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DEVELOPMENT OF A METHODOLOGICAL FRAMEWORK AND SUPPORTING DATA BASE FOR AIR POLLUTION IMPACT SCOPING IN SOUTH AFRICAN INDUSTRIAL PLANNING

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ABSTRACT

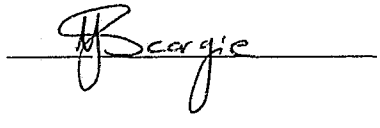
The principles of Integrated Environmental Management have been adopted by South Africa, and mandatory environmental scoping and impact assessments recently introduced. Air pollution scoping studies have, however, been hindered by the absence of objective scoping criteria and a readily accessible atmospheric dispersion climatology data base. The purpose of this research was to develop a conceptual methodological framework within which industrial planners may assess whether proposed developments will impact significantly on the air quality of the receiving environment. The primary function of the conceptual framework is the identification of pertinent data, and the integration of such data into the decision making process.

The study comprises the development of several data and model bases including: an industrial data and model base to facilitate the inventory of emissions from proposed iron and steel industries; an ambient air quality data and model base able to characterise the existing air quality at the proposed site; an atmospheric dispersion climatology data and model base to parameterise and reconcile the macro- and meso-scale ventilation potentials of the site; and an environmental risk identification data and model base to assess the sensitivity of the receiving environment. The methodological framework includes a procedure for the integration of the findings of the industrial, ambient air quality, atmospheric dispersion potential and risk identification model bases into the final decision making process.

The decision-making framework proposed is designed to ensure that informed, transparent and reproducible decisions are made with regard to the acceptability of the proposed development, or the need for further assessment. Such a framework could enhance communication, promote the review of project options early on in the planning phase, and assist in the resolution of disputes regarding the proposed process. In instances where no compromises are possible, or where the impact of the proposed development requires further study, the methodological framework can provide useful baseline information and establish the precedent for transparency and consistency in the subsequent air pollution impact assessments.

The practical applicability of the methodological framework has been evaluated, based on a review of the various assumptions made and of the potential model-output inaccuracies related to the unavailability of data. The utility of the framework could most effectively be enhanced through the expansion of the industrial data base to include further types of industries, and the extension of the dispersion climatology data and model base to allow for the parameterisation of meso-ventilation potentials at coastal sites.

I declare that this dissertation is my own, unaided work and that it has not been submