1/2}, \quad x > 10\ \text{km} \end{aligned} \tag{6.38}$$

An adopted form for F_z, which must remain tentative pending further work is given by

$$\begin{aligned} F_z(x) &= (1 + 0.018\,x^{0.5})^{-1}, \quad L < 0 \\ F_z(x) &= \left(1 + 0.098\left(\frac{x}{30}\right)^{E}\right)^{-1}, \quad L > 0 \end{aligned} \tag{6.39}$$

where the exponent E varies linearly from 0.5 to 0.81 as the Monin-Obukhov stability 10/L varies from 0 to 3.

The fundamental assumption of stationary homogeneous turbulence upon which statistical theory is based is rarely, if ever, satisfied in the atmospheric boundary layer. Robins and Fackrell (1979) point out that although σ_v and σ_w may be fairly constant at heights well clear of the ground, the turbulence intensities and consequently σ_θ and σ_ϕ do vary with height.

The best results from the application of the theory can therefore be expected for lateral dispersion since σ_v (if not σ_θ) is quite constant with height. In addition, the theory may also be applicable to vertical dispersion above the lower 10% of the planetary boundary layer where σ_w assumes a constant value with height.

(ii) Eddy Diffusion or K-theory

Simple diffusion, the basis of K-theory, is a process in which the rate of transfer of material in any particular direction is dependent upon the product of a diffusion coefficient and the gradient of the material concentration in that direction.

If turbulent fluxes of pollutants in the atmosphere are also represented by such a gradient relationship, consideration of the equations of fluid motion yields the following time-dependent diffusion equation:

$$\frac{\partial \chi}{\partial t} + \frac{u\partial \chi}{\partial x} + \frac{v\partial \chi}{\partial y} + \frac{w\partial \chi}{\partial z} = \frac{\partial}{\partial x}\left(K_x \frac{\partial \chi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \chi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial \chi}{\partial z}\right) \qquad (6.40)$$

where χ is the concentration of pollutant,

K_x, K_y and K_z are the diffusion coefficients (eddy diffusivity) in the x, y, z directions respectively, and

u, v and w are the wind components in the x, y, z directions respectively.

The major difficulty of K-theory involves the specification of the eddy diffusivities. If these can be specified throughout the depth of the planetary boundary layer, then the diffusion equation may be solved by numerical means. However, the general applicability of the method warrants serious consideration.

As in the case of molecular diffusion, the K-theory approach may be expected to be most appropriate when the spatial and temporal scales of turbulence are small in comparison to the corresponding scales in the concentration field. If there are turbulent displacements of whole sections of a plume, then the notion of a diffusion coefficient has little physical relevance and simple diffusion cannot represent adequately the physical process.

Pasquill (1974) concluded that this scaling constraint is best met in the case of vertical dispersion in conditions where the vertical scale of turbulence is limited; either by the ground or by a stable density gradient aloft. Robins and Fackrell (1979), however, contend that use of the eddy diffusion method may be valid for any conditions in the vicinity and downwind of the maximum ground level concentration, in which case both vertical and lateral spread increase beyond the scale of most of the energy-containing eddies. In a similar manner Rye (1982) proposes that the technique is generally applicable for times greater than the Lagrangian timescale τ_L, represented by downwind distances greater than 1-3 km in the case of the Kwinana work.

The eddy diffusion approach is clearly appropriate for both lateral and vertical spread from ground level area sources where the scaling constraint is readily met. For this reason, the method is particularly popular for the modelling of photochemical pollution.

A number of different approaches have been used in the determination of the eddy diffusivities. These include, for the vertical coefficient K_z, an analogy to the diffusion of momentum combined with surface similarity theory (Rayner, 1981a) and the use of statistical results (Smith and Blackall, 1979).

To determine a value for the eddy diffusivity K_z, the diffusion of matter has conventionally been related to the diffusion of momentum (Pasquill, 1974). Hence, K_z may be determined from

$$K_z = \tau \Big/ \left(\rho \frac{du}{dz}\right) \qquad (6.41)$$

In the surface constant-stress layer Equation (6.41) may be combined with the surface similarity theory to give

$$K_z = \frac{k\, u_* z}{\phi_m\left(\frac{z}{L}\right)} \qquad (6.42)$$

which may be readily evaluated from surface wind and temperature profile measurements. Higher in the layer, however, where wind speed gradients are small, K_z cannot be sensitively prescribed from Equation (6.42).

An alternative more recent prescription for K_z, summarised by Smith and Blackall (1979), combines diffusion and statistical results to give

$$K_z = \sigma_w^2 \tau_L \tag{6.43}$$

Further modification and assumptions allow Equation (6.43) to be evaluated from estimates of σ_w and λ_m, the spectral length scale. Both of these parameters have been well characterised in recent planetary boundary layer experiments, as functions of the surface turbulent fluxes and the boundary layer height.

The estimation of K_y is rendered simpler by the vertical uniformity of σ_v which may therefore be obtained from measurements in the surface layer. Field measurements of τ_L for horizontal turbulence have been made (Draxler, 1976) but disagree to an extent that makes any conclusion on the vertical uniformity of this parameter impossible.

An alternative approach involves using the large distance limit of plume widths. Where a dependence on the square root of distance has been detected (Willis and Deardorff, 1978; Pasquill, 1976), Equation (6.35) may be used to estimate τ_L. Present published plume width values do not provide any information on the change of τ_L with height so that the values used in such studies as that of Rye (1982) have been assumed to be height-independent.

(iii) The Gaussian Plume

There are obvious advantages in respect to efficiency of calculation if the dispersion of plume material is given in terms of a simple analytical expression. The Gaussian plume formula is such an expression and represents a statistical distribution of material relevant to an ensemble of observations over a specified sampling interval. The Gaussian shape of the distribution is scaled so that the mass of the material is conserved at all downwind distances.

For a continuous point source, the general form of the Gaussian plume equation (Turner, 1970) is:

$$\chi(x,y,z,H) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left(\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right) \tag{6.44}$$

where χ is concentration,
Q is source emission rate,
H is effective plume centreline height and
x,y,z are downwind, crosswind and vertical coordinates respectively.

Pasquill (1974) discusses the origins of the Gaussian plume formula given above. Gaussian or normal distributions for the spread of gaseous material by molecular diffusion are directly predicted by Fickian theory, although the analogy with turbulent convective dispersion is dubious. Gaussian distributions for turbulent dispersion are also indicated from the statistical theory of G.I. Taylor (Section 6.4.1(i)) coupled with the observation that turbulent eddy velocities have a Gaussian probability distribution.

Instantaneous cross section profiles of an elevated smoke plume may depart markedly from Gaussian. In view of the prediction of Gaussian profiles from the statistics of turbulence (noted above), a Gaussian distribution can only be expected in an ensemble average of many plume cross section observations. This is illustrated in Figure 6.7 which shows an instantaneous plume and the concentration distributions for different sampling times. The Gaussian profile dimensions given by Turner (1970) refer to 10-minute average cross sections of a plume.

Pasquill (1974) summarises several field experiments in which averaged crosswind plume profiles were analysed and concludes that, although individual profiles vary considerably, there is no sound reason to adopt an analytical form different from Gaussian. The laboratory experiments of Willis and Deardorff (1976) show that the Gaussian distribution adequately describes the lateral spread of ensemble averaged plume material for all downwind distances under convective conditions. These and subsequent experiments by the same authors have shown, however, that vertical spread from an elevated source in strongly convective conditions cannot adequately be described as Gaussian. Further, Pasquill (1974) observes that vertical spread from a ground level source is systematically different from Gaussian, tending towards an exponential form. Apart from these two exceptions the precise prescription of plume distribution, whether Gaussian or some similar form, is not as critical as a correct specification of plume spreads σ_y and σ_z.

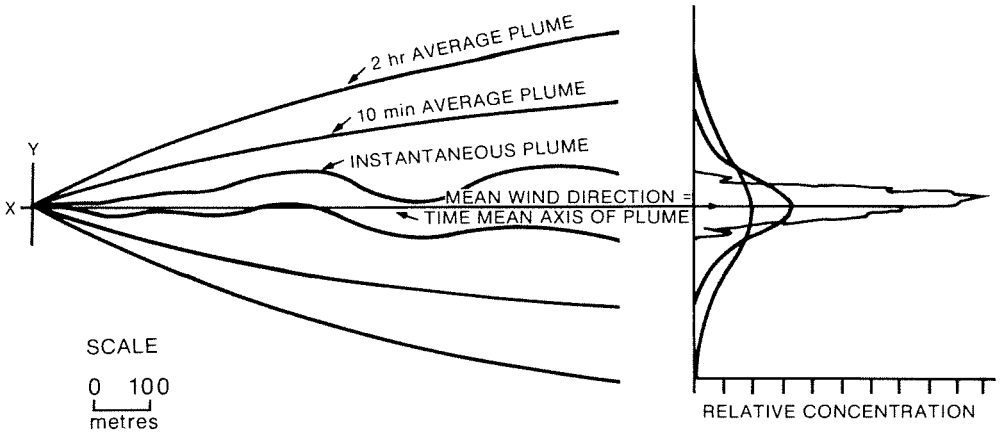


Figure 6.7. Plume boundaries as a function of averaging time (source: Slade, 1968).

(iv) Mixed Layer Scaling

The application of mixed layer scaling to the problem of dispersion in the convective planetary boundary layer followed from the laboratory experiments of Willis and Deardorff (1974). The data from the experiments were analysed in terms of the mixed layer velocity scale w_* and the mixed layer depth h.

The lateral plume spread was found to be closely Gaussian and obeyed both the short and long travel time limits of Taylor's statistical theory (Equations (6.34) and (6.35)). Close to the source the vertical spread was also reasonably well described as Gaussian and obeyed Taylor's short travel time diffusion limit. Beyond this distance, however, the vertical concentration field was drastically modified by the influence of atmospheric thermals which swept elements of the plume high into the mixed layer resulting in elevated concentration maxima.

Willis and Deardorff (1978 and 1981) have conducted experiments with two more elevated release points (greater stack heights) and have observed the plume concentration maxima to descend to ground level prior to the 'sweeping out' effect of thermals. Neither a Gaussian distribution nor an eddy diffusivity treatment can adequately simulate the plume behaviour under these conditions.

No general parameterisation for vertical spread has so far been advanced by Willis and Deardorff. The availability of the parameters h and w_* from the output of the mixing depth model (Section 6.3.2), however, means that this theory, when completed, may be easily incorporated into the models developed for KAMS.

6.4.2 Estimating Dispersion Parameters

The eddy diffusion approach described above relies on the specification of σ_v and σ_w (or σ_θ and σ_ϕ) to evaluate K_y and K_z. Similarly, the statistical method uses σ_θ and σ_ϕ to evaluate σ_y and σ_z which, in turn, may be used in the Gaussian plume formula (Equation (6.44)). Hence, determination of the velocity fluctuations σ_v and σ_w or their corresponding wind direction fluctuations σ_θ and σ_ϕ is central to estimating dispersion. Methods for achieving this are described below. Firstly, however, the widely used scheme of estimating σ_y and σ_z via discrete stability categories is considered for comparison.

The researchers Pasquill, Gifford and Turner have developed, at various stages over the past two decades, a simple procedure for estimating σ_y and σ_z from routine meteorological observations. The method is clearly described by Turner (1970) and is implicitly an energy budget approach to describe the turbulent state of the atmosphere. The method is very well known and widely used, so the tables and graphs have not been reproduced here. It provides a means for quickly estimating dispersion from point sources.

However, as individual researchers have stressed, the method has definite limitations:

- It should only be used if σ_θ and σ_ϕ estimates are not available.
- It is applicable to ground level sources and may give large errors if applied to elevated sources.
- The stability category scheme does not account for the important effects of surface roughness variation, surface sensible and latent heat variations and the mixing height dependence of convective turbulence.
- The σ_y and σ_z curves are specified for a sampling period of about 10 minutes and correction to other sampling times is not trivial.
- The form of the σ_y and σ_z curves beyond 800 m downwind is quite unsupported.

Further, as shown in Section 5.2.2, the simple stability category and Gaussian plume approach proves to be quite inadequate for a shoreline environment. For both coastal and inland areas the stability categorisation may prove to be too coarse to confidently predict dispersion patterns.

In summary, the method is valuable for calculations where its applicability in a particular situation may be examined, but it is not suitable for an extensive modelling exercise such as KAMS.

It is common practice in atmospheric dispersion studies to measure directly σ_θ and σ_ϕ, using electronic circuits known as sigma meters. The methods available to measure these parameters and the problems encountered with the use of sigma meters to measure σ_θ during KAMS are described in Rosher, Rayner and Paparo (1982). No direct measure of σ_ϕ was attempted during the study.

Whilst the σ_θ data for KAMS were of reasonable quality, alternative means for estimating σ_θ and σ_ϕ were adopted for use in the Gaussian model (Rosher, Rayner and Paparo, 1982). These were based on the theoretical relationships given in Table 6.1.

The parameters u_*, L and h are available from the surface layer and mixing depth models described in the previous sections. The expressions for σ_θ have been shown by Rosher, Rayner and Paparo (1982) to compare favourably with measurements for unstable conditions, but overestimate σ_θ in stable conditions. The latter problem may reflect many factors, including instrument response, and must remain an area for future work.

Table 6.1 Theoretical expressions for σ_θ and σ_ϕ (Rosher, Rayner and Paparo, 1982; Rye, 1982)

Expressions for σ_θ

$$\frac{z}{L} < 0 : \sigma_\theta = \frac{u_*}{u}\left(12 - 0.5\,\frac{h}{L}\right)^{1/3}$$

$$\frac{z}{L} \geqslant 0 : \sigma_\theta = 2.3\,\frac{u_*}{u}$$

Expressions for σ_ϕ

$$\frac{z}{L} < 0 : \sigma_\phi = 1.3\,\frac{u_*}{u}\,(1-A)^{1/3}$$

$$\text{where } A = \begin{cases} \dfrac{3z}{L}, & z < 0.08h \\ \dfrac{0.24h}{L}, & z \geqslant 0.08h \end{cases}$$

$$\frac{z}{L} \geqslant 0 : \sigma_\phi = 1.3\,\frac{u_*}{u}\left(1 + \frac{z}{L}\right)$$

6.5 DISPERSION IN A COASTAL REGION

Dispersion of chimney plumes emanating from tall stacks near a shoreline is greatly complicated by the interaction of onshore flow with the ground and, in the case of sea breezes, with the air aloft. Any model of dispersion in a coastal region must include the important features of these interactions.

Sea breezes are a regular feature in the summer months in Western Australia and in many other places. There have been some successful attempts to model the formation and development of the sea breeze (Physik, 1976; Rye, 1980) but the complexity of these models makes them unsuitable for routine dispersion calculations.

Fortunately, once a sea breeze is well established, the depth of the sea breeze and the dynamics of its interface with the synoptic flow become relatively unimportant compared to the effect of the internal boundary layer formed at the coast. Beyond about 15 km inland, however, the internal boundary layer has usually grown to several hundred metres and dispersion is quite rapid. In most cases, therefore, it is sufficient to specify the broad features of the sea breeze in an approximate manner, and then to concentrate on the dynamics of the internal boundary layer.

The formation of thermal and mechanical internal boundary layers (TIBLs and MIBLs) has been described in Section 6.3.4. The phenomenon known as shoreline fumigation which occurs when a rising plume intersects a growing internal boundary layer was described in Section 2.2.5. This aspect has received close attention in KAMS and a theoretical description is given by Rosher, Rayner and Paparo (1982). A summary of this work is given below.

6.5.1 Fumigation under a TIBL

Figure 6.8 shows schematically a plan and elevation view of a plume, initially released above a TIBL, and subsequently entrained into the TIBL further downwind. The concepts employed in this model are largely based on those first proposed by Lyons and Cole (1973) but with several significant modifications.

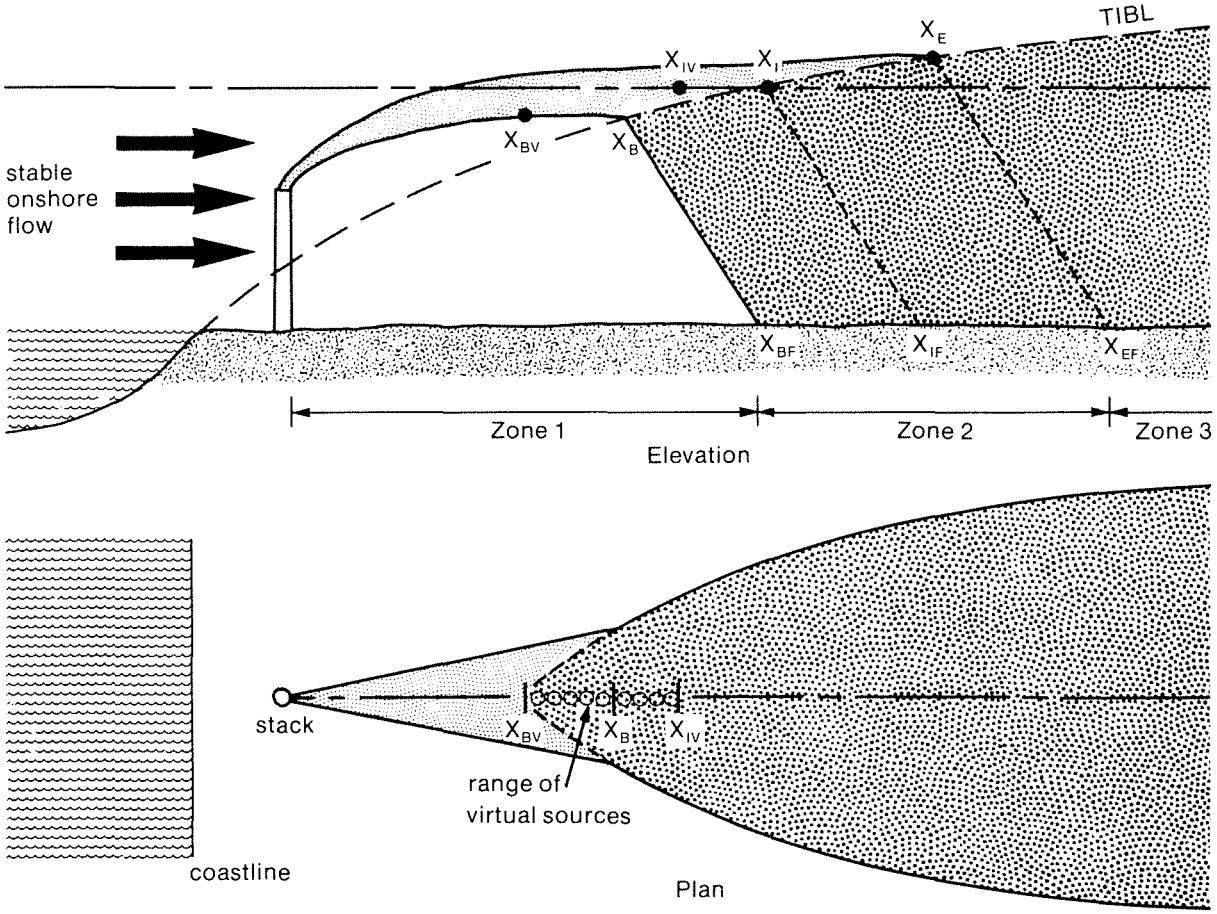


Figure 6.8. A schematic representation of the plume geometry used to model fumigation under a TIBL.

The growth of the TIBL is given by Equation (6.31). The points of intersection, X_B, X_I and X_E, are obtained by equating plume rise to TIBL height, where the upper and lower boundaries of the plume are defined as 2.15 σ_z from the centreline.

In Zone 1, the plume spreads slowly in the stable marine air and the dispersion parameters $\sigma_{\theta s}$ and $\sigma_{\phi s}$ are calculated from Table 6.1 given that

$$\frac{u}{u_*} = \left(C_{DN} \right)^{1/2} \tag{6.45}$$

where C_{DN} is the neutral drag coefficient over water.

Zone 2 commences at the point x_{BF} where plume material is first expected to reach ground level. This is estimated to be

$$X_{BF} = X_B + \sigma_\phi h_B \tag{6.46}$$

where σ_ϕ is the value appropriate to the TIBL.

Within Zone 2, a plume segment entrained by the TIBL at, say, X_B will undergo enhanced lateral spread before its concentration is registered at the ground at X_{BF}. At X_B, the plume segment has a lateral spread

$$\sigma_{ys}(X_B) = \sigma_{\theta s} X_B F_y (X_B) \tag{6.47}$$

For dispersion of this segment in the TIBL, a virtual source X_{BV} can be defined such that

$$\sigma_{ys}(X_B) = \sigma_\theta \Delta X_B F_y (\Delta X_B) \tag{6.48}$$

where $\Delta X_B = X_B - X_{BV}$. Rosher, Rayner and Paparo (1982) show that, for increasing fractions of plume entrained in the TIBL, the virtual source may be considered to move from X_{BV} to X_{IV}, but not beyond.

Dispersion calculations within Zone 2 are based on the fraction Q_F of plume mixed to ground level at a particular distance, given by

$$Q_F = \int_{-\infty}^{p} (2\pi)^{-1/2} \exp\left(\frac{-p_1^{\,2}}{2}\right) dp_1$$

where (6.49)

$$p = (h(x) - H_e)\,\sigma_{zs}(x)$$

and where h is the TIBL height and H_e is the plume centreline height.

Dispersion in Zone 3 is calculated on the basis of complete vertical mixing up to h(x), with the virtual source at X_{IV}.

Rosher, Rayner and Paparo (1982) provide an extensive description of the procedures employed to incorporate this model of TIBL fumigation into the Gaussian dispersion model.

6.5.2 Dispersion under a MIBL

The mechanics of dispersion in onshore flows where there is little or no surface thermal convection is governed by the formation of a mechanical internal boundary layer (MIBL). MIBL growth is given by Equation (6.32). Rosher, Rayner and Paparo (1982) point out that treatment of dispersion under a MIBL along the lines of that for a TIBL would be very difficult. However, the enhanced dispersion within a MIBL cannot be ignored. Rosher, Rayner and Paparo (1982) therefore adopt an approach which is illustrated in Figure 6.9.

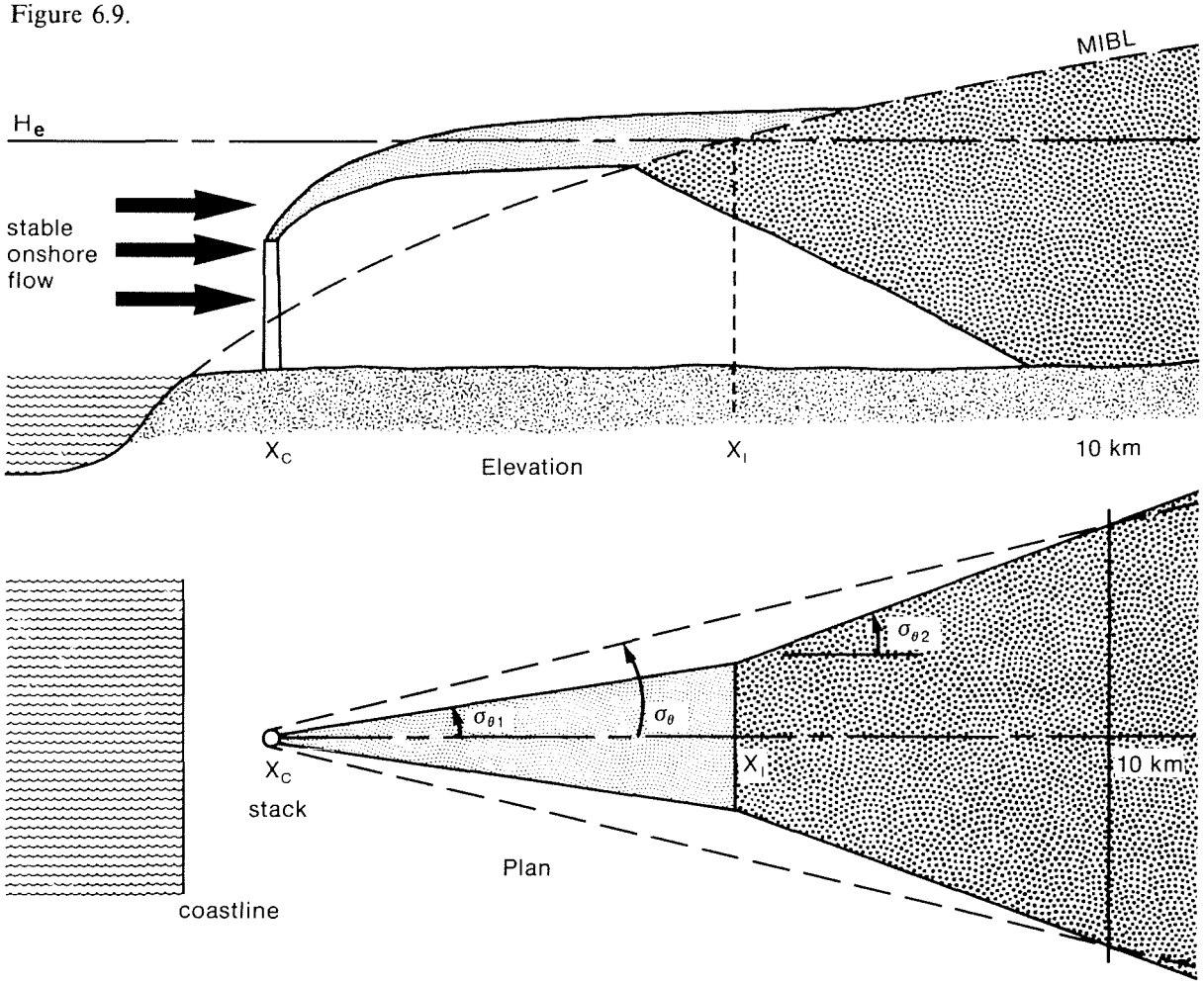


Figure 6.9. A schematic representation of the plume geometry used to model fumigation under a MIBL.

The elevated plume intersects the growing MIBL at a downwind distance X_I:

$$X_I = H_e^{\,3}\left(\frac{g\gamma u}{2.5\,u_*^{\,3}\,T}\right) - X_c \qquad (6.50)$$

where X_c is the downwind distance from the coast to the stack. For a region of interest of, say, 10 km downwind, an effective value of σ_θ (or σ_ϕ) is obtained from

$$\sigma_\theta = \tan^{-1}\left(\frac{X_1 \tan \sigma_{\theta 1} + (10000 - X_1) \tan \sigma_{\theta 2}}{10000}\right) \quad (6.51)$$

where $\sigma_{\theta 1}$ and $\sigma_{\theta 2}$ are the values outside and within the MIBL respectively. As with procedures developed for TIBLSs, this expression is quite empirical, but it will reproduce the essential effect of a MIBL on both high and low plumes. An alternative scheme to compute an average value of turbulent energy in the marine flow was also considered (equivalent to averaging the variances σ_θ^2 and σ_ϕ^2). However, this method does not correctly differentiate between elevated and low plumes.

Chapter 7

STRUCTURE AND VALIDATION OF MODELS

The process by which the theory detailed in Chapter 6 is implemented into a working dispersion model is necessarily complex, requiring the creation of extensive data bases and the linking of separate computer programs performing various subsidiary tasks.

However, to fit the models within the size and financial limits of the computer resources available, simplifications had to be made for the study. The initial sections of this chapter explain the way in which each model implemented dispersion theory and the simplifications needed to permit the operation of the models on the computers used.

Once created, the models were tested to determine whether their simplifications had resulted in any significant errors. The effects of possible changes in uncertain parameters, such as turbulent velocity scales, were also considered. This process was largely iterative, involving review and alteration of chosen parameterisations, in the light of comparisons between model calculations and field measurements. The final results of these 'validation' studies form the remainder of the chapter.

7.1 KAMS DISPERSION MODELS

Two comprehensive dispersion models were developed for the Kwinana study. The first of these is based on the standard Gaussian distribution for plume pollutant concentration, with variations to include such mechanisms as limited mixing depth due to inversions and the coastal thermal internal boundary layer. Dispersion parameters are not limited to the discrete stability categories which are most often used for this type of model, but are obtained from the measured meteorological data. The Gaussian model performs best for short source to receptor pollutant travel times and in terrain that is approximately flat and homogeneous.

In order that variations in meteorological parameters over the study area and with height could be accommodated, a finite difference model was also developed. This model considers not the behaviour of individual plumes but the transport of pollutants between a selected, three-dimensional grid of 'boxes' in the atmosphere. The concentration in any box results from the transport of clean or polluted air from others upwind, turbulent transfer from neighbours and the addition of pollutants from nearby sources. Dispersion parameters are derived from long-range plume width measurements and as a result the finite difference model is most applicable at distances of 5 to 10 kilometres from the source.

Each model has certain advantages and shortcomings, but, taken together, the models provide a valuable quantitative tool with which the air quality at Kwinana can be determined. The models are outlined below.

7.1.1 The Gaussian Model (Model 1)

(i) Structure

The Gaussian model developed for the study (Rosher, Rayner and Paparo, 1982) incorporates a two-dimensional Gaussian description of plume spread with spread parameters σ_y and σ_z (Section 6.4.1(iii)).

The model mechanics involve the calculation of pollutant concentration at each point of a one by one kilometre grid, superimposed on the study area. Each source is represented on the grid and the continuous source Gaussian formula solved for each 10-minute period of the day for each grid point receptor downwind of the source. The flow of model operations is shown in Figure 7.1 and is explained briefly below.

Data required by the model are read from three data files. The first file contains control information for

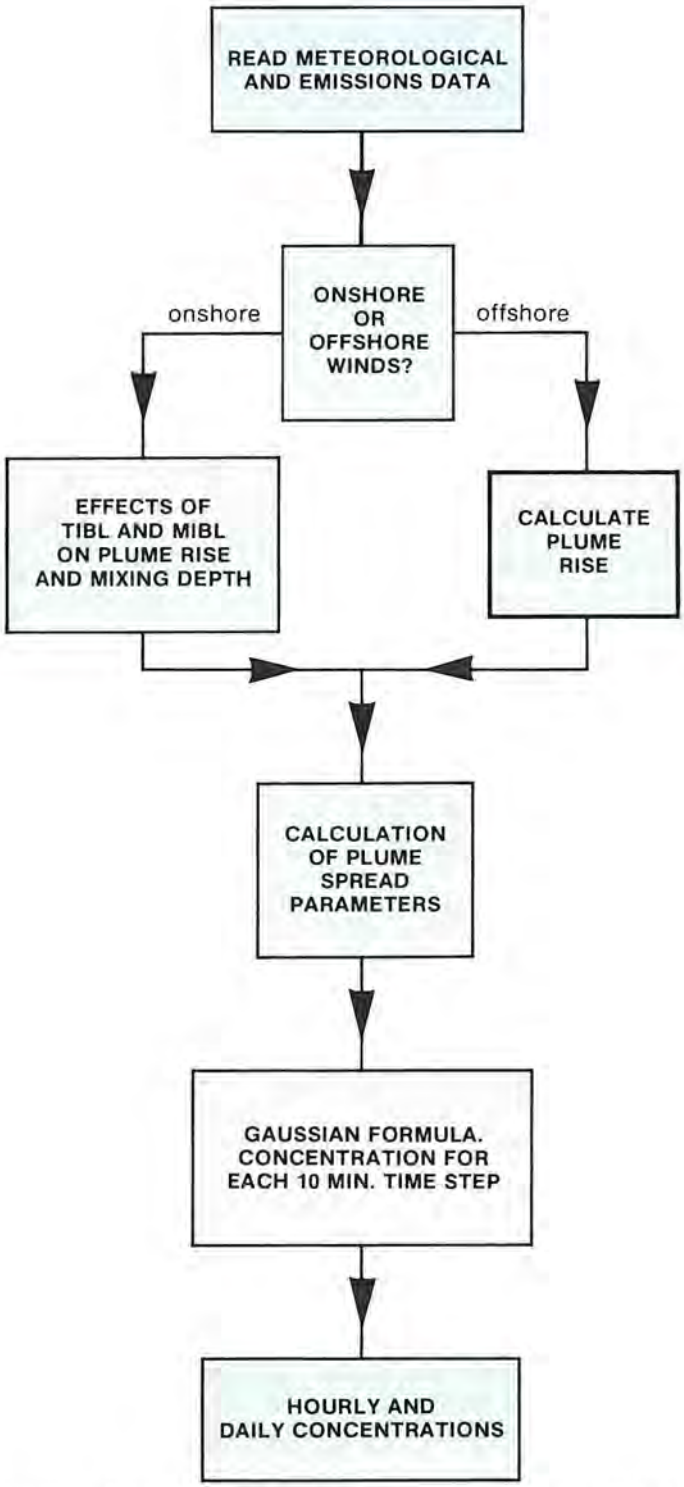


Figure 7.1. Flow diagram showing the major components of Model 1.

the establishment of source locations, physical data relevant to each stack and dimensions of the grid network. All emissions data for the sources are contained in a separate file. This includes stack volume and mass fluxes, exhaust temperatures and sulphur dioxide emission rates. The third file contains meteorological data from the base station in addition to mixing layer depth and turbulence data from the output of the mixing layer and turbulence models (Rayner, 1981a, b). The control information file is read at the commencement of each model run while emission and meteorological data are read in at the beginning of each day's computation.

For a particular 10-minute record, source and grid location an initial test is applied to determine whether the wind is blowing onshore or offshore. If the wind direction shows an onshore flow, the effects of a coastal boundary layer (TIBL or MIBL, Section 6.3.4) are included in the dispersion calculations. Appropriate plume rise formulae (Section 6.1) are used to determine whether plumes are trapped within, emitted above or partially penetrate the boundary layer.

In the case where the plume is emitted above a TIBL and intersects it further downwind, the point of intersection is calculated. Beyond this point, the portion of the plume entrained in the TIBL is mixed uniformly downward at a rate determined by the intensity of convective turbulence. The horizontal dispersion parameter σ_y is based on a weighted calculation taking into account the small plume growth in the stable marine air above the boundary layer and the unstable conditions within the layer. In the case where the plume is emitted above a MIBL and intersects it further downwind, empirical expressions for plume spread are employed which take account of the enhanced dispersion within the MIBL. The mixing depth in each case is based on the calculation of the boundary layer height (Equation (6.31) and (6.32)) at each grid point receptor.

For plumes under the influence of offshore breezes, mixing depth is read directly from the meteorological data file. Plume rise is determined from the formulae of Section 6.1.

Stability data for all conditions are calculated using the model described in Section 6.2 and are read in as input for each 10-minute period. The plume spread parameters σ_y and σ_z are then determined using the statistical theory outlined in Section 6.4.2.

Pollutant concentration at each grid receptor point is determined from Equation (6.44) using the calculated values of σ_y and σ_z, plume rise, mixing depth, the measured wind speed and the pollutant emission rate. The contribution from each source is summed to provide a 10-minute average concentration at the grid point.
In order to estimate the frequency of short-term pollution episodes, the 10-minute concentrations are averaged to provide 1-hour average concentrations which are then compared to 1-hour average concentrations of 500, 1000, 1400 and 2000 $\mu g/m^3$. The number of times each of these levels is exceeded at each grid point and the predicted daily concentration forms the output of the model.

(ii) Limitations

Since hourly averages are calculated over fixed 'clock' hours (6 am to 7 am, 7 am to 8 am and so on), it is possible that short bursts of pollutant concentration giving a 1-hour average in excess of the four reference levels but occurring in between the fixed 1-hour periods could be missed. This is of small concern at low concentrations but of potential significance at higher levels when periods of exposure are often short. The limitation is discussed in more detail in Section 7.2.2.

In addition, the assumption of a straight plume axis leads to an underestimate of high 1-hour average concentrations at large distances when the wind direction changes from one 10-minute period to the next. The error only occurs at distances reached after more than 10 minutes travel time, typically 3 to 5 kilometres.

Tests showed that at the extremes of the model grid about 15-20% of periods over 500 $\mu g/m^3$ were missed as a result of this effect. At higher concentrations, the fraction increased to about 30-40%. It should be noted however, that this model limitation has very little effect on longer-term averages over the area (24-hour and annual, for example).

7.1.2 The Finite Difference Model (Model 2)

(i) Structure

This model (Rye, 1982) calculates the effects of wind and turbulence in transporting pollutants between adjacent 'boxes' arranged in a three-dimensional grid (Figure 7.2). Mathematical formulae allow the changes of concentration in each box to be related to concentrations in adjacent boxes, and to the wind velocity and atmospheric turbulence. In particular, topographic and frictional influences on wind can be included, as well as the deepening of mixing depth by convection over the land surface. The flow of model operations is shown in Figure 7.3 and explained briefly below.

The 'conditional sampling' approach used allows the finite difference model to be applied to the long-term study of air pollution episodes. At each hour of the modelled period, the likelihood of an inland pollution episode at Kwinana is estimated through analysis of wind direction, mixing depth and turbulence data. If these combine to produce high inland concentrations of pollutants at ground level, the model is run using recorded pollutant emission rates, and transports pollutants through advection by wind and turbulence. When the modelled pollutants have been transported fully across the grid, the ground level section of the grid is scanned to find points where any of the four reference levels (500, 700, 1000 and 1400 $\mu g/m^3$) are exceeded. A record of the number of these for each level at each surface grid point is accumulated.

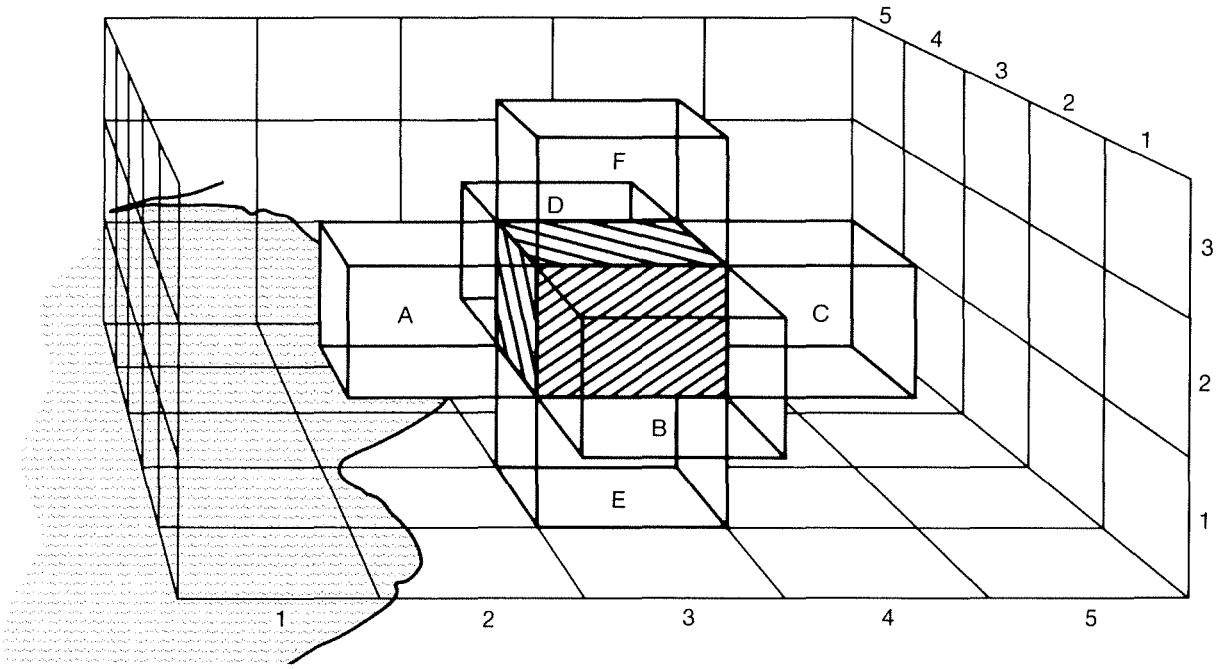


Figure 7.2. A schematic representation of the grid used for Model 2. The concentration changes in the central box (shaded) may be due to transport from box A by a westerly wind component, from B by a southerly component, from C by an easterly component, and so on. Turbulence transports pollutants between the central box and all six neighbours. Each box is labelled by three numbers for reference in the computer program: for example the shaded box is referenced (3,2,2).

This record is reprocessed, using the statistics of wind fluctuations to estimate how many of the periods of exposure would have lasted an hour or more. These estimates are the final output of the model.

(ii) Implementation of Dispersion Theory

The necessary meteorological variables are usually estimated using the theory of the planetary boundary layer (Section 6.1). Velocity variances are modelled using measured wind direction variability, along with the convection velocity scale obtained from solar radiation intensity. The Monin-Obukhov length is used to specify the form of the variation of wind in the vertical direction.

Mixing depth is represented in the manner outlined in Section 6.3, except for those periods of onshore wind when a representation of the growth of the thermal internal boundary layer (TIBL) is used. In both cases, the rate of growth of the depth of the planetary boundary layer depends on the stability of the atmosphere, into which it is growing.

The growth of the TIBL is also dependent on atmospheric stability. As a result of the much shorter times involved in the growth of the TIBL, however, its depth remains low. Therefore, the stability estimate used has a critical effect on mixing depth. In order to improve the accuracy of the representation of inflow stability, data from the Perth Sea Breeze Project (Walker and Allen, 1975) were used, inflow temperature profiles being classified as a function of surface air temperature (Rye, 1982, Figure 4).

Alternatively, it is possible to obtain wind, stability and mixing depths directly from the data output of the numerical sea breeze model. This allows study of the relative importance of such effects as TIBL growth, wind shear and the horizontal change of atmospheric stability, and was used to determine parameters which are required for modelling from measured data.

The advection of pollutants is modelled using a fourth-order finite difference formula, which possesses the important characteristic of conserving plume width. The feature is particularly important since some alternative schemes lead to a widening of the plume, to a greater degree than actually occurs as a result of atmospheric turbulence. In view of the observed narrowness of the Kwinana plume, such errors would prevent accurate modelling of pollutant concentrations. Since dispersion parameters are derived from long-range plume width measurements, the model is most applicable at distances of relevance to land use planning.

Data available for plume rise estimation include not only such factors as stack temperature and buoyancy flux, but also calculated mixing depth, atmospheric stability above this level and mixing

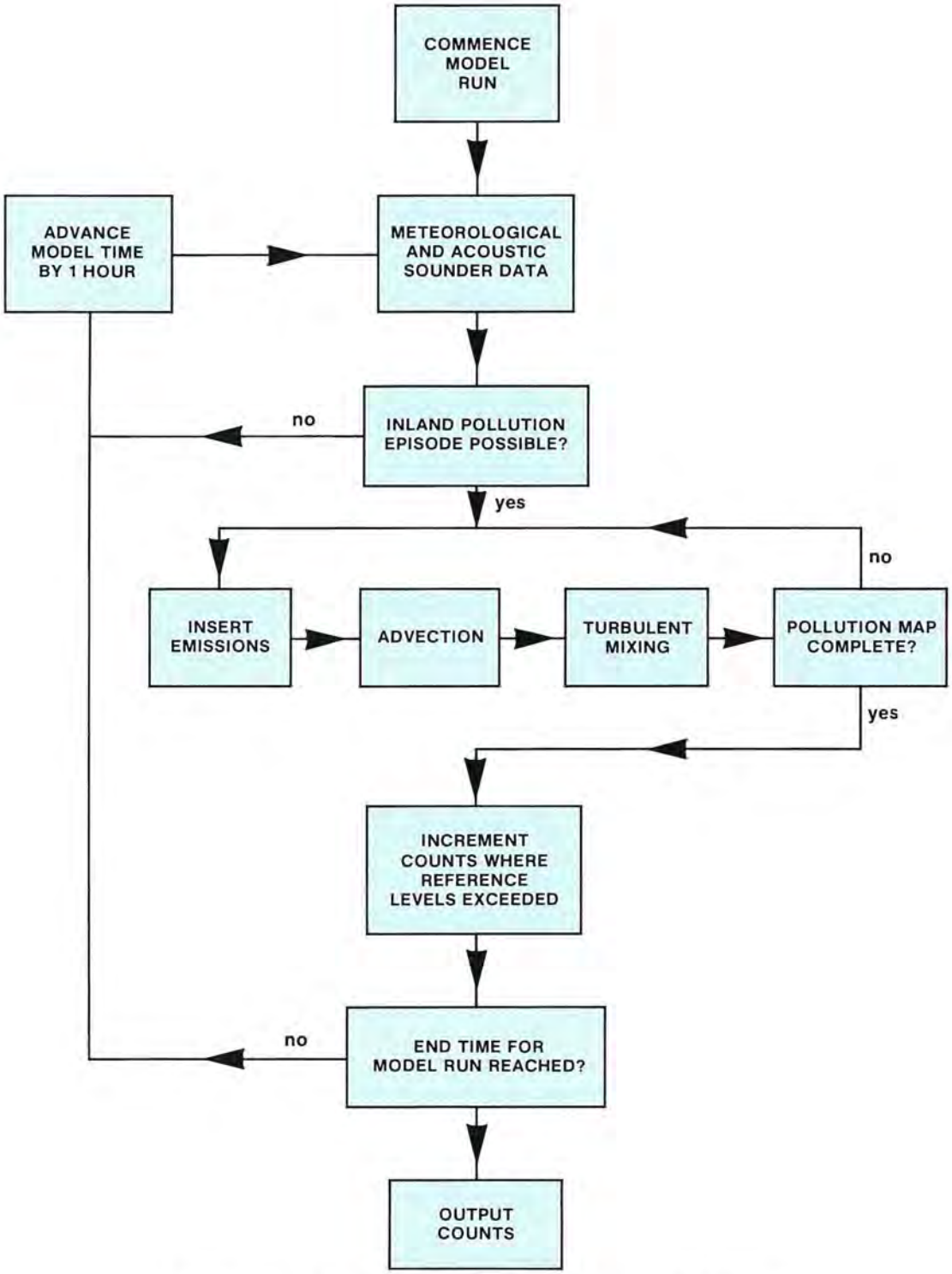


Figure 7.3. Flow diagram showing the major components of Model 2.

depth based on acoustic sounder measurements when these are available. If a stack is located wholly within the planetary boundary layer, the neutral-conditions formula (Equation (6.4)) is used. Otherwise, the stable-conditions expression is used (Equation (6.2)). In either case, plume rise is limited by the measured maximum mixing depth.

With the transition from neutral to stable conditions above the TIBL, there remains a possibility that the modelled level of a plume emerging from a stack just within the planetary boundary layer might be higher than that for a similar stack with its top just above that layer. However, with smaller stacks being associated, in general, with lower plume rise, and in view of the relatively coarse vertical resolution of the model, this problem is not of major concern.

The finite difference model is suited to the explicit treatment of processes such as deposition and chemical transformation of pollutants. It has been estimated that, because of the small travel times involved, such processes would decrease concentrations of sulphur dioxide by a maximum of 5 to 10% at the extremity of the model grid. As a consequence, these minor processes are not included in the model for the study.

(iii) Limitations

Pollutant transport is modelled entirely by advection and turbulent exchange, separately at each grid element, and therefore no information on the distance of pollutants from their sources, or of their distribution within each grid element, is used. This gives rise to two limitations.

Firstly, the ascent of a plume due to its buoyancy can not be represented in detail, and therefore plumes are modelled as rising instantaneously to their final levels. In practice, this problem is of minor concern, since for the stable inflows which are the basic cause of most high ground-level pollutant concentrations, reliable plume-rise parameterisations only specify the final level of plumes (Section 6.1.2). Also, the final plume level is generally achieved within a kilometre or two of its source, a distance well short of areas of proposed or existing residential development.

The second limitation arises from the necessary use of K-theory (Section 6.4.1(ii)) to represent the effects of turbulence. As a result, at each step in model time, the squares of both the vertical and horizontal plume widths increase by a constant amount. This means that the near-source form of a plume, where the widths themselves increase uniformly, is inaccurately represented. However, at distances where the plume has been in existence for longer than the Lagrangian timescale of the turbulence (Section 6.4.1), the applicability of the concentration gradient approach improves. The most commonly used theoretical relation has suggested that at a distance of 4 km from the source, the error in the horizontal plume width is about 10%, with less than 5% error at 10 km. Similarly, the error in vertical plume width is probably less than 10% at a typical distance of 2 km, although this estimate is subject to some uncertainties in the Lagrangian timescale for vertical turbulence (Rye, 1982).

7.2 MODEL VALIDATION

An important part of the development of a mathematical dispersion model is a comparison, over a wide range of conditions, of estimated results with those measured in the field. For the Kwinana study, this validation process was undertaken for the controlled release of tracer gases during the sea breeze and for the routine release of sulphur dioxide by all major industries.

Mathematical models were run for short periods coinciding with the release of inert tracer gases during the sea breeze seasons in 1978 and 1980. Average sulphur dioxide estimates for timescales ranging from 10 minutes to a full year were also compared to values measured during the study period. A description of the model validation process is given in the following sections.

7.2.1 Tracer Studies

The two major intensive field studies, conducted on 2 March 1978 and 21 January 1980, provided opportunities to investigate the limitations of the dispersion models developed for KAMS, and to clarify the relevance of various factors in determining pollutant concentrations north-east of Kwinana (Chapter 5). The first study was conducted on a day when a good example of an autumn sea breeze occurred and the January date for the second was selected in order to give data on the stronger sea breezes which dominate the summer season.

Both models were able to use data from the meteorological base stations, and Model 2 was also operated using the wind, mixing depth and atmospheric stability estimates generated by the numerical sea breeze model (Section 6.3.3). It therefore was possible to review relationships, not only between measured and modelled tracer concentrations, but between the models themselves. In this manner, the relevance of the assumptions used in the models could be tested.

The sea breeze during the 1978 exercise was of the so-called 'non-cooling' type and was characterised by a lighter and more westerly surface wind than experienced during most of the summer. Radiosonde measurements indicated a weak inversion, and modelling of this sea breeze supported the implication of a mixing depth and associated inflow which grew rapidly inland from the coast. The measured concentrations of tracer gases showed an unusually rapid decrease downwind from their ground level maximum, and neither Model 1 nor Model 2 in its standard form (Rye, 1982, Figure 8(a)) could represent such a phenomenon adequately.

Deardorff and Willis (1978) found, in hydrodynamic modelling of pollutant dispersion during strongly unstable conditions, that vertical transport may be dominated by the effects of convection currents. The effects include a rapid decrease of concentration downwind of the ground level peak, as convection lifts pollutants higher into the atmosphere. A modification of the dispersion scheme used in Model 2 approximated this process and showed an improvement in the qualitative form of the computed concentrations (Rye, 1982, Figure 8(b)). However, the estimated peak ground level concentration was still significantly higher than that measured, leading to the conclusion that the complexities of the mixing depth growth, vertical motion and turbulent dispersion could not be readily represented by any model.

It is fortunate that the conditions found during the 1978 study were characterised by high dispersion and consequently low ground level concentrations in areas of concern at Kwinana. Because of this, the accuracy of long-term estimates produced by the models was not significantly affected by their failure to represent dispersion in these conditions accurately.

The second tracer study was conducted during a more typical sea breeze, with a strong inversion present which was thought to have persisted well inland. As a result, the ability of the models to represent conditions which dominate the summer climate of the region could be tested. In particular, the greater stability of the cool inflow air meant that the growth of the thermal internal boundary layer was slow, a process the models needed to take into account.

The significance of the slow growth of the internal boundary layer on ground level concentrations at Kwinana had been demonstrated following the 1980 study (Department of Conservation and Environment, 1980b). The mechanism was subsequently included in the models and, as shown in Figures 7.4 and 7.5, both models were able to represent the consequences of the TIBL satisfactorily for the second study day. In particular, the magnitude and location of the peak concentration were estimated fairly accurately. The different averaging times for the two models (30 minutes for Model 1 and 10 minutes for Model 2) were made necessary by the model mechanics but in no way does this affect the tracer validation exercise for either model.

Comparison of the calculations of both models shows one significant discrepancy which was not resolved properly by measurements. While Model 1 indicated high concentrations of tracers at Wattleup, Model 2 did not, and at a cursory inspection the measurements seemed to support Model 1. However, the data on which this conclusion rested were from a single point, with no significant concentrations at adjacent sampling sites. The tracer exercise conducted as part of the Coogee Air Pollution Study had shown a similar, isolated high value and airflow measurements suggested that the cause might have been a turbulent eddy in the location of Mount Brown (Environmental Protection Authority, 1974).

In addition, since the high wind speeds during the experiment would have introduced a significant amount of shear-generated turbulence into the TIBL, Model 1 would have possibly overestimated the rate of plume mixing into the TIBL and hence, concentrations around Wattleup. This supports the view that the very high concentration measured at Wattleup was anomalous.

7.2.2 Sulphur Dioxide Concentrations

Fundamental to the development of confidence in the models was a comparison of the calculated sulphur dioxide concentrations with available measurements. These comparisons were made for a variety of timescales ranging from 10 minutes to a year.

Short-term pollution episodes were studied by comparing measured and modelled 10-minute averages. Figure 7.6 shows a comparison for an episode at Wattleup using concentrations calculated by Model 2. Several comparisons carried out over a range of conditions revealed that major discrepancies did not occur systematically and consequently it was expected that errors over longer averaging periods would also be relatively small.

Figure 7.7 shows the relationship of measured daily average sulphur dioxide at Wattleup to values calculated using Model 1, for the year July 1979 to June 1980. A model which represented measured values precisely would produce a horizontal line in the figure, giving a constant, unit ratio of calculated to measured results. The actual line obtained followed the ideal to an error of less than 20% in about 50% of cases, the other 50% being equally distributed between overestimates and underestimates. The considerable extent of agreement was unusual in comparison to reports of overseas experience, and indicated that an adequate representation of dispersion parameters had been achieved.

Application of both models to the region surrounding Kwinana was therefore expected to show fair accuracy, and studies were made of the estimated distributions of short-term, relatively high level concentrations as well as of annual average concentrations.

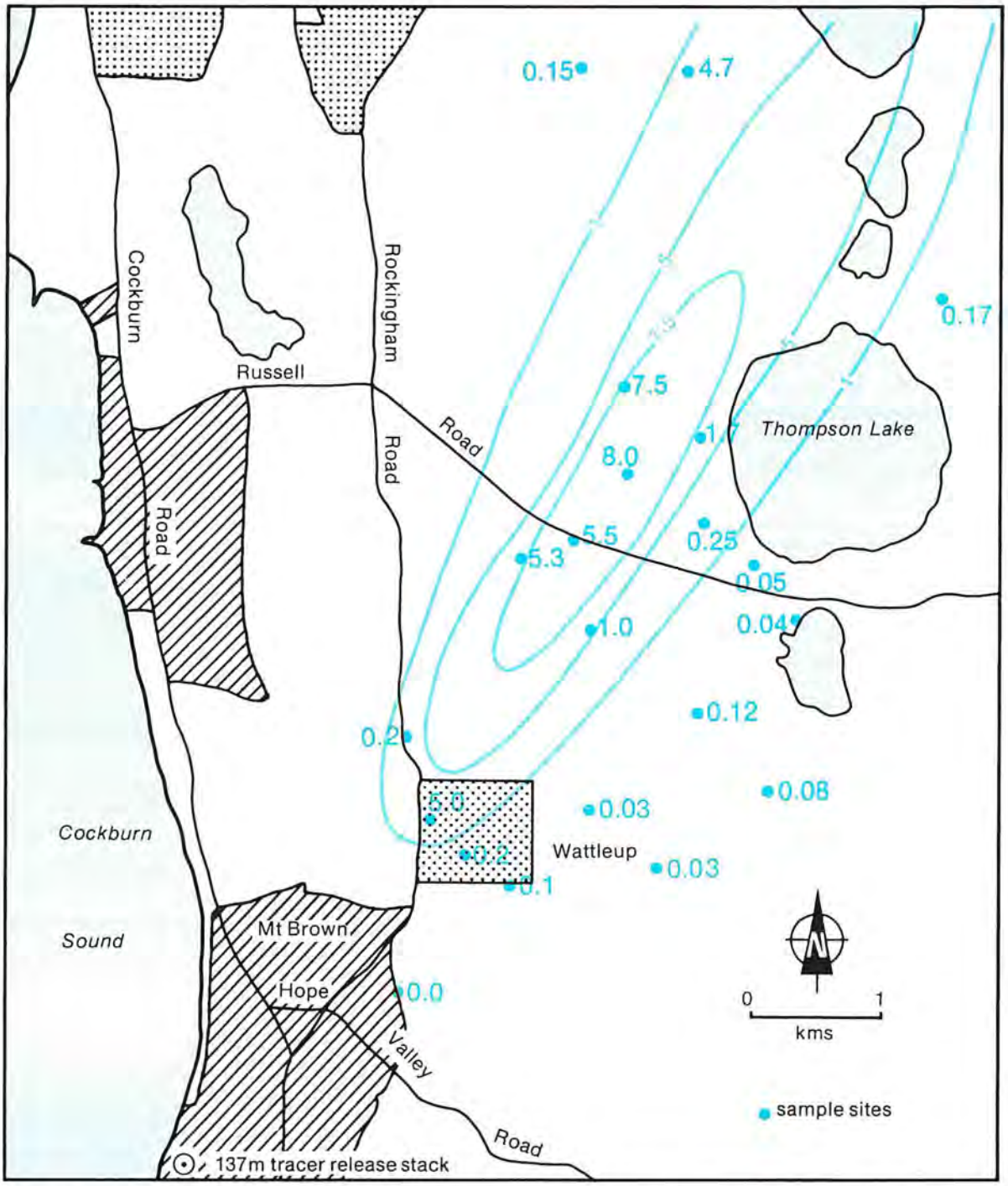


Figure 7.4. The 31 January 1980 tracer study showing estimated 30-minute average SF_6 contours (Model 1) and the measured values (•). All concentrations are in $\mu g/m^3$.

As a consequence of the slightly different bias in the original designs, the approach used in the two models differed. Model 1 estimated average concentrations at a standard 0° C over each of 24 whole hours in a day, and these were compared to a selected range of concentrations (500, 1000, 1400 and 2000 $\mu g/m^3$) to find the frequency with which each level was exceeded. Daily and longer-term averages were obtained from the hourly average.

Model 2 was applied in a statistical manner, calculating 10-minute average concentrations on the hour, for periods with a high pollution potential (as determined from meteorological considerations). Climatological wind direction statistics were then used to convert the 10-minute to hourly averages. The frequency (on an annual basis) with which each of 500, 700, 1000 and 1400 $\mu g/m^3$ was exceeded was the sole direct output. To determine how these high level events contributed to the annual average, the concentration weighted sum of the four frequencies was calculated, to give a 'high level event only' average.

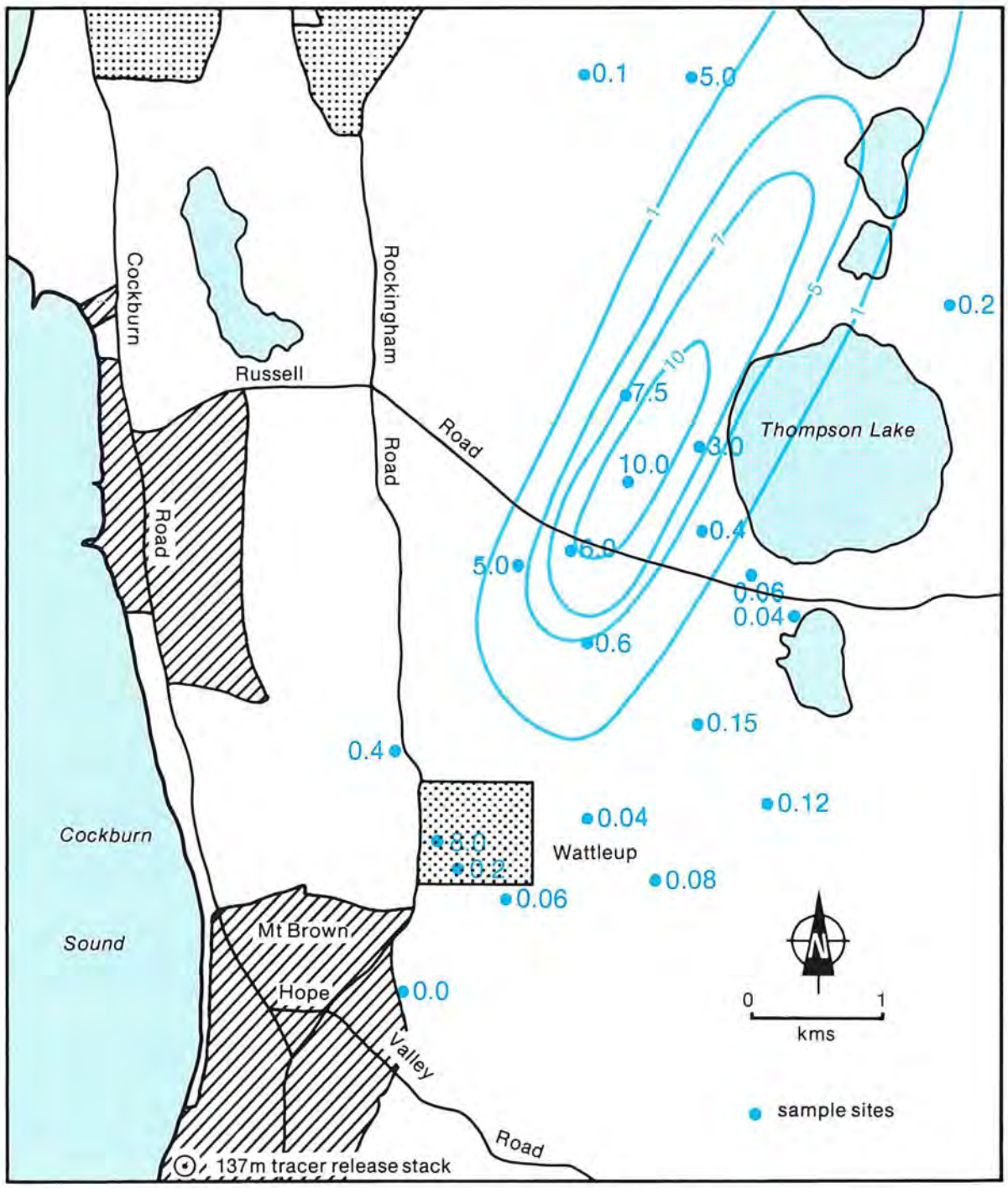


Figure 7.5. The 31 January 1980 tracer study showing estimated 10-minute average SF_6 contours (Model 2) and measured values (•). All concentrations are in $\mu g/m^3$.

For each approach it was possible to extract from the Wattleup base station records a set of statistics corresponding to the variables estimated by the models. Table 7.1 summarises these statistics and also the annual averages estimated. Both models can be seen to behave creditably, with the only significant differences between modelled and measured values occurring at 1000 $\mu g/m^3$ for Model 1 and 500 $\mu g/m^3$ for Model 2. As noted by Rye (1982), the physical significance of these errors is likely to be small, the former error, in fact, corresponding to a mean error in concentration of only 20% and the latter to 11%.

The discrepancy between the two sets of results (Model 1 and Model 2) evident in Table 7.1 was largely due to the two factors previously indicated. The principal difference arose from the use in Model 1 of 24 fixed hourly intervals for which concentrations were calculated each day. On the other hand, Model 2 enabled any (non-clock) 1-hour concentration in excess of a particular concentration level to be included in the results. In addition, Model 1 calculations were made for 0° C equivalent air temperature, not ambient temperature, as was the case for Model 2.

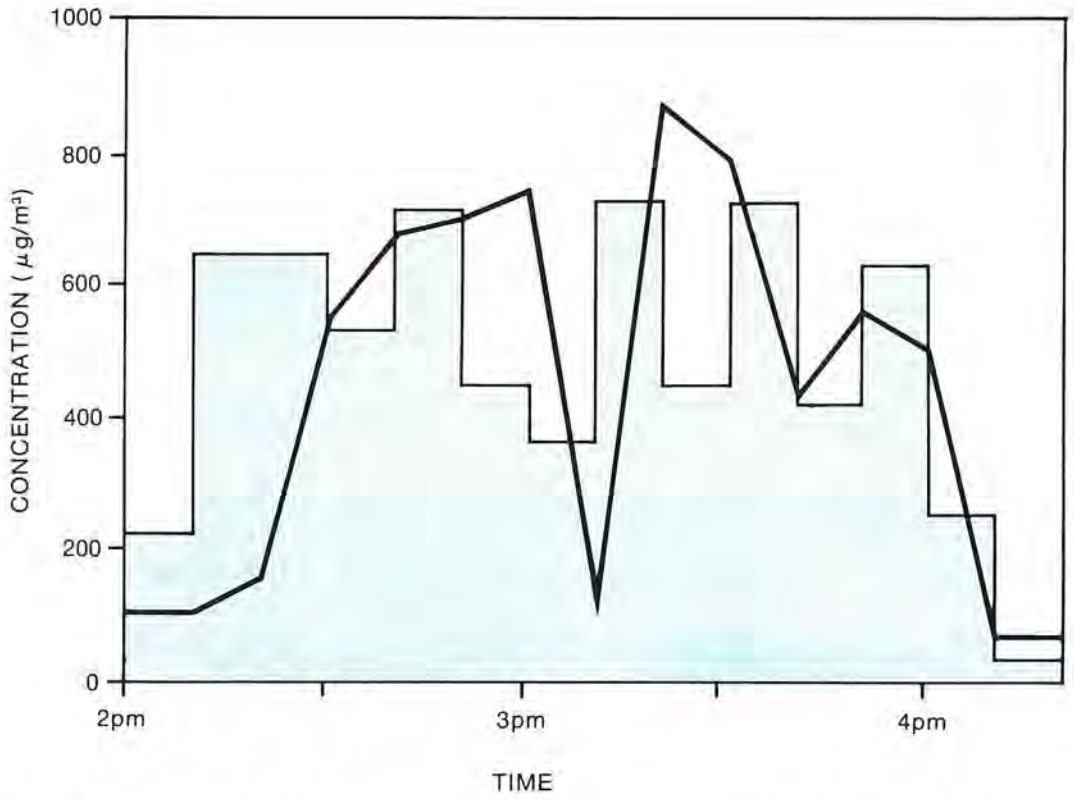


Figure 7.6. Variation with time of sulphur dioxide concentration measured at Wattleup (shaded) compared to that estimated using Model 2 (heavy line). The simulation was for a sea breeze episode on 3 January 1980.

The former difference was important when concentrations exceeded the reference level for only a short period of time. For example, if the actual hourly-averaged sulphur dioxide concentration exceeded one of the selected levels for 30 minutes during a single day, Model 1, operating accurately, would only have recorded the occurrence if one of its hourly calculation periods commenced within that 30-minute span. Thus, there would be only a 50% chance that the event would be detected. Model 2, in contrast, would have registered the fact that the particular level had been exceeded.

For periods of a few hours in excess of any selected level, this difference between the model mechanics was expected to be of minor concern. For the higher levels however, the periods for which the level was exceeded would generally have been much shorter, and in such cases, considerable differences could occur between estimates produced by the two models.

The lower frequency of events, detected by Model 1, as a result of the use of fixed hourly intervals, is somewhat masked in Table 7.1 by the standard 0° C temperature used for the model. Since density is increased with a reduction in air temperature (ambient to 0° C), sulphur dioxide concentrations expressed in $\mu g/m^3$ will also increase. Consequently, Model 1 results are higher than they would be if expressed at ambient temperature. In particular, the measured number of hours over 1400 $\mu g/m^3$ is shown to be greater for Model 1 at 0° C than for Model 2, despite the fact that 'fixed hours' are used in the former.

The small difference between the two annual average estimates supported the observation that most air pollution episodes at Wattleup were due to short periods of relatively high concentration. It is again notable that the agreement between estimates and measurement is better than that generally expected of air pollution models.

Comparisons with other available validation data were necessarily less detailed, due to the 24-hour recording periods of the sequential sulphur dioxide samplers operated by the Department of Public Health. Table 7.2 indicates the variation of annual average concentration estimated by Model 1 (Model 2 estimates being of similar form, but of fractionally lower concentration). It is significant that, while there is reasonable agreement at some locations, others show large discrepancies. Subsequent analysis has indicated that this is likely to be due to both the inherent variability of the measurement method at daily average concentrations below 200 $\mu g/m^3$ (USEPA, 1977) and the tendency of the equipment to underestimate concentrations during hot summer periods (Rosher and Martin, 1982). Though the sequential samplers have a useful role in defining the extent of air pollution impact areas, they are not suitable for determining the magnitude of this impact which is necessary in the validation of mathematical models.

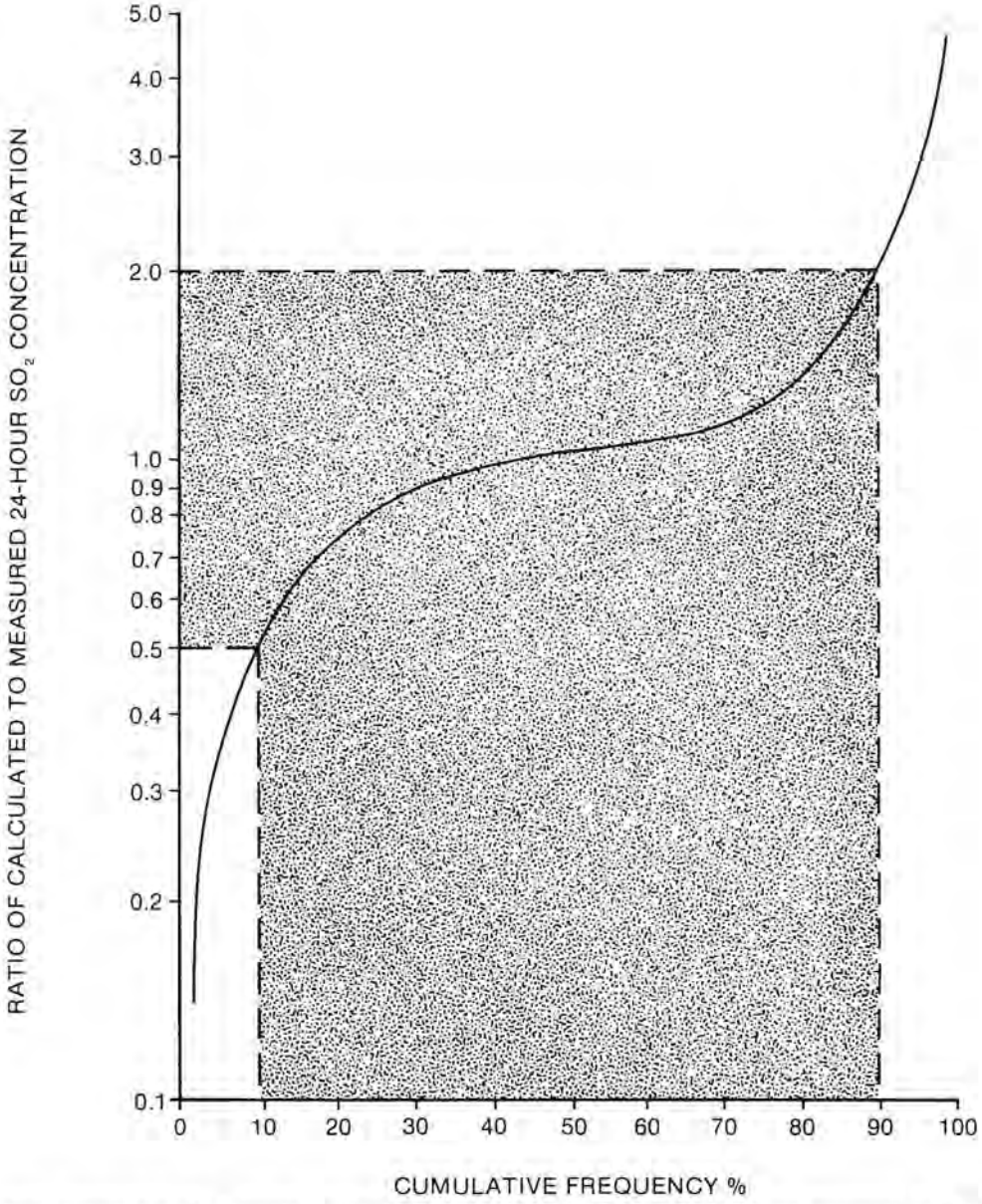


Figure 7.7. The comparison of measured 24-hour average sulphur dioxide concentrations measured at Wattleup and those calculated using Model 1 for the year July 1979 to June 1980. The shaded area indicates the proportion of the calculated values which are within a factor of 2 of the measured concentrations.

Both models were able to represent month-to-month variations of hours over each concentration level. Table 7.3 summarises these calculations for the Wattleup location, and the measured number of hours over the same levels. Although there was a tendency to overestimate slightly the winter concentrations, and underestimate those in summer, the overall trends were in fair agreement.

7.3 APPLICABILITY OF MODELS

The validation exercises confirmed that both models were capable of accurately representing the dispersion of pollutants from the Kwinana industrial area. However, as a result of their design and implementation, the models possessed strengths in different applications.

Model 1 was very much less expensive to run than Model 2 and hence could be run using the year's continuous data to give annual, daily and hour-by-hour summaries. Comparisons with annual and daily-average standards were therefore made using Model 1. In addition, despite the 'fixed-hours' limitation, it was possible to compare model estimates with the Victorian EPA hourly-average, 'acceptable' objective.

Since higher concentrations tended to persist for short periods which were detected by the 'arbitrary hours' analysis of Model 2, and because of this model's better validation at high concentrations, the estimates produced by Model 2 were used in the interpretation of frequencies of concentrations over 1000 $\mu g/m^3$. The statistical analysis used to produce hourly estimates was also extended to 3-hour periods, giving results which could be compared with the United States EPA 3-hour secondary standard.

Table 7.1. Comparison of measured and modelled sulphur dioxide statistics for the Wattleup base station site for the period July 1979 to June 1980. Reference levels were chosen to approximate Victorian EPA 1-hour objectives and WHO 24-hour guidelines.

	MODEL 1*		MODEL 2†	
	Measured	Modelled	Measured	Modelled
Annual average concentration ($\mu g/m^3$)	44	43	40	35**
Frequency of 24-hour average concentrations exceeding:				
100 $\mu g/m^3$	49	51		
150 $\mu g/m^3$	19	18		
Frequency of 1-hour average concentrations exceeding:				
500 $\mu g/m^3$	183	169	208	161
1000 $\mu g/m^3$	14	4	18	23
1400 $\mu g/m^3$	4	1	2	2
Frequency of daily maximum 1-hour average concentrations exceeding:				
500 $\mu g/m^3$	82	87		

* Calculated for 24 fixed 1-hour periods per day at 0°C

† Calculated for 'non-clock' hours at ambient temperature

** Inferred from 'over 500 $\mu g/m^3$' statistics.

Table 7.2. Comparison of measured and modelled annual average sulphur dioxide concentrations the sequential sampler sites for the period July 1979 to June 1980. The modelled estimates were derived using Model 1 and all concentrations have been calculated for 0°C reference temperature.

SITE	ANNUAL AVERAGE CONCENTRATION ($\mu g/m^3$)	
	Measured	Modelled
Banganup	17	23
Hillman	16	5
Medina	2	13
Orelia	9	14
Rockingham	8	5
Kwinana	4	10
Naval Base	10	40
Wattleup	22	35
Mandogalup	2	20

Table 7.3. Comparison of the monthly variation of measured and modelled sulphur dioxide concentration statistics for the Wattleup base station site during the period July 1979 to June 1980.

MONTH	FREQUENCY OF 1-HOUR AVERAGE CONCENTRATIONS EXCEEDING 500 $\mu g/m^3$				FREQUENCY OF 1-HOUR AVERAGE CONCENTRATIONS EXCEEDING 1000 $\mu g/m^3$			
	Model 1*		Model 2†		Model 1*		Model 2†	
	Measured	Modelled	Measured	Modelled	Measured	Modelled	Measured	Modelled
July	1	2	1	0	0	0	0	0
August	1	2	1	7	0	0	0	0
September	9	9	1	5	3	1	3	0
October	2	15	6	11	0	0	0	1
November	22	13	24	17	1	0	0	1
December	33	31	36	30	0	0	1	3
January	30	38	37	32	3	1	7	6
February	41	24	45	23	4	2	3	5
March	32	17	36	14	2	0	3	2
April	10	11	10	10	1	0	1	1
May	2	5	2	6	0	0	0	1
June	0	4	0	4	0	0	0	1

* Calculated for 24 fixed 1-hour periods per day at 0°C

† Calculated for 'non-clock' hours at ambient temperature

Chapter 8

THE STUDY RESULTS

Air pollutant concentrations, whether derived from field measurements or mathematical dispersion models, can only be of value to land use planning agencies of they are related to appropriate air quality standards (Section 2.5). The following sections cover the standards chosen as references for the study, the reasons for their choice, and present measured and modelled sulphur dioxide results.

8.1 AMBIENT AIR QUALITY STANDARDS FOR SULPHUR DIOXIDE

8.1.1 Time Periods for Standards

Annual and daily averages in the definition of air pollution standards were used traditionally because of the difficulty of measuring low quantities of pollutants accurately. The apparent connection between annual average concentration and related clinical conditions also made the specification of health limits less difficult than it might otherwise have been. With recent improvements in the technology of measurement (both of small quantities of pollutant and of human performance under stress) the detection of shorter episodes and their consequent health effects has become feasible. Thus, recent trends in air quality management have been towards the specification of a range of limits appropriate to various averaging times.

The smallest averaging time specified is usually 3 minutes, used in Australia by the New South Wales State Pollution Control Commission for some design purposes. However, most authorities normally work with a longer averaging period in the modelling of air pollutants to reduce the effects of random atmospheric fluctuations. Thus, with a 10-minute data sampling interval, an hourly period includes six data samples whose average is unlikely to differ greatly from the statistical mean of the distribution from which the six samples were obtained. Air pollution models approved by the USEPA, for example, are designed to use hourly data so that a 3-hour average is the practical minimum period for which pollution limits can be set by authorities in the United States.

Much effort has been expended in determining the relationship between expected maximum pollutant concentration and averaging period, since knowledge of such a relationship would clearly make the task of air pollution control agencies much easier. Based on the analysis of data from a large number of North American cities, Larsen (1971) has developed a method to estimate short-term maximal pollutant concentrations from the known annual mean concentration and concentration distribution statistics. This work is based on the assumption that pollutant concentrations are lognormally distributed , i.e. plots as a straight line on logarithmic graph paper, and that the maximum concentration is inversely proportional to the averaging time raised to an exponent.

Larsen has pointed out that most aerometric data are closely lognormal near the centres of large cities but may depart markedly from lognormality near strong isolated pollutant sources. Application of the Larsen model in such circumstances may lead to grossly inaccurate predictions.

Figure 8.1 shows that the distribution of sulphur dioxide concentration at Wattleup is not lognormal. In addition, maximum concentration for various averaging times does not plot as a straight line on logarithmic graph paper (Figure 8.2). Consequently, the use of a Larsen-type model on these data may result in the prediction of short-term concentrations that are significantly lower than those experienced. Such predictions should therefore not be used to determine compliance with any chosen short-term standards. In particular, it cannot be assumed that compliance with annual and 24-hour standards would necessarily preclude violation of 3-hour and 1-hour standards.

The difference between the Kwinana data and that typically found in big cities is further illustrated by Table 8.1 and Figure 8.3. The ratio of maximum 1-hour average concentration to maximum 24-hour average concentration indicates that sulphur dioxide concentration is far more uniform in the American cities than at Wattleup, where exposure is likely to be limited to less than 5 hours per day during the summer (Figures 8.4 and 8.5). The steadiness of the sea breeze during the time of exposure is a major cause of the high short-term concentrations found at Wattleup and consequently, the high ratio in Table 8.1. In addition, Figure 8.3 shows that about 95% of daily maximum 1-hour average concentrations exceeded the corresponding 24-hour average concentration by a factor of 5 or greater.

Broad consideration of the air pollution impact in the study area must take into account the short-term

episodes which make such a large contribution to the annual average sulphur dioxide concentration experienced. Since it is not possible to determine short-term concentration peaks from long-term data, they must be measured directly for comparison to be made with appropriate standards.

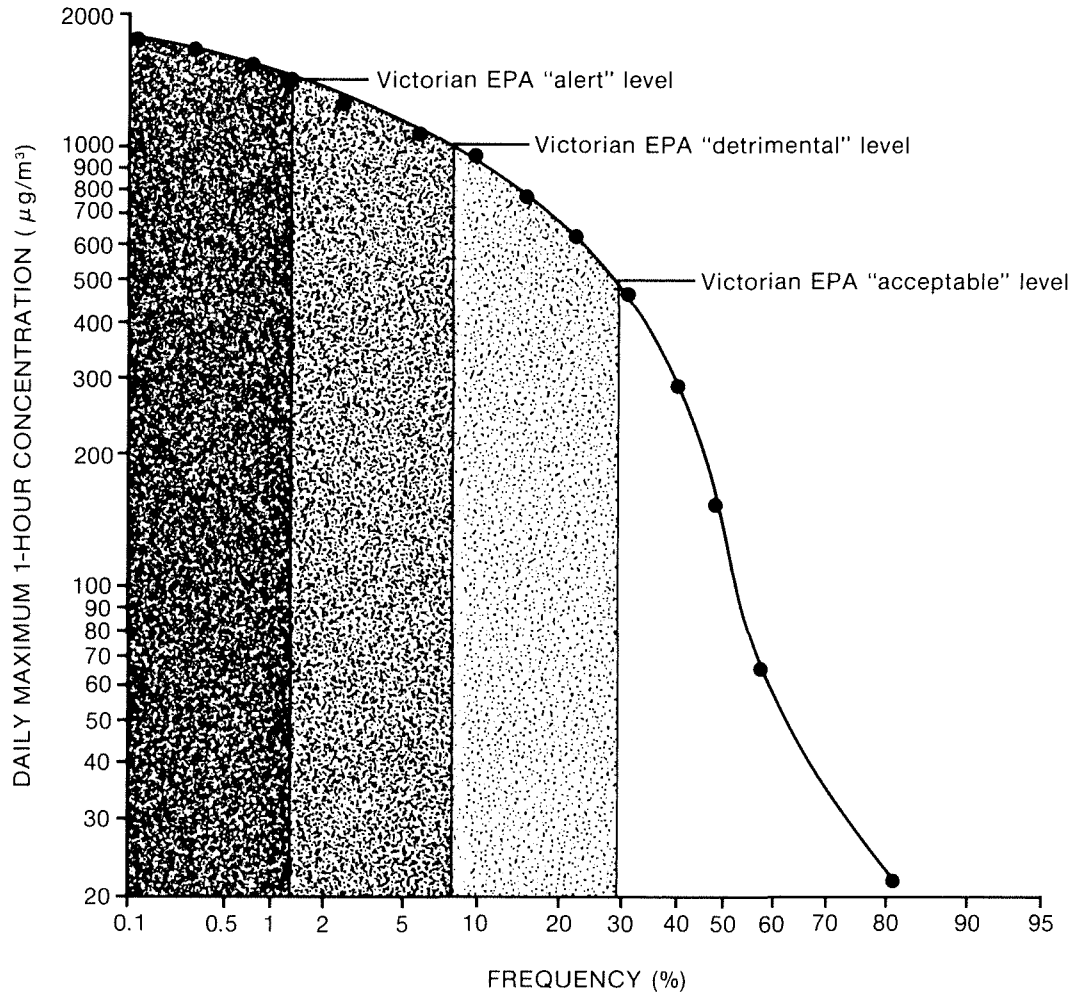


Figure 8.1. The frequency with which the daily maximum 1-hour average sulphur dioxide concentration measured at Wattleup exceeded various values for the period July 1979 to June 1980.

8.1.2 Sulphur Dioxide Standards Chosen for the Study

In order to evaluate air pollution at Kwinana, suitable sulphur dioxide standards (objectives) covering a range of averaging periods were required for reference. Criteria were subsequently chosen for annual, 24-hour and short-term (3-hour and 1-hour) averaging periods.

The 1979 World Health Organisation guidelines of 40-60 $\mu g/m^3$ for a 24-hour average were considered appropriate (Table 2.1). These guidelines allow potential long- and medium-term sulphur dioxide problems at Kwinana to be identified. They are more stringent than the earlier 1972 levels upon which the NHMRC recommendations are based (Section 2.5).

The USEPA 3-hour secondary standard (Table 2.1) is the most strictly defined of all short-term limits for sulphur dioxide concentrations. When pollution impact is estimated using models approved by that authority, and with hourly US National Weather Service data, the 3-hour average must be shown never to exceed 1300 $\mu g/m^3$. The 3-hour standard was therefore considered a useful reference with which to evaluate the short-term impact of air pollution at Kwinana.

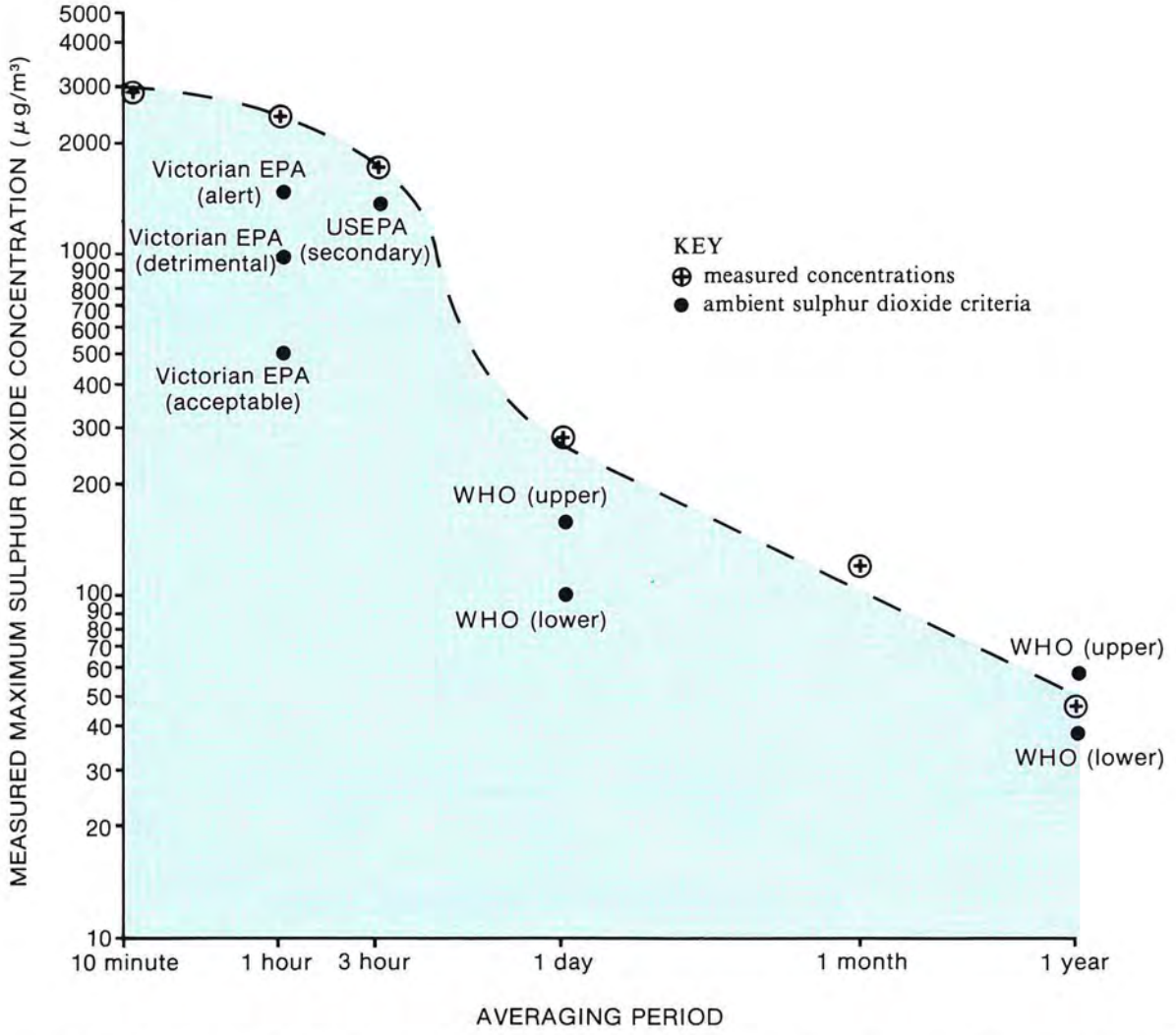


Figure 8.2. The maximum sulphur dioxide concentration for various averaging times measured at Wattleup for the period June 1978 to January 1981.

Table 8.1. The average ratio of maximum 1-hour average to maximum 24-hour average sulphur dioxide concentrations measured at a number of different locations.

LOCATION	AVERAGE RATIO OF MAXIMUM 1-HOUR/MAXIMUM 24-HOUR CONCENTRATIONS
Chicago*	2.1
Cincinnati*	3.1
Los Angeles*	2.9
Philadelphia*	2.2
Washington	2.4
Wattleup+	6.3

* Recorded over the period 1962-1968 (Table 10, Larsen, 1971)

\+ Recorded from June 1978 to February 1981

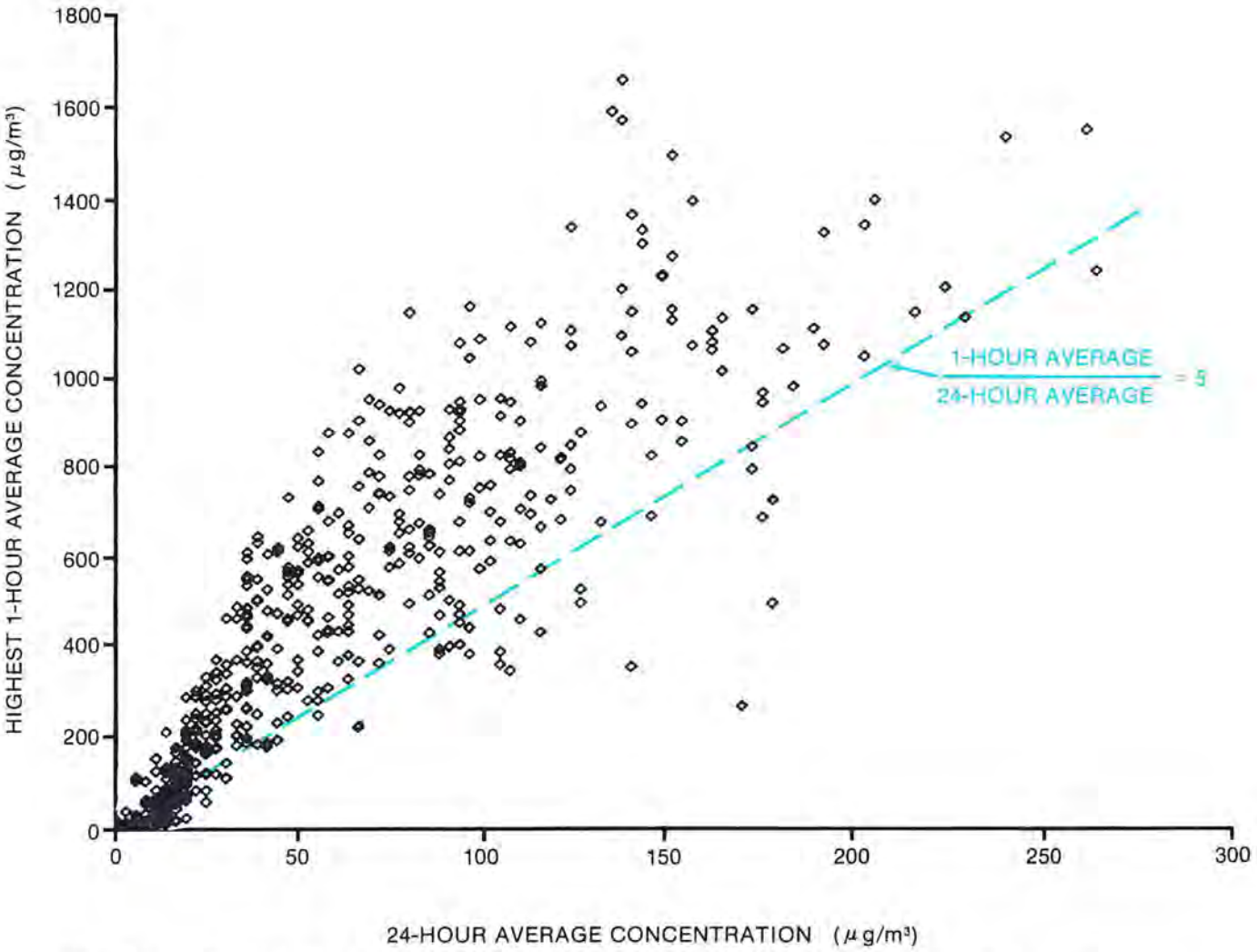


Figure 8.3. The highest 1-hour average sulphur dioxide concentration plotted against the 24-hour average concentration for each day at Wattleup for the period June 1978 to January 1981.

The Victorian EPA 1-hour average sulphur dioxide objectives, being the only Australian figures available, were adopted for use in the study. The 'acceptable' level of about 500 $\mu g/m^3$ (0.17 ppm) is not to be exceeded on more than 3 days per year while the 'detrimental' level of about 1000 $\mu g/m^3$ (0.34 ppm), above which adverse effects are known to occur, is never to be exceeded. The third level specified, the 'alert' level of about 1400 $\mu g/m^3$ (0.5 ppm), is defined as that "... above which most members of the exposed population are likely to be adversely affected" (Victorian Government Gazette, Vol. 63, 1981).

Table 8.2 summarises the annual, 24-hour, 3-hour and 1-hour standards chosen for comparison purposes in the study.

8.3 MEASURED SULPHUR DIOXIDE CONCENTRATIONS

Sulphur dioxide concentrations were measured continuously at two base stations and over a 24-hour averaging period at nine other sites for the duration of the study at Kwinana (Chapter 4). The most important information available from the measured data, that from the Wattleup base station, is summarised below.

Table 8.3 gives the monthly variation of sulphur dioxide concentration at Wattleup, with respect to:

- the monthly mean ($\mu g/m^3$)
- the number of 24-hour periods with an average concentration exceeding 100 $\mu g/m^3$
- the number of 24-hour periods with an average concentration exceeding 150 $\mu g/m^3$
- the number of 3-hour average concentrations exceeding 1300 $\mu g/m^3$
- the number of 1-hour average concentrations exceeding 500 $\mu g/m^3$
- the number of days where the maximum 1-hour average concentration exceeded 500 $\mu g/m^3$
- the number of 1-hour average concentrations exceeding 1000 $\mu g/m^3$
- the number of 1-hour average concentrations exceeding 1400 $\mu g/m^3$.

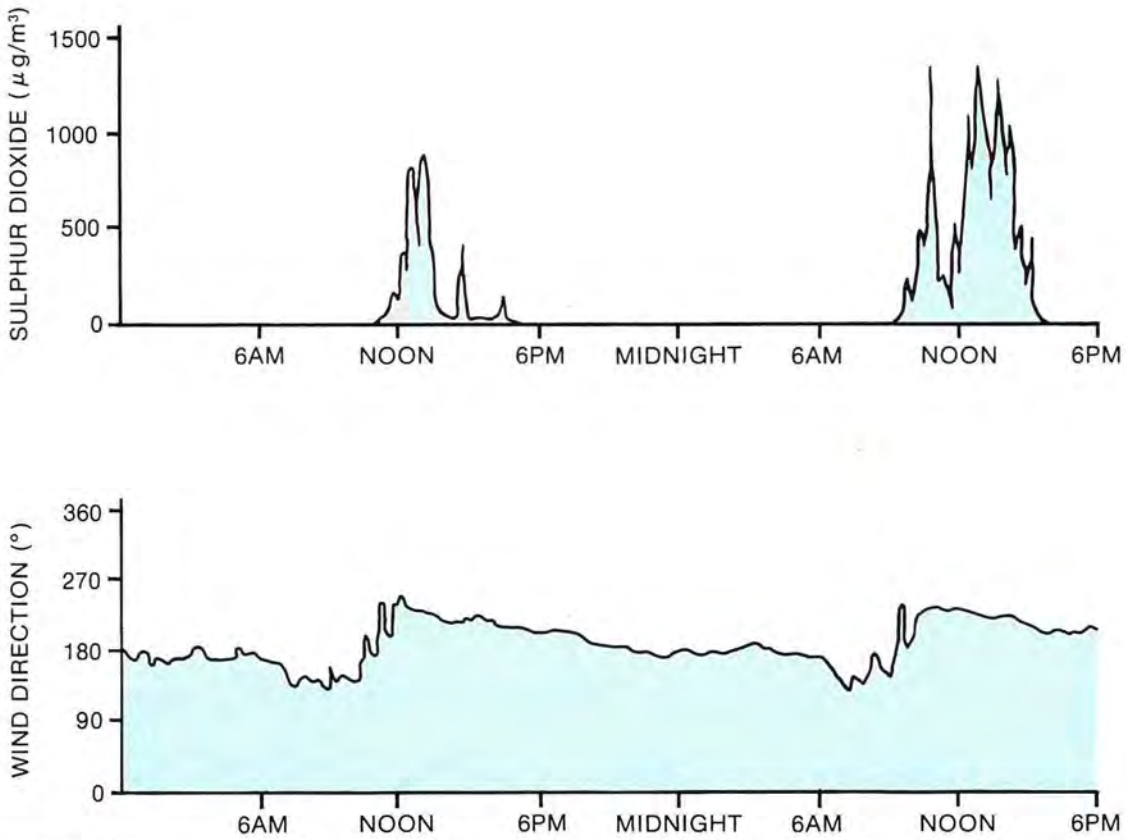


Figure 8.4. The variation of sulphur dioxide concentration measured at Wattleup during the sea breeze/land breeze cycle on 11-12 December 1980.

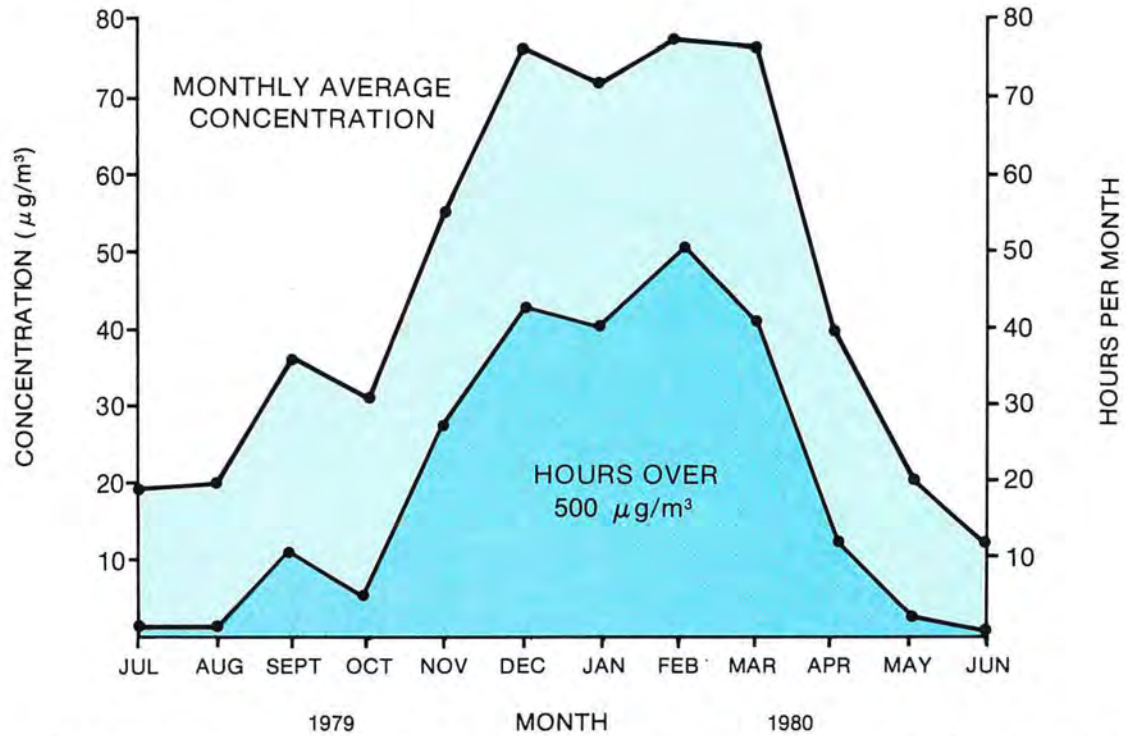


Figure 8.5. The monthly variation of sulphur dioxide concentrations measured at Wattleup for the period July 1979 to June 1980. The bottom graph shows the number of hours for each month where 1-hour average concentrations exceeded 500 $\mu g/m^3$.

A summary of the Wattleup data for 1979 and 1980 is given in Table 8.4. The annual average concentration of sulphur dioxide at Wattleup is, for both years, below the upper limit but within the range given in the WHO guidelines.

Table 8.2. The principal ambient sulphur dioxide criteria used as references in the Kwinana Air Modelling Study.

AVERAGING PERIOD	SOURCE	AMBIENT CONCENTRATION ($\mu g/m^3$)
1-year	World Health Organisation	40-60
24-hour	World Health Organisation	100-150
3-hour	USEPA Secondary Standard	1300
1-hour	Victoria EPA 'acceptable'	500
	Victorian EPA 'detrimental'	1000
	Victorian EPA 'alert'	1400

The number of 24-hour average concentrations in excess of a range of levels is also given. Neither the USEPA primary standard (365 $\mu g/m^3$) nor the Victorian EPA 'detrimental' level (310 $\mu g/m^3$) was exceeded at Wattleup during the two years. However, the superseded WHO guideline (Section 2.5), the Victorian EPA 'acceptable' level (Table 2.1) and the upper and lower limits of the current WHO guideline were exceeded regularly.

Short-term concentrations exceeded the USEPA 3-hour secondary standard on three occasions in 1979 and not at all in 1980. The Victorian EPA 'alert' level was reached nine times in 1979 and twice in 1980.

Both Victorian EPA 'acceptable' and 'detrimental' 1-hour average levels were significantly exceeded at Wattleup in 1979 and 1980. The 'acceptable' level was exceeded, in total, for approximately 25% of the days in each year.

The frequency distribution for daily maximum 1-hour averages of sulphur dioxide at Wattleup is given in Figure 8.1.

8.3 MODELLING RESULTS

The models used to estimate pollutant dispersion at Kwinana were validated against all available data and were shown to have an adequate accuracy to satisfy the objectives of the study. The Gaussian model (Model 1) was used to determine longer-term averages (annual and 24-hours) and the occurrence of moderately high (500 $\mu g/m^3$) short-term episodes. The finite difference model (Model 2) was better able to represent higher concentration (over 1000 $\mu g/m^3$) short-term episodes and was also used to investigate changes in pollutant emissions and the effect of new sources.

8.3.1 Long-Term Effects

The estimated annual average sulphur dioxide concentration for July 1979 to June 1980 (Figure 8.6) indicated that the area of greatest air pollution impact at Kwinana was in the vicinity of Wattleup and to the north and north-east of the study area. Another lobe of relatively high long-term average concentration occurred near the BP refinery site. In both cases, annual average concentrations were generally below the WHO guidelines of 40-60 $\mu g/m^3$.

The extreme seasonal variation of sulphur dioxide concentrations, in the northern part of the study area in particular, is illustrated by Figure 8.7 (a), (b). During the summer (January 1980), the monthly average concentration was at least 50 $\mu g/m^3$ in the major impact area, while in winter (July 1979) levels were less than 10% of this figure. This clearly demonstrated (as in Section 8.1) that the annual air pollution problem at Kwinana was dominated by the summer contribution.

8.3.2 Daily Average Concentrations

Figure 8.8 (a), (b) shows that the WHO 24-hour average upper and lower limits (150 $\mu g/m^3$ and 100 $\mu g/m^3$ respectively) were exceeded over a significant part of the study area. As with the annual average concentration, the main impact area was around Wattleup and to the north-east.

8.3.3 Short-term Effects

Figure 8.9 shows the calculated annual frequency of 3-hour periods with an average sulphur dioxide concentration greater than the USEPA secondary standard of 1300 $\mu g/m^3$. The model indicates a peak frequency of about two to five cases per annum in the area to the west of Wattleup, but less than one per annum in the general Wattleup area itself. The south-north orientation of the high concentration axis is an apparent consequence of the alignment of major sources along it, and the steadiness of the well developed sea breezes responsible for this pollutant transport. Thus, high concentrations can be expected to persist for longer periods in the area to the west of Rockingham Road.

Table 8.3. Monthly variations of measured sulphur dioxide concentration statistics for the Wattleup base station site. The concentrations have been calculated for 0°C reference temperature.

Month	Monthly mean ($\mu g/m^3$)	Frequency of 24-hour average concentrations exceeding 100 $\mu g/m^3$	Frequency of 24-hour average concentrations exceeding 150 $\mu g/m^3$	Frequency of 3-hour average concentrations exceeding 1300 $\mu g/m^3$	Frequency of 1-hour average concentrations exceeding 500 $\mu g/m^3$	Frequency of daily maximum 1-hour average concentrations exceeding 500 $\mu g/m^3$	Frequency of 1-hour average concentrations exceeding 1000 $\mu g/m^3$	Frequency of 1-hour average concentrations exceeding 1400 $\mu g/m^3$	Data recovery (%)
1978									
June	11								51.4
July	5								98.3
August	12			3	3				48.4
September	26								37.6
October	32								63.9
November	101	3		10	4	3			16.5
December	58	7	2	34	12	7			82.2
1979									
January	125	19	9	2	81	25	30	9	99.5
February	76	7	3		30	10	5		85.0
March	60	3	2		26	14	4	1	83.8
April	39	4	1		19	7	1		98.4
May	31	1	1		12	4	6		93.8
June	19								85.1
July	19				1	1			95.8
August	20				1	1			90.9
September	36	2	1	1	11	5	3	2	98.8
October	31	2			7	6			92.2
November	55	5	1		28	11	1		93.4
December	76	8	3		43	18	1		99.2
1980									
January	72	10	4		41	16	8	1	99.3
February	77	11	5		51	16	9	1	97.5
March	76	8	5		42	16	4		96.4
April	39	3			14	8	1		97.9
May	20				2	2			98.5
June	11								53.9
July	16								43.0
August	16								99.7
September	40	2	1		12	7			99.3
October	56	5	1		29	15			96.6
November	75	9	3		36	13	7		95.1
December	64	5			24	13	1		88.6
1981									
January	35				9	7			88.3
ALL DATA		114	42	3	566	234	91	14	

The data of Figure 8.9 must, nevertheless, be applied with caution, since the modelled period of one year was much shorter than that required to give a reliable sample of possible ranges of variables. A variation of up to a factor of two in the estimates is a conceivable consequence of an extension to longer periods. In particular, any adverse combination of meteorological and/or emission conditions may result in large variations, from year to year, in the frequency with which high concentration levels are exceeded. Table 8.4, for example, shows that the summer of 1978-79 was relatively more severe in respect to high 3-hour average concentrations than was the 1979-80 summer used for the modelling exercise. However, on the basis of a range of indicators

(annual average to 1-hour average concentrations), the two summers were remarkably similar.

Contours were generated to show the number of hours where sulphur dioxide concentration exceeded 500 $\mu g/m^3$ for the year July 1979 to June 1980 (Figure 8.10). In order that these results could be judged against the Victorian EPA 'acceptable' level, contours showing the number of days for which the maximum 1-hour average concentration exceeded 500 $\mu g/m^3$ were also provided (Figure 8.11). The 'acceptable' level of 3 days per year is shown to be violated over a large part of the study area to the north of Medina. A strip of land along the coast towards Rockingham was also affected.

Table 8.4. A summary of sulphur dioxide concentration statistics for the Wattleup base station for the years 1979 and 1980. The concentrations have been calculated for 0°C reference temperature.

	1979	1980
Annual average concentration ($\mu g/m^3$)	47	49
Frequency of 24-hour average concentrations exceeding:		
365 $\mu g/m^3$	0	0
310 $\mu g/m^3$	0	0
200 $\mu g/m^3$	8	0
170 $\mu g/m^3$	14	10
150 $\mu g/m^3$	21	19
100 $\mu g/m^3$	51	53
Frequency of 3-hour average concentrations exceeding:		
1300 $\mu g/m^3$	3	0
Frequency of 1-hour average concentrations exceeding:		
1400 $\mu g/m^3$	12	2
1000 $\mu g/m^3$	51	30
500 $\mu g/m^3$	259	251
Frequency of daily maximum 1-hour average concentrations exceeding:		
500 $\mu g/m^3$	102	106

The Victorian EPA 1-hour average 'detrimental' level was also exceeded on many occasions to the north and north-east of major industry at Kwinana (Figure 8.12).

Contours expressing the frequency of violation of the Victorian EPA 'alert' level (1400 $\mu g/m^3$) are given in Figure 8.13. These show that the level was exceeded on a number of occasions, particularly along axes lying to the north and west of Wattleup. This trend was most marked at the higher concentrations, and was consistent with the small spread of major sources perpendicular to this direction. Comparison of Figures 8.11, 8.12 and 8.13 show that, while the axis of highest frequency with which the Victorian EPA 'acceptable' objective is exceeded passes through Wattleup, the 'detrimental' and 'alert' level axes pass to the west. This means that, although air pollution episodes are of greatest frequency near Wattleup, their severity is greater to the west of Rockingham Road. (It is notable that this area was found to be the centre of greatest sulphur dioxide impact in the Coogee Air Pollution Study.)

8.4 GENERAL AIR QUALITY AT KWINANA

Though the determination of air quality at Kwinana is closely dependent upon the ambient standards used for reference, the study has nevertheless indicated that the potential for problems is greatest as a result of short-term, relatively high concentration air pollution episodes.

Annual average sulphur dioxide concentrations are not severe at Kwinana, approaching the WHO annual average upper limit of 60 $\mu g/m^3$ only in a few localised areas close to industry. The USEPA primary standard of 80 $\mu g/m^3$ (Table 2.1) on the othe hand is not at all exceeded in the study area.

The WHO 150 $\mu g/m^3$ 24-hour average upper limit was exceeded over a wide section of the modelled region but reference to other standards, such as the Victorian EPA 'acceptable' and the superseded WHO guideline (Section 2.5), showed reductions in the affected area. In addition, both the USEPA primary standard and the Victorian EPA 'detrimental' level were exceeded only rarely in all but those areas closest to industry.

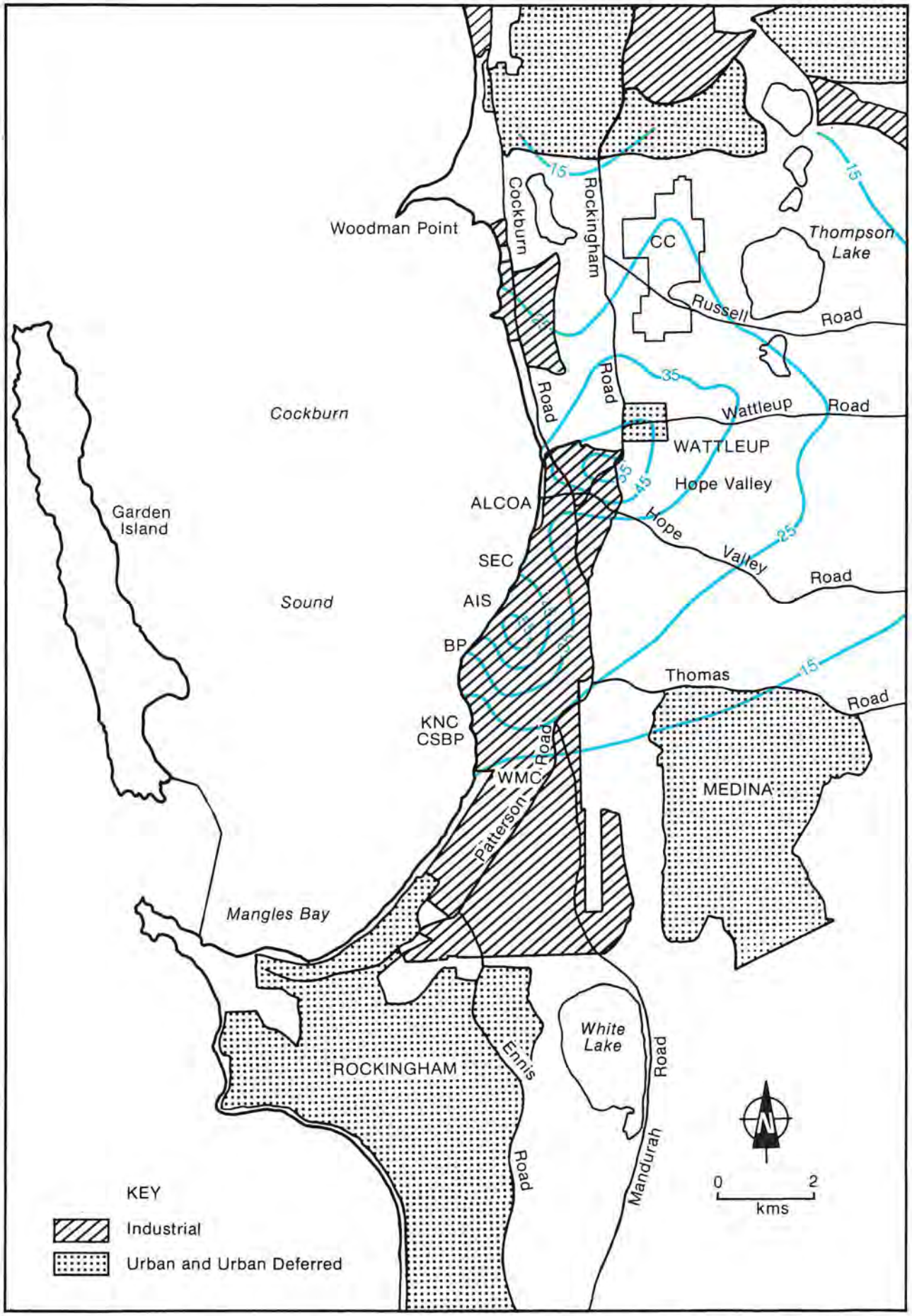


Figure 8.6. Contours of annual average sulphur dioxide concentration ($\mu g/m^3$) estimated using Model 1 for the year July 1979 to June 1980.

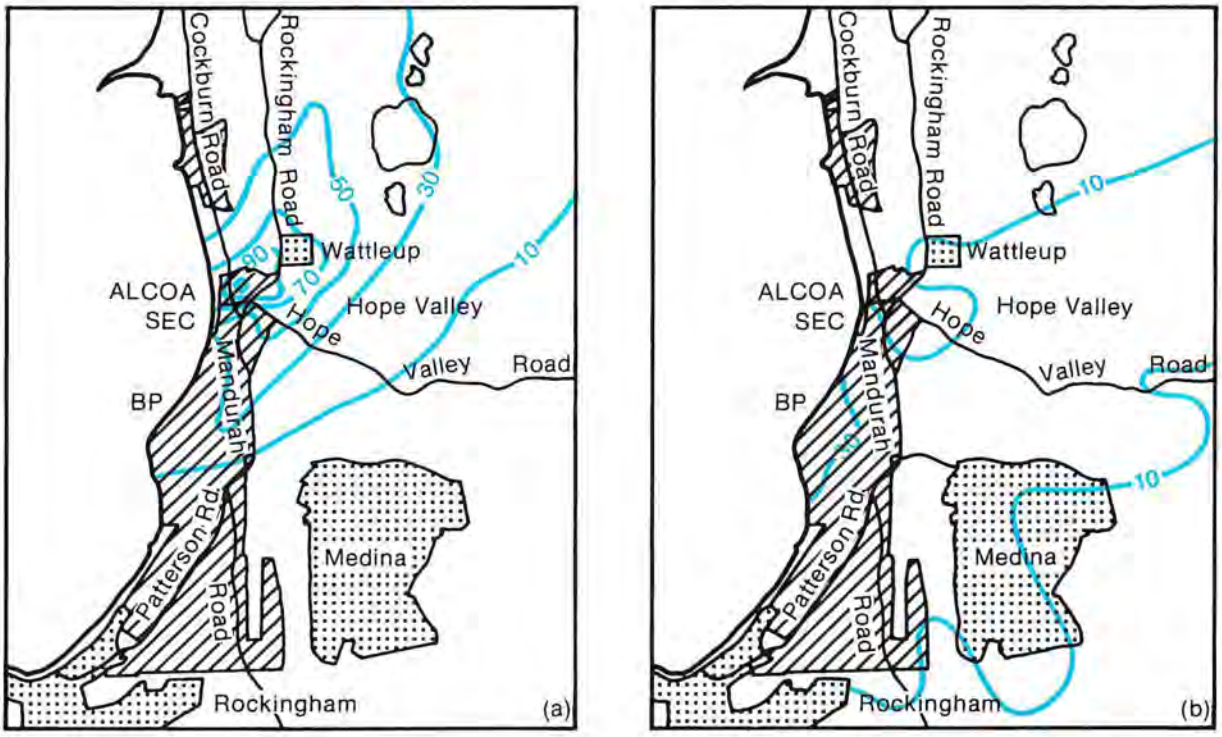


Figure 8.7. Contours of monthly average sulphur dioxide concentration ($\mu g/m^3$) estimated using Model 1 for (a) January 1980 and (b) July 1979.

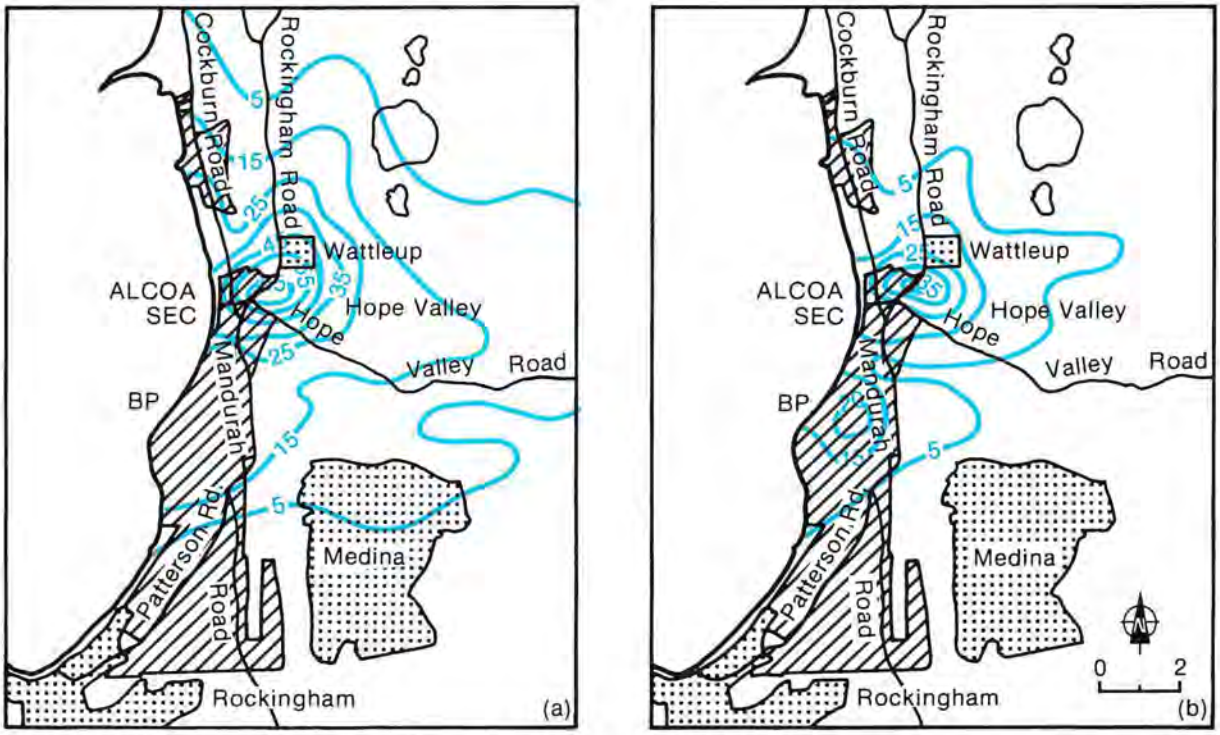


Figure 8.8. Contours of the number of days where the 24-hour average sulphur dioxide concentration exceeded (a) 100 $\mu g/m^3$ and (b) 150 $\mu g/m^3$ for the year July 1979 to June 1980. The estimates were derived using Model 1.

Shorter-term analyses suggested that a 3-hour average of over 1300 $\mu g/m^3$ may occur a few times per year to the north and west of Wattleup. It is relevant that such a prediction is consistent with limited measurements during the period of monitoring at Wattleup (Table 8.4).

Air pollution at Kwinana is most severe for short-term episodes of high sulphur dioxide concentrations. Both the Victorian EPA 'acceptable' and 'detrimental' levels for 1-hour average concentrations of sulphur dioxide were significantly exceeded over a wide area to the north-east of Kwinana. In addition, the Victorian EPA 'alert' level was exceeded on a number of occasions.

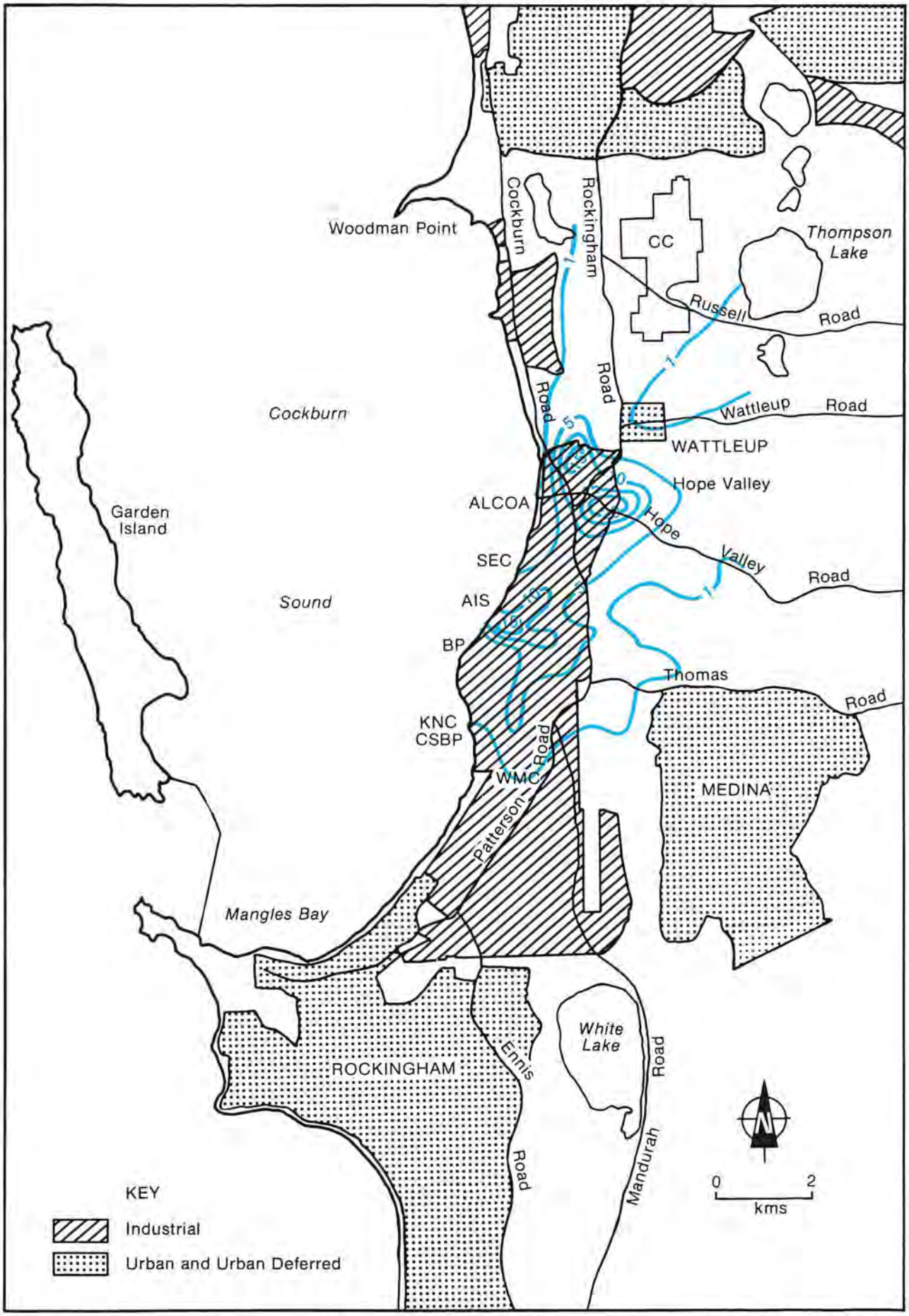


Figure 8.9. Contours of the frequency of 3-hour average sulphur dioxide concentrations exceeding 1300 $\mu g/m^3$ for the year July 1979 to June 1980. The estimates were derived using Model 2.

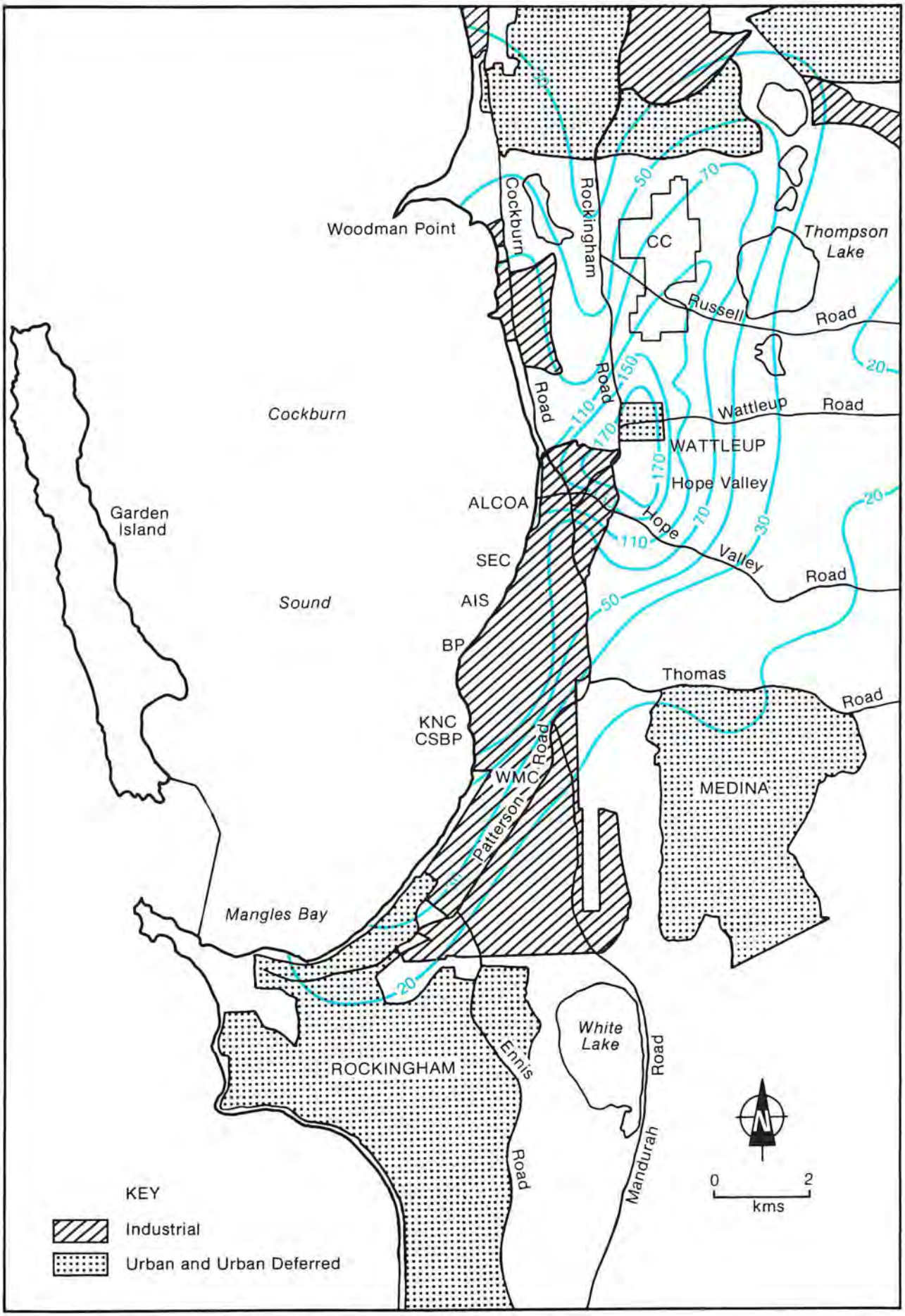


Figure 8.10. Contours of the frequency of 1-hour average sulphur dioxide concentrations exceeding 500 $\mu g/m^3$ for the year July 1979 to June 1980. The estimates were derived using Model 1.

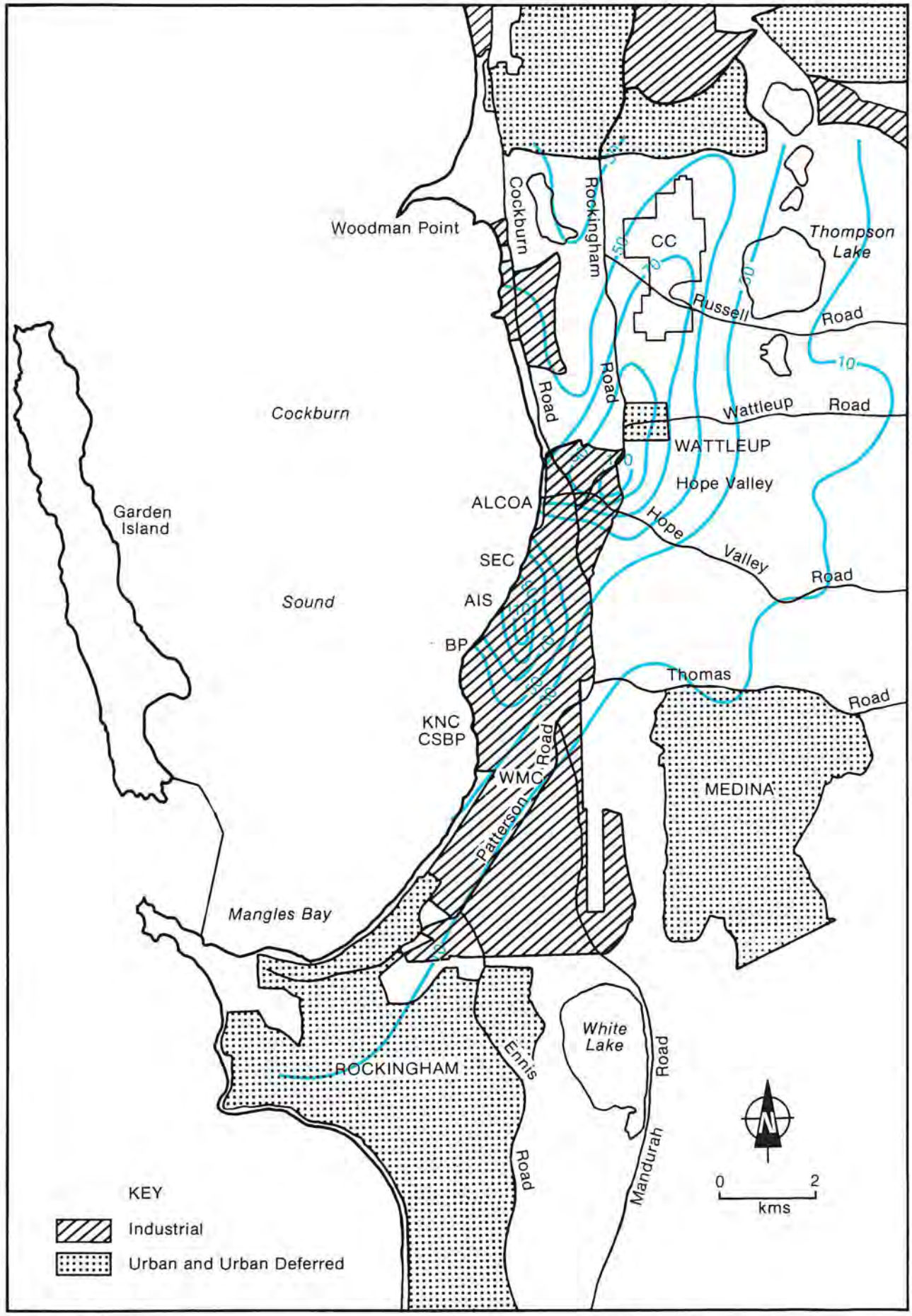


Figure 8.11. Contours of the number of days where maximum 1-hour average sulphur dioxide concentration exceeded 500 $\mu g/m^3$ for the year July 1979 to June 1980. The estimates were derived using Model 1.

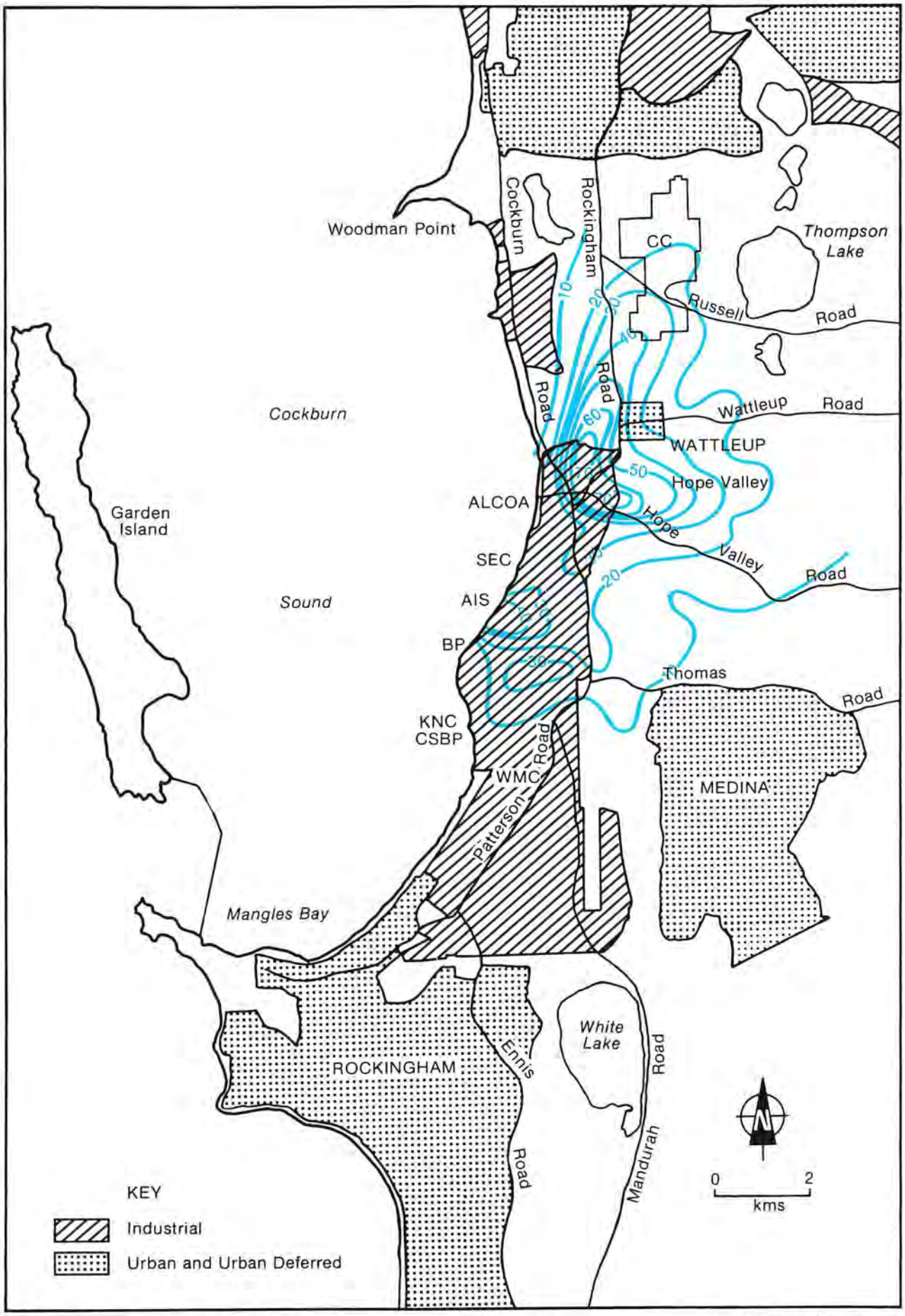


Figure 8.12. Contours of the frequency of 1-hour average sulphur dioxide concentrations exceeding 1000 $\mu g/m^3$ for the year July 1979 to June 1980. The estimates were derived using Model 2.

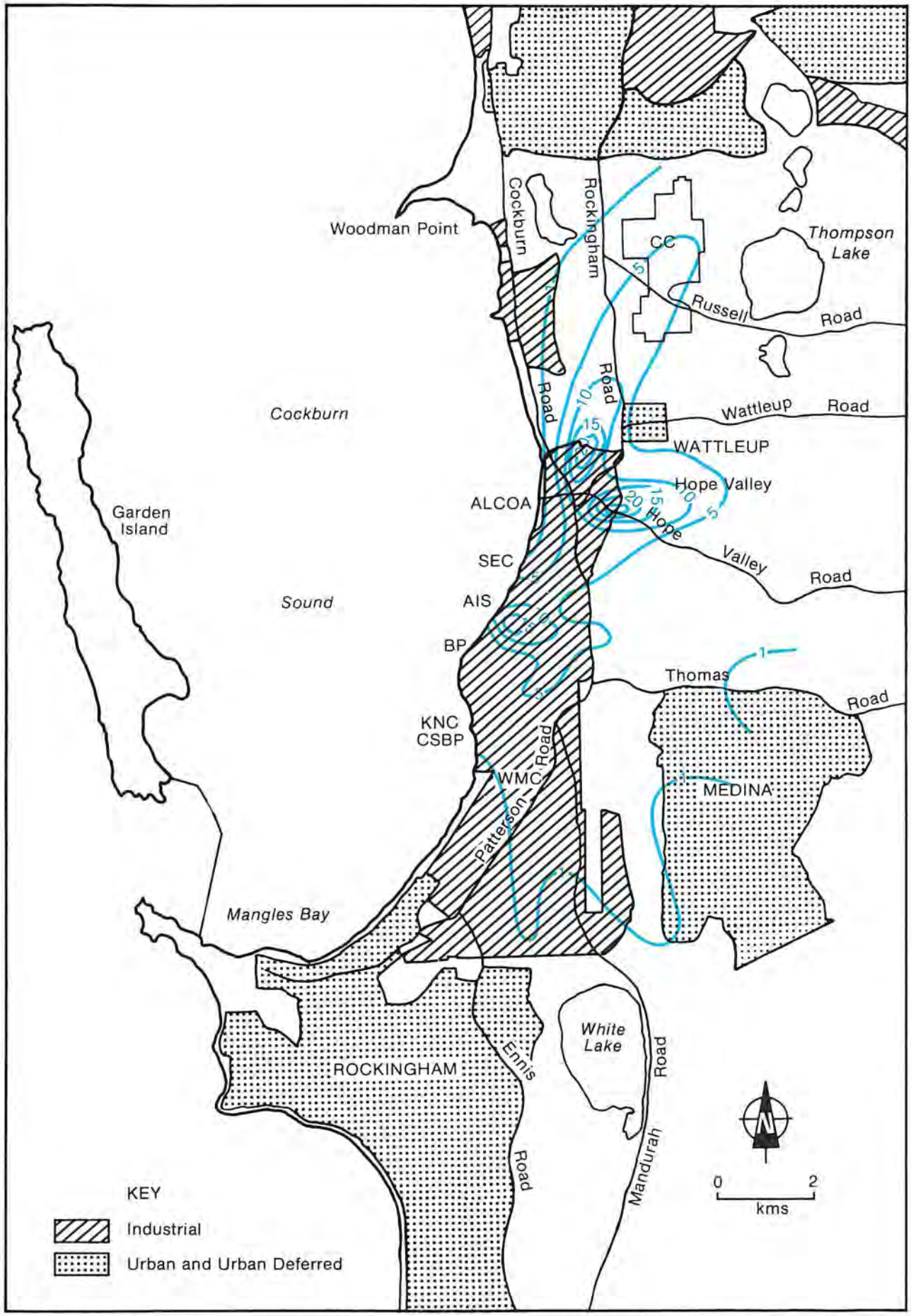


Figure 8.13. Contours of the frequency of 1-hour average sulphur dioxide concentrations exceeding 1400 $\mu g/m^3$ for the year July 1979 to June 1980. The estimates were derived using Model 2.

The study results strongly indicate that some areas of Kwinana are subject to chronic short-term exposure to high sulphur dioxide concentrations. Based on the criteria of the Victorian EPA (1981), such exposure is undesirable.

8.5 FURTHER APPLICATION OF THE MODELS

The principal attribute of a properly validated mathematical pollutant dispersion model is its capacity to estimate pollution impact for a wide range of parameters. Variations in fuel types, process conditions and stack configuration can be readily accommodated in a mathematical model to determine their effect on ambient concentrations.

A range of possible changes in existing emissions is considered below to illustrate both the capability of the models developed for KAMS and the consequences of the changes.

A further study of the impact of a new sulphur dioxide source located in the south-east region of the Kwinana industrial area was also conducted using Model 2.

8.5.1 Changes in Fuel Used by Existing Industry

Model 2 was used to investigate the effect that changes in existing emissions of sulphur dioxide would have on the short-term air pollution impact presently experienced at Kwinana. A number of possible emission configurations were considered and the model run for the month of January 1979 using, in turn:

- all existing emissions – providing reference data
- alumina refinery emissions omitted – simulating the conversion of fuel used to natural gas (Section 3.2.1)
- alumina refinery emissions omitted but petroleum refinery emissions increased – representing possible increases in the sulphur content in crude oil processed
- power station and alumina refinery emissions omitted – a projected minimum emissions inventory arising from the maximum likely conversion to natural gas.

The month of January 1979 was used for comparison because, of all the months of the study, it showed the highest frequency of pollution episodes. It therefore provided the best statistical sample of such episodes, for the least computer program execution time.

Calculations were carried out to determine the frequency with which 1-hour average sulphur dioxide concentrations exceeded 500, 1000 and 1400 $\mu g/m^3$ during January 1979 (Rye, 1982). The 500 $\mu g/m^3$ level is used to indicate the effect of the possible fuel changes in this report. The model results are shown to underestimate the number of hours over 500 $\mu g/m^3$, giving 61 in comparison to 77 hours measured at Wattleup. Underestimations were more significant for the higher concentrations (Rye, 1982).

Changes in emissions, from the SEC in particular, since 1979 are relatively minor and the 'existing emissions' contours in Figure 8.14(a) will approximate closely the present air pollution impact at Kwinana. The effect that possible changes in fuel types, and thus emissions, have on this impact is detailed in (i)-(iii) below.

(i) Natural Gas Conversion of Alumina Refinery

A change from oil to natural gas in the fuel used by the alumina refinery would result in the almost complete elimination of sulphur dioxide from its emissions. The benefit of this change would be considerable, with the estimated number of hours over 500 $\mu g/m^3$ being approximately halved at large distances (Figure 8.14(b)). Nevertheless, the results indicate that this improvement is well short of that needed to ensure long-term compliance with the Victorian EPA 'acceptable' objective (1-hour average not to exceed 500 $\mu g/m^3$ on more than 3 separate days per year). Similarly, occurrences over 1000 $\mu g/m^3$ (the 'detrimental' level) were only eliminated from the area north and west of Wattleup (Rye, 1982).

(ii) Changes in Petroleum Refinery Emissions

The assumed use of natural gas by the alumina refinery defined the base for the second study, since this was a probable representation of future developments. Emissions from the petroleum refinery were increased by a nominal 50%. The two changes together were found to have compensating effects, with the overall change from the 'existing emissions' simulation (Figure 8.14(a)) being a relocation southwards of the major impact area (Figure 8.14(c)). This investigation demonstrated a need for careful projections of actual crude oil usage by the petroleum refinery in any specific modelling of future air pollution trends.

(iii) Maximum Natural Gas Conversion

The greatest reduction of sulphur dioxide emissions from Kwinana is likely to be achieved if the alumina refinery is converted to natural gas usage and the power station to a combination of coal and natural gas. A conservative estimate of the impact of such changes was obtained by eliminating totally emissions from both plants for the dispersion calculations.

Figure 8.14(d) shows that, despite this large reduction in emissions, 1-hour average concentrations exceeding 500 $\mu g/m^3$ will still frequently occur in the vicinity of Wattleup and to the north. The same analysis (Rye, 1982) showed that along the axis of peak frequencies in excess of 500 $\mu g/m^3$, the Victorian EPA 'detrimental' level of 1000 $\mu g/m^3$ was also exceeded on two to three occasions for the month.

8.5.2 Impact of New Industry

The most common application of dispersion models is in forecasting the air pollution impact of new industry. Model 2 was used in such a role, applied to a hypothetical source in the south-eastern section of the Kwinana industrial area. The predicted frequency of hourly averages over 1000 $\mu g/m^3$, calculated using an emission rate of 1 kg/sec from a 100 m stack and data for the 1979-80 summer season, is shown in Figure 8.15.

Frequencies of hours over 500, 700, 1000 and 1400 $\mu g/m^3$ were all estimated (Rye, 1982), and from these data it was possible to propose a limit on sulphur dioxide emissions. In principle, the process involved reading the frequency of hours over each concentration, at the residential area experiencing greatest impact. If the emissions from the proposed industry were reduced to less than 1 kg/sec, these frequencies would have been appropriate to a proportionately smaller set of hourly average concentrations. The emission which decreased the frequency at any proposed ambient concentration limit to less than that specified for that limit then defined the allowed emission. In the present case, for example, the limit which ensured compliance with the Victorian EPA 'detrimental' level was 0.62 kg/sec while a value of 0.36 kg/sec was required to meet the 'acceptable' level. If the Victorian criteria were applied, the emission rate limit would then have been the lesser of these two values, 0.36 kg/sec.

This exercise can be applied in a reverse manner, estimating the minimum distance to residential zones for various emission rates.

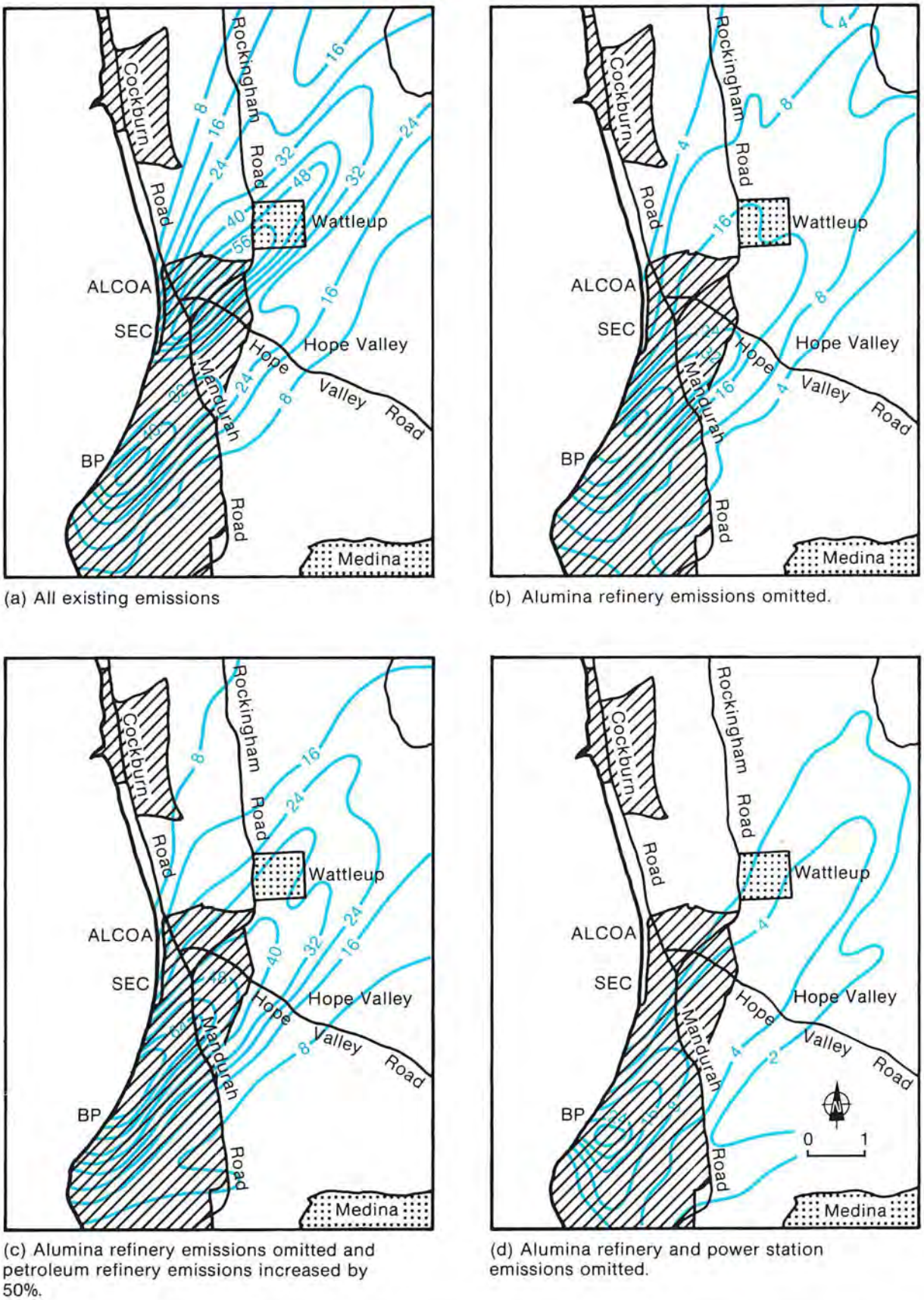
8.5.3 Pollution Potential Roses

In addition to the determination of concentration estimates based on existing sulphur dioxide emissions at Kwinana, Model 1 was also used more generally to examine the long-term pollution impact of an arbitrary source located on the Perth coastal plain. Calculations were carried out for a hypothetical 1 kg/sec emission from a 100 m stack located at distances of 50 m, 750 m and 3000 m inland from a north-south coast. The July 1979-June 1980 Kwinana meteorological data were used in the model to produce contours of annual average concentrations and the frequency of 1-hour average concentrations exceeding 350 $\mu g/m^3$, 500 $\mu g/m^3$ and 750 $\mu g/m^3$. The model results are shown in Figure 8.16.

The contours of Figure 8.16 illustrate the effect of the coastal boundary layer (Chapter 6) on the sources located close to the coast. In particular the long-term average impact (annual average concentration (a)) is significantly less for the stack located 50 m from the coast than it is for the stacks further inland. The frequency of 1-hour average concentrations exceeding 350 $\mu g/m^3$ (Figure 8.16(b)) also followed the same trend.

High concentration, short-term air pollution episodes are more frequent for the source that is close to the coast where the pollutant is emitted above the boundary layer. The maximum number of 1-hour average concentrations exceeding 750 $\mu g/m^3$ is approximately three times higher for the stack located 50 m from the coast than for the stack at 3000 m (Figure 8.16(d)). However, the boundary layer has little effect on the number of 1-hour average concentrations exceeding 500 $\mu g/m^3$ (Figure 8.16(c)).

Though the air pollution impact of a particular source on the Perth coastal plain is dependent on the actual emission level, stack height and heat of emission, some general conclusions can be made based on analysis of Figure 8.16. The effect of the coastal boundary layer is to increase maximum short-term, high concentration levels but to decrease maximum long-term average concentrations produced by emissions from a tall stack located near the coast. Consequently the optimum siting of a proposed stack will depend on whether short- or long-term average concentrations are required to be minimised.



(a) All existing emissions

(b) Alumina refinery emissions omitted.

(c) Alumina refinery emissions omitted and petroleum refinery emissions increased by 50%.

(d) Alumina refinery and power station emissions omitted.

Figure 8.14. Contours of the frequency of 1-hour average sulphur dioxide concentrations exceeding 500 $\mu g/m^3$ during January 1979 for various emission configurations. The estimates were derived using Model 2.

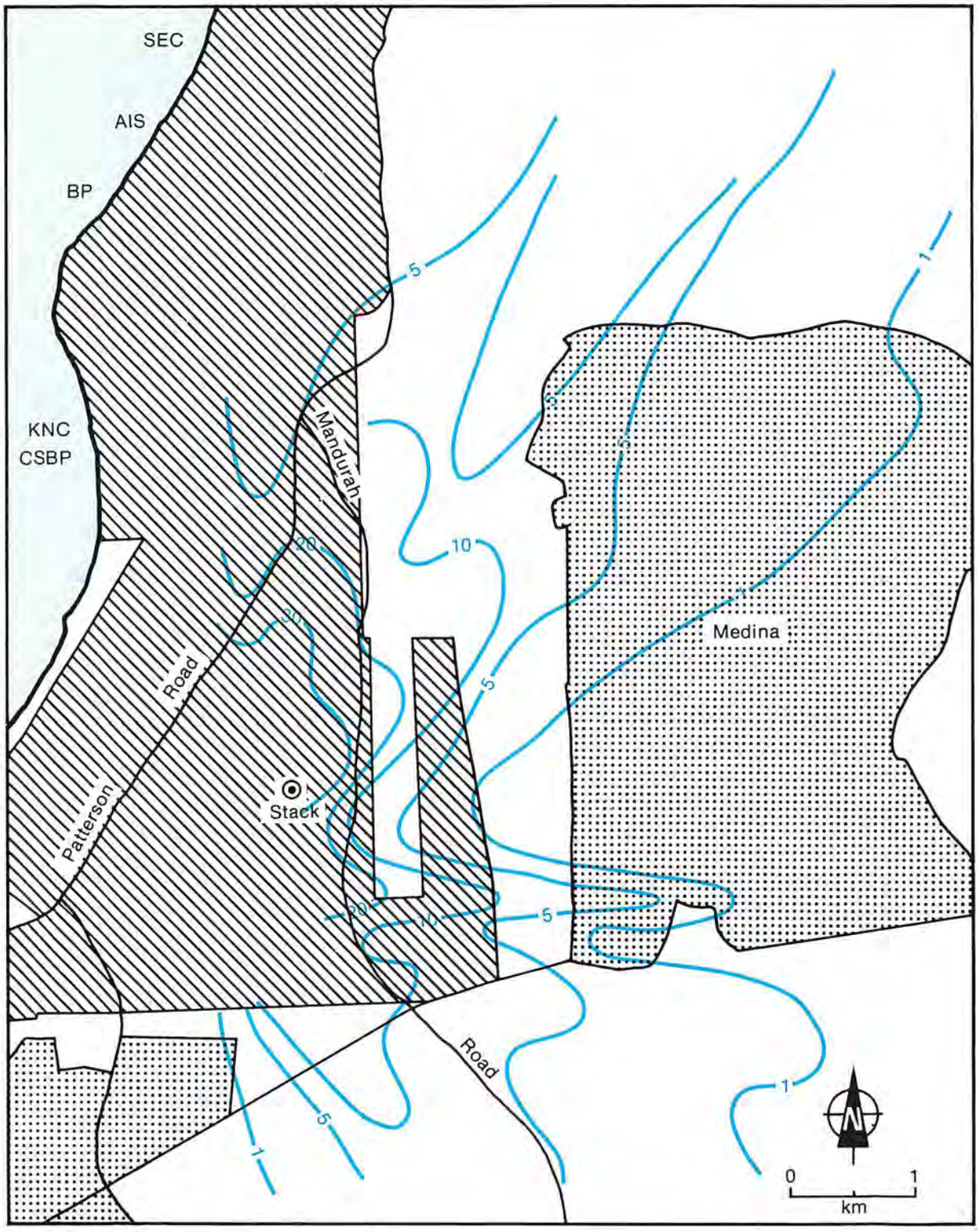


Figure 8.15. Contours of the frequency of 1-hour average sulphur dioxide concentrations exceeding 1000 $\mu g/m^3$ for the period December 1979 to February 1980. The estimates were derived using Model 2 for a 1 kg/sec source located in the SE portion of the industrial area at Kwinana. The emission level is approximately equivalent to the emission from a large power station or oil refinery.

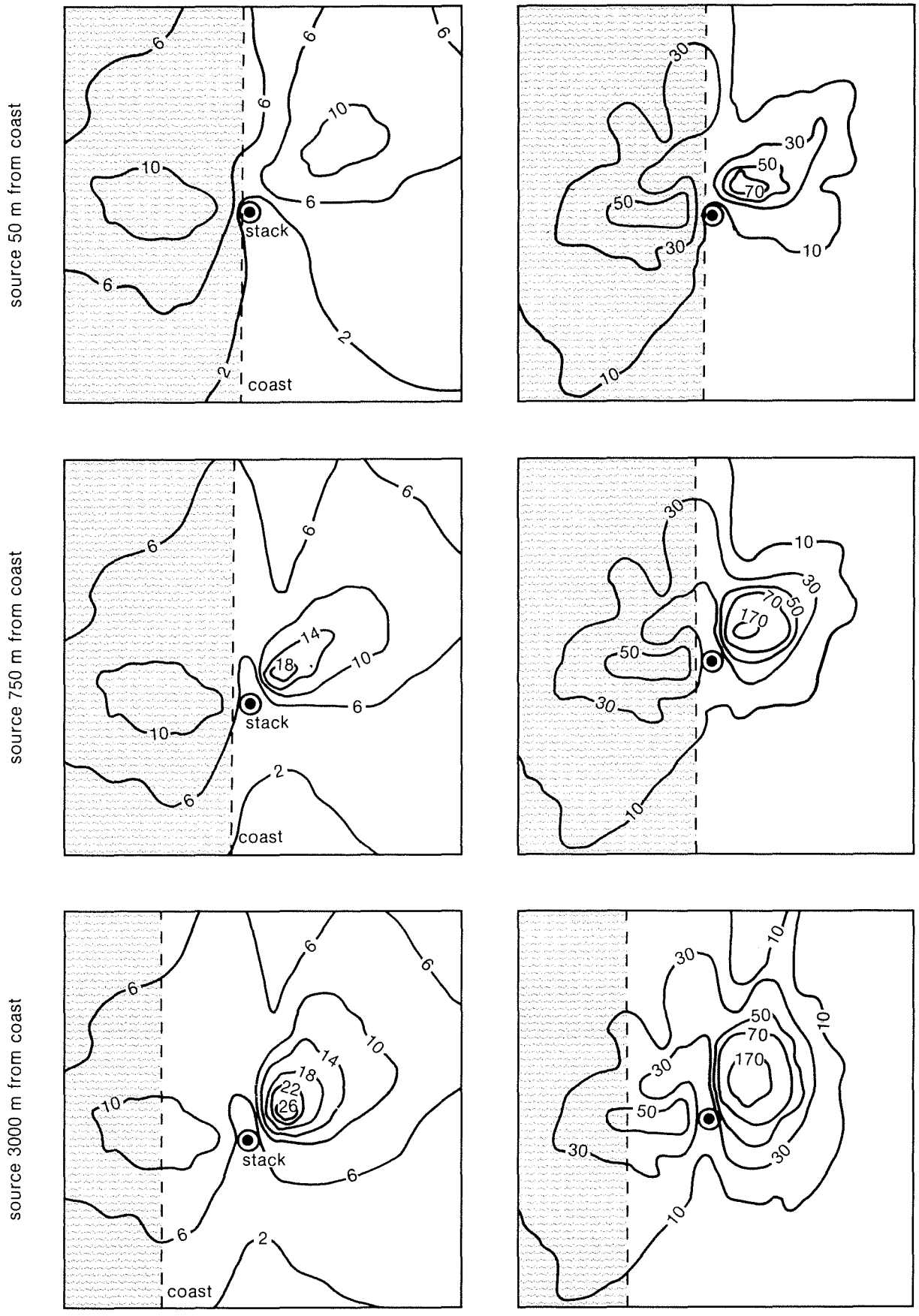
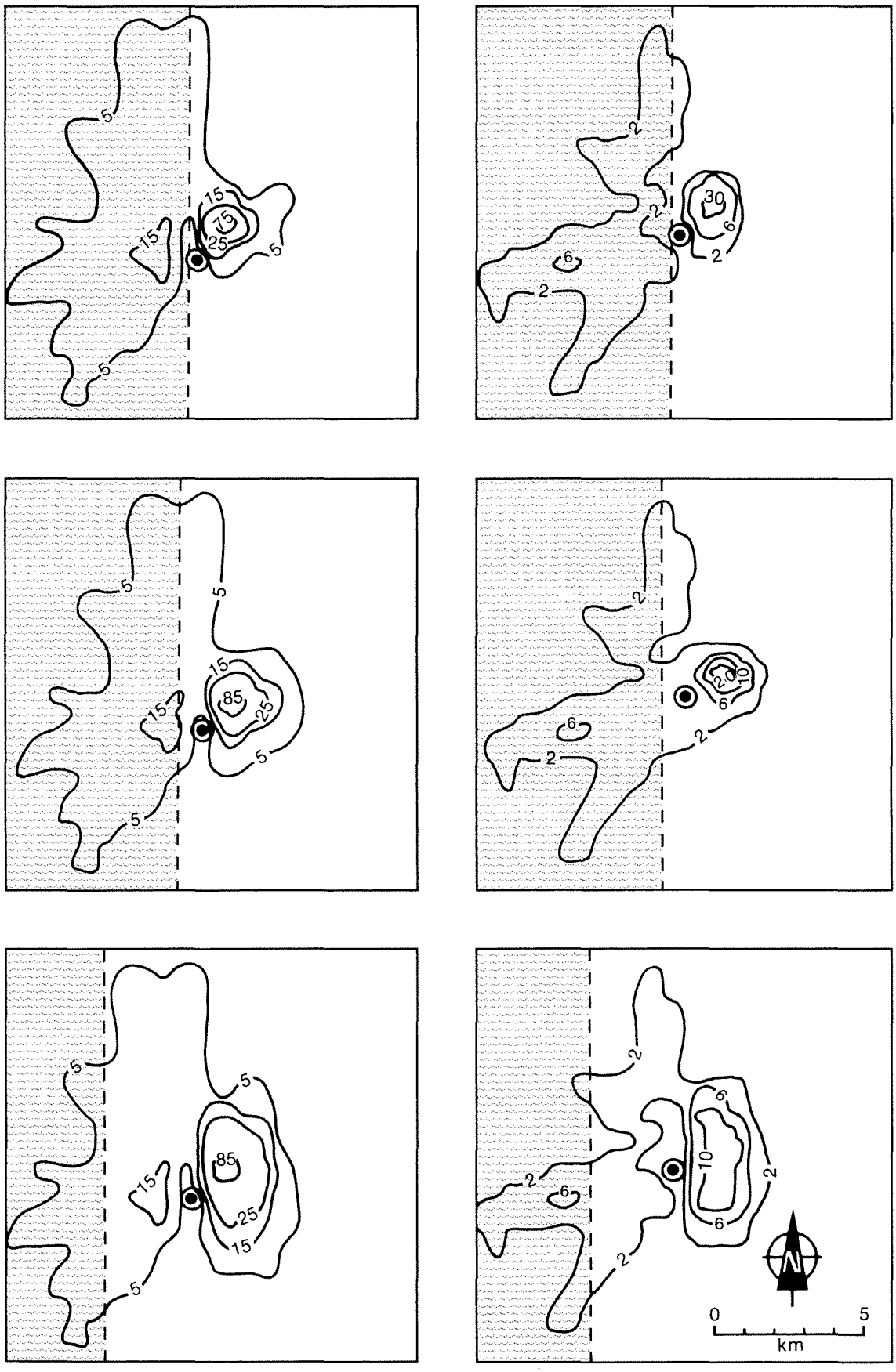


Figure 8.16. Contours of the air pollution impact of a 1 kg/sec source released from a 100 m stack located at various distances from the coast at Kwinana. The estimates were derived using Model 1 for the year July 1979 to June 1980.



(c) Hours over 500 $\mu g/m^3$

(d) Hours over 750 $\mu g/m^3$

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

9.1.1 General

(i) The air dispersion models developed for the study enabled the effects of air pollution in the study area to be determined with reasonable confidence.

(ii) As a result of experimental studies and mathematical modelling, an understanding of coastal meteorology and, in particular, the sea breeze fumigation process, was obtained.

(iii) Valuable experience was gained and expertise developed in the operation of meteorological, pollutant monitoring and data logging equipment required for air dispersion studies. In addition, efficient data processing and numerical modelling schemes were developed.

(iv) The approach adopted in KAMS was one where study components were introduced or upgraded as the Core Group of research officers learned more about a particular aspect. The result, however, is that the State now has at its disposal high quality expertise and information such that Government response to issues involving land use planning and siting of industry can be accurate and prompt.

(v) Knowledge gained through KAMS has already been applied to other parts of Western Australia including co-operative studies with the State Energy Commission at Bunbury and a mining company at Kalgoorlie. In addition, the likely effects of new industry located in the south-east portion of the Kwinana industrial area has been the subject of a preliminary investigation for the Metropolitan Region Planning Authority.

The role of the State in all of these studies is to provide expertise and coordinate, in a regional sense, the efforts of Government agencies, tertiary institutions and private organisations. In this way, an understanding can be gained of an area in which individual industries may be sited and effective advice given on the best way to manage any air emissions from those industries.

9.1.2 KAMS Results

(i) The study has identified the location of the major air pollution impact areas to the north and north-east of industry at Kwinana. These areas are strongly dependent on the geometrical configuration of the existing pollutant sources and the meteorological characteristics at Kwinana.

(ii) Air pollution at Kwinana was shown to be dominated by short periods of relatively high concentrations of sulphur dioxide occurring in the summer months. These episodes are commonly of 1-5 hours duration, and generally coincide with the occurrence of the sea breeze. Consequently, 24-hour and monthly averages of sulphur dioxide are elevated over summer compared to other seasons, and are a major contribution to the annual average concentrations.

(iii) Pollutants emitted into the sea breeze from tall chimneys near the coast disperse quite slowly until they encounter a growing turbulent boundary layer a few kilometres downwind of the source and are brought rapidly to ground level. This results in the production of relatively high pollutant concentrations as far downwind as 7 kilometres.

(iv) The short-term nature of air pollution episodes at Kwinana was only identified when detailed continuous meteorological and sulphur dioxide measurements were made. It was therefore considered that the use of air pollutant ambient standards with a range of averaging times for comparison with measured and calculated results was necessary to define adequately pollution impact at Kwinana. The main standards chosen for reference were for 1-year, 24-hour, 3-hour and 1-hour averaging periods.

(v) On the basis of the model validation carried out during KAMS, with all available data, it is considered that the mathematical models adequately represent pollutant dispersion at Kwinana. However, though much of the validation procedure involved the principal area of concern around Wattleup, it should be noted that validation data for other areas were sparse.

(vi) Based on the modelling results for the year July 1979 to June 1980, it was shown that air pollution most significantly affects the area to the north and north-east of industry at Kwinana. Figures are given below which specify the lowest modelled impact (boundary values) for the region between Wattleup and Thompson Lake.

It should be emphasised, however, that levels are significantly higher than the figures quoted below in areas around and to the west of Wattleup and, in some cases, exceed the standards used for comparison.

These results are:

- The annual average SO_2 concentration approached but was generally below the WHO guideline (annual mean less than 40-60 $\mu g/m^3$) (Figure 8.6).
- The 24-hour average SO_2 concentration exceeded the upper limit of the WHO guideline (24-hour average less than 100-150 $\mu g/m^3$) on at least 5 days (Figure 8.8).
- The 3-hour average SO_2 concentration would, on average, exceed the USEPA secondary standard (3-hour average not to exceed 1300 $\mu g/m^3$ more than once per year) every 1-2 years (Figure 8.9).
- The 1-hour average SO_2 concentration exceeded the Victorian EPA 'acceptable' level (1-hour average not to exceed 500 $\mu g/m^3$ on more than 3 days per year) on more than 10 days (Figure 8.11).
- The 1-hour average SO_2 concentration exceeded the Victorian EPA 'detrimental' level (1-hour average not to exceed 1000 $\mu g/m^3$) on more than 10 occasions (Figure 8.12).
- The 1-hour average SO_2 concentration exceeded the Victorian EPA 'alert' level (1400 $\mu g/m^3$) on at least one occasion (Figure 8.13).

(vii) In the document *Planning Strategy for the South-West Corridor* (MRPA, 1980) an interim buffer zone or affected area was defined at Kwinana, based on the experience and judgement of KAMS study participants and officers from the Department of Public Health. Large scale urban development was subsequently deferred in the area included in the interim buffer zone, pending the final KAMS results. The adequacy with which the interim buffer zone reflects the impact of sulphur dioxide pollution at Kwinana can now be assessed using the model estimates.

Figure 9.1 shows modelled frequency contours corresponding most closely to the 1980 buffer zone in the region to the north and east of industry at Kwinana. It can be seen that, over most of the buffer zone, the lower and upper limits of the WHO 24-hour guidelines were exceeded on at least 15 and 5 days respectively (Figure 9.1 (a), (b)). Similarly, the Victorian EPA 1-hour 'detrimental' and 'alert' levels were exceeded on at least 15 and three occasions respectively (Figures 9.1 (c), (d)).

Thus, the buffer zone, originally proposed as a conservative estimate, has been found to be much less than conservative in its northern section. The southern part, on the other hand, has been shown to be less affected by air pollution than believed. However, the southern area of the industrial zone is presently largely undeveloped and any additional sulphur dioxide sources there will increase concentrations in the region of the southern buffer (Section 8.5.2).

On the basis of the standards chosen for reference in this study the interim buffer zone illustrated in Figure 9.1 should be seen, therefore, as a minimum requirement to protect against the adverse effects of existing air pollution at Kwinana.

(viii) Though the models have been developed and run using existing sulphur dioxide emissions at Kwinana, they have the capability to produce concentration estimates for most air pollutants and for any source configuration located on the Perth coastal plain. Investigations have already been carried out into the effects of the use of natural gas by the alumina industry (Section 8.5.1(i)), increased SO_2 emissions from the oil refinery (Section 8.5.1(ii)) and new industry in the south-east part of Kwinana (Section 8.5.2).

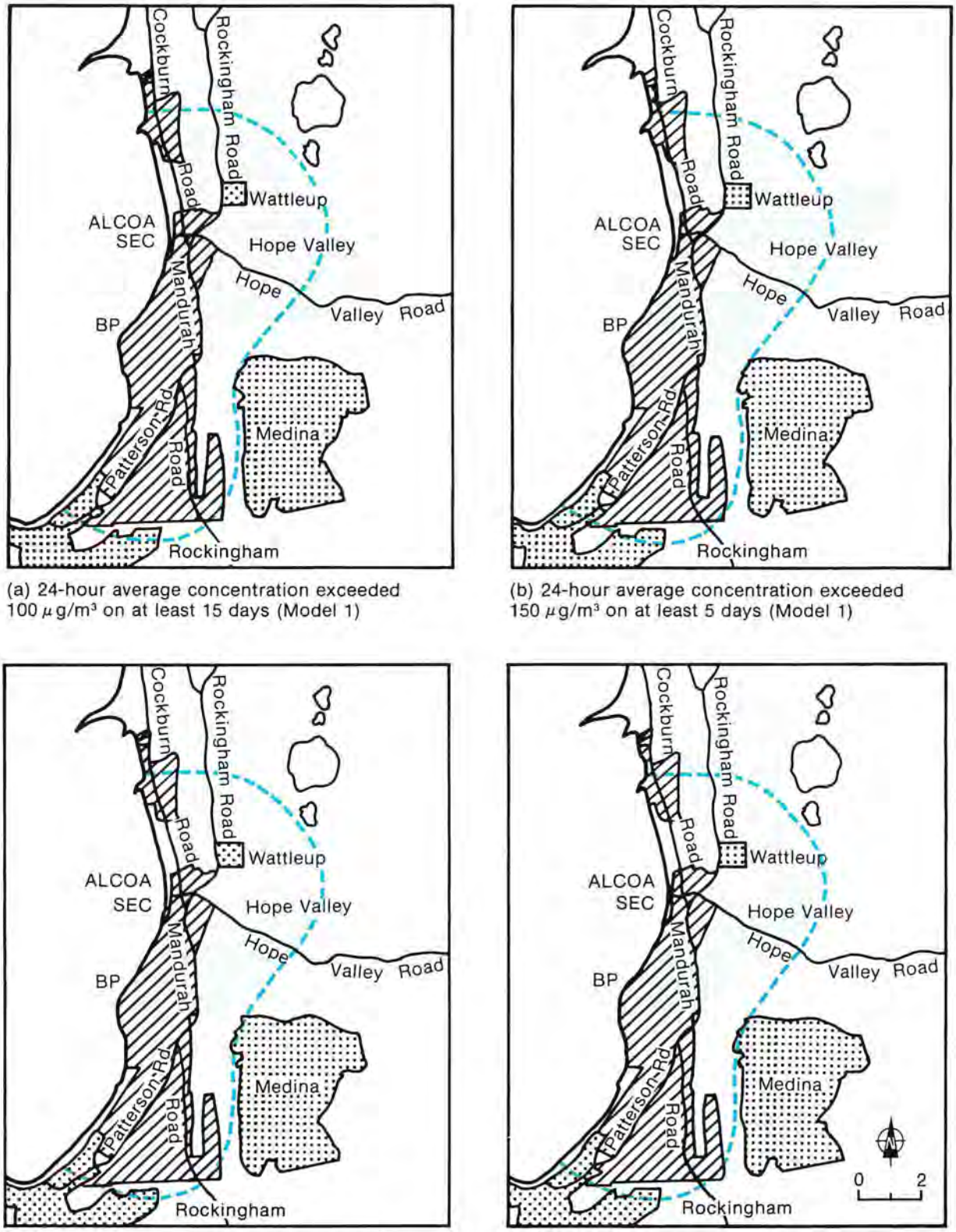
9.1.3 Implications for Land Use at Kwinana

The results of KAMS provide the planning authorities such as the Metropolitan Region Planning Authority and local government with the means of integrating air quality information into the planning process. The constraints imposed by air pollution on the uses to which particular land can be put will depend on the degree of emission control and the air pollution standards adopted.

For example, without major reductions in the emission of sulphur dioxide from industry at Kwinana, and on the basis of the standards chosen for reference in this study (Table 8.2), the area defined by the 1980 interim buffer zone would be considered unsuitable for further residential development. Furthermore, some areas to the north-east that are outside the interim buffer zone are also subject to significant air pollution impact. The extent of the affected region varies according to the ambient standards used and consideration of less stringent standards would, of course, result in a smaller region alienated by the existing pollutant emissions.

Major reductions of sulphur dioxide emissions at Kwinana, though reducing significantly the impact of air

pollution on land adjacent to industry, would not eliminate this impact (Section 8.5.1). The extent to which emissions are reduced and the time taken to achieve chosen air quality objectives would, of course, be determined by economic considerations, and community values and aspirations.



(a) 24-hour average concentration exceeded 100 μg/m^3 on at least 15 days (Model 1)

(b) 24-hour average concentration exceeded 150 μg/m^3 on at least 5 days (Model 1)

(c) 1-hour average concentration exceeded 1000 μg/m^3 on at least 15 occasions (Model 2)

(d) 1-hour average concentration exceeded 1400 μg/m^3 on at least 3 occasions (Model 2)

Figure 9.1. Modelled air pollution impact (shaded area) for the year July 1979 to June 1980 based on the criteria indicated. The dashed line represents the interim 'buffer zone' proposed in MRPA (1980).

9.2 RECOMMENDATIONS

9.2.1 Air Quality Standards

(i) In the absence of statutory air quality standards in Western Australia, limits to be accepted for various land uses in the Kwinana region are a matter for discussion and agreement. In particular, it is recommended that the Air Pollution Control Council consider the whole question of short-term ambient air quality standards and adopt a range of criteria covering both long and short-term periods of exposure.

(ii) The ambient air quality criteria chosen for the Kwinana Air Modelling Study are considered to be satisfactory indicators of air quality over a range of averaging periods. The 1979 World Health Organisation annual and 24-hour levels and the Victorian EPA 1-hour objectives are recommended to the Air Pollution Control Council as guidelines for sulphur dioxide.

9.2.2 Land Use Planning

(i) The results of this study suggest that planning of future uses for the area to the north and east of Kwinana must take ambient air quality into account, particularly within the area of the interim buffer zone given in Figure 9.1. The planning process must include consideration of existing air pollutant levels together with possible emission controls, so that urban, rural and industrial land uses may be arranged to protect against adverse effects of air pollution.

In particular, any hospitals, schools and institutions for aged persons which would attract a greater proportion of the susceptible population must be carefully located.

Without a major reduction in sulphur dioxide emissions at Kwinana, the population density within the areas of concern should be minimised as should any commercial activities which might be adversely affected by air pollution. In any event, urban development should not be encouraged within the zone proposed in 1980 (Figure 9.1).

(ii) Proposals for the expansion of existing, and development of new industry in any part of the Kwinana region should be subject to review on the basis of models of the type used for this study (Section 8.5.2, for example). Investigations should include not only the effect on overall sulphur dioxide concentrations at Kwinana, but the levels of other pollutants such as atmospheric particulates and oxides of nitrogen and definition of potential impacts on existing and proposed residential areas.

9.2.3 Emission Reduction Options

It is recommended that the Department of Public Health arrange meetings with representatives of Kwinana industry to discuss the findings of the study and to explore ways of reducing air pollution during critical times.

9.2.4 Public Awareness

It is recommended that the public be made fully aware of the extent of air pollution impact at Kwinana. An education programme should be directed at the present residents of the major air pollution impact region, and at intending new residents. Such a programme should be promoted and implemented by the Department of Public Health and the three local government authorities concerned.

9.2.5 Further Work

(i) The inland limit of air pollution impact and the extent of lateral dispersion of plumes, at all distances, depend critically on the rate of growth inland of the atmospheric mixing depth within the sea breeze inflow. The representations used by the KAMS models employed the best available data, but further study of the dynamics of the thermal internal boundary layer, and of the deepening of the sea breeze inland, would allow greater confidence in the application of the models, particularly in the area around Thompson Lake.

(ii) The prediction, by both models, of relatively high sulphur dioxide concentrations well inland, particularly in the vicinity of Thompson Lake, indicates the need for further continuous monitoring in this area.

(iii) The techniques of data recovery, analysis and modelling developed in this study, should be applied in other areas of the State, to provide further information on a wider range of atmospheric dispersion conditions, such as occur inland. This would permit the rapid evaluation of the likely air pollution impact of industrial expansion in all regions of Western Australia.

(iv) The policy of co-operation between State Government departments and the tertiary institutions in Western Australia should be continued in the air pollution field. The mutual benefit of developing and maintaining local expertise in air quality management has been clearly demonstrated in this study.

REFERENCES

Anderson, I., Lundqvist, G.R., Jensen, P.L., and Proctor, D.F. 1974. Human response to controlled levels of sulphur dioxide. Arch. Environ. Health, 28, 31-39.

Bates, D.V. 1972. Air pollutants and the human lung. Amer. Rev. Resp. Dis., 105, 1-13.

Briggs, G.A. 1975. Plume predictions, Lectures on air pollution and environmental impact analyses. American Meteorological Society, Boston, Mass, 59-105.

Bureau of Meteorology 1969. The climate of Perth Western Australia. Capital City Series, Commonwealth of Australia, Department of the Interior.

Department of Conservation and Environment 1978a. Kwinana Air Modelling Study, Tracer experiment 1. Tech. Report KAMS-03, Department of Conservation and Environment, Western Australia.

Department of Conservation and Environment 1978b. Kwinana Air Modelling Study, Intensive episode study workshop. Tech. Report KAMS-04, Department of Conservation and Environment, Western Australia.

Department of Conservation and Environment 1980a. Kwinana Air Modelling Study, Tracer experiment 2. Tech. Report KAMS-05, Department of Conservation and Environment, Western Australia.

Department of Conservation and Environment 1980b. Kwinana Air Modelling Study, Intensive episode study 2 workshop. Tech. Report KAMS-06, Department of Conservation and Environment, Western Australia.

Department of the Environment, Scottish Development Department, Welsh Office 1956. Chimney Heights, Third edition of the 1956 Clean Air Memorandum. Her Majesty's Stationary Office, London.

Deardorff, J.W. 1972. Numerical investigation of neutral and unstable planetary boundary layers. J. Atmos. Sci., 29, 91-115.

Draxler, R.R. 1976. Determination of atmospheric diffusion parameters. Atmos. Environ. 10, 99-105.

Environment Protection Authority of Victoria 1979. Draft State environment protection policy for the air environment of Victoria and explanatory document. Environment Protection Authority of Victoria.

Environmental Protection Authority of Western Australia 1974. Coogee Air Pollution Study. Environmental Protection Authority of Western Australia.

Feilman Planning Consultants Pty. Ltd. 1978. Cockburn Sound recreation survey: A report to the Cockburn Sound study group. Department of Conservation and Environment, Western Australia.

Garratt, J.R. 1978. Transfer characteristics for a heterogeneous surface of large aerodynamic roughness. Quart. J. R. Met. Soc., 104, 491-502.

Gilpin, A. 1978. Air pollution. University of Queensland Press.

Glossop, L.G. and Hamilton, B.H. 1977. Tracer methodology II. Tech. Report KAMS-01, Department of Conservation and Environment, Western Australia.

Larsen, R.I. 1971. A mathematical model for relating air quality measurements to air quality standards. Office of Air Programs, Environmental Protection Agency, Research Triangle Park, North Carolina.

Lyons, W. and Cole, H. 1973. Fumigation and plume trapping on the shores of Lake Michigan during stable onshore flow. J. Appl. Met., 12, 494-510.

Manins, P.C. 1979. Partial penetration of an elevated inversion layer by chimney plumes. Atmos. Environ., 13, 733-741.

Martin, D.J. and Rosher, J.E. 1982. Kwinana Air Modelling Study emissions inventory. Tech. Report KAMS-19, Department of Conservation and Environment, Western Australia.

MRPA 1970. The corridor plan for Perth. The Metropolitan Region Planning Authority, Western Australia.

MRPA 1980. A planning strategy for the South-West Corridor. The Metropolitan Region Planning Authority, Western Australia.

National Health and Medical Research Council 1981. Report of the ninety-second session.

Office of the Federal Register 1977. Code of Federal Regulations, 40, Protection of Environment. Parts 50-59. US Government Printing Office, Washington.

Panofsky, H.A., Tennekes, H., Lenschow, D.H. and Wyngaard, J.C. 1977. The characteristics of turbulent components in the surface layer under convective conditions. Bound.-Layer Met., 11, 355-361.

Paulson, C.A. 1970. The mathematical representation of wind speed and temperature profiles in the unstable layer. J. Appl. Met., 9, 857-861.

Pasquill, F. 1971. Atmospheric dispersion of air pollution. Quart. J. Roy. Met. Soc., 97, 369-395.

Pasquill, F. 1974. Atmospheric diffusion. 2nd Edition. John Wiley and Sons, London.

Pasquill, F. 1976. Atmospheric dispersion parameters in Gaussian plume modelling, Part II. Possible requirements for change in the Turner Workbook values. Office of Air Programs, Environmental Protection Agency, Research Triangle Park, North Carolina.

Physik, W.L. 1976. A numerical model of the sea breeze phenomenon over a lake or gulf. J. Atmos. Sci., 33, 2107-2135.

Rayner, K.N. 1974. Turbulent bouyant jet theory with applications to the analysis of smoke plume behaviour. Honours thesis, Faculty of Engineering, University of Western Australia.

Rayner, K.N. 1981a. Atmospheric surface layer stability modelling. Tech. Report KAMS-15, Department of Conservation and Environment, Western Australia.

Rayner, K.N. 1981b. Modelling the atmospheric mixing depth. Tech. Report KAMS-16. Department of Conservation and Environment, Western Australia.

Rayner, K.N. and Rosher, J.E. 1981. Field study of a radiation inversion. Tech. Report KAMS-13, Department of Conservation and Environment, Western Australia.

Rayner, K.N. and Watson, I.D. 1981. Analysis of Perth Airport radiosonde data for use in the Kwinana Air Modelling Study. Tech. Report KAMS-14. Department of Conservation and Environment, Western Australia.

Rigden, D.T. 1977. Report on application of climatological data to zoning of industrial and residential areas. Public Health Department, Division of Occupational Health, Clean Air and Noise Abatement, Western Australia.

Robins, A.G. and Fackrell, J.E. 1979. Continuous plumes – their structure and prediction, Mathematical modelling of turbulent diffusion in the environment. Ed. C.J. Harris, Academic Press, London.

Rosher, J.E., Rayner, K.N. and Paparo, V.S. 1982. An efficient Gaussian dispersion model for use in coastal regions. Tech. Report KAMS-23, Department of Conservation and Environment, Western Australia.

Rosher, J.E., Rayner, K.N., Raich, V. and Martin, D.J. 1982. Kwinana Air Modelling Study data monitoring, processing, analysis and presentation. Tech. Report KAMS-21, Department of Conservation and Environment, Western Australia.

Rosher, J.E. and Martin, D.J. 1982. Comparison of two methods of sulphur dioxide measurements. Tech. Report KAMS-24, Department of Conservation and Environment, Western Australia.

Rye, P.J. 1980. A model for pollutant dispersal by the sea breeze; 1. Structure and validation of sea breeze model. Western Australian Institute of Technology, Department of Physics Internal Report PD 239/1980/AM 34. (Tech. Report KAMS-08, Department of Conservation and Environment, Western Australia.)

Rye, P.J. 1982. A finite-difference pollutant dispersal model for the Kwinana region. Tech. Report KAMS-22, Department of Conservation and Environment, Western Australia.

Slade, D.H. 1968. Meteorology and atomic energy. US Atomic Energy Commission, Div. Tech. Inf.

Smith, F.B. and Blackall, R.M. 1979. The application of field-experiment data to the parameterization of dispersion of plumes from ground-level and elevated sources, Mathematical modelling of turbulent diffusion in the environment. Ed. C.J. Harris, Academic Press, London.

Stern, A.C. 1977. Air pollution. Vol. V, Air quality management. Academic Press, London.

Swinbank, W.C. 1963. Longwave radiation from clear skies. Quart. J. R. Met. Soc., 89, 339-348.

Taylor, G.I. 1921. Diffusion by continuous movements. Proc. London Math. Soc., Ser. 2, 20, 196-212.

Tennekes, H. 1973. A model for the dynamics of the inversion above a convective boundary layer. J. Atmos. Sci., 30, 558-567.

Turner, D.B. 1970. Workbook of atmospheric dispersion estimates. Office of Air Programs, Environmental Protection Agency, Research Triangle Park, North Carolina.

USEPA 1977. Quality assurance handbook for air pollution measurement systems, Vol. II. Ambient air specific methods. Environmental Protection Agency, Research Triangle Park, North Carolina.

Venkatram, A. 1977. A model of internal boundary layer development. Bound.-Layer Met., 11, 419-437.

Venkatram, A. 1980. Estimating the Monin-Obukhov Length in the stable boundary layer for dispersion calculations. Bound.-Layer Met., 19, 481-485.

Victorian Government Gazette No. 63, 1981. State environment protection policy (The air environment). Government Printer, Melbourne.

Walker, D. and Allen, S. 1975. The Perth Sea Breeze Project, 1966: Data. Australian Government Publishing Service, Canberra.

Werner, M. and Stern, A.C. 1974. The world's air quality management standards. Vol. I: The air quality management standards of the World, including United States Federal Standards. US Environmental Protection Agency, Office of Research and Development, Washington, D.C.

West, P.W. and Gaeke, G.C. 1956. Fixation of sulphur dioxide as sulfiteomercurate III and subsequent colorimetric determination. Anal. Chem., 23, 1816.

Willis, G.E. and Deardorff, J.W. 1974. A laboratory model of the unstable planetary boundary layer. J. Atmos. Sci., 31, 1291-1307.

Willis, G.E. and Deardorff, J.W. 1976. A laboratory model of diffusion into the convective planetary boundary layer. Quart. J. Roy. Met. Soc., 102, 427-445.

Willis, G.E. and Deardorff, J.W. 1978. A laboratory study of dispersion from an elevated source within a modelled convective planetary boundary layer. Atmos. Environ. 12, 1305-1311.

Willis, G.E. and Deardorff, J.W. 1981. PBL similarity profiles determined from a level-2 turbulence closure model. Bound.-Layer Met., 17, 333-351.

World Health Organisation 1972. Air quality criteria and guides for urban air pollutants. WHO Tech. Report Series No. 506, WHO, Geneva.

World Health Organisation 1979. Sulphur oxides and suspended matter. Environmental Health Criteria 8. WHO, Geneva.

Zilitinkevich, S.S. 1972. On the determination of the height of the Ekman boundary layer. Bound.-Layer Met., 3, 141-145.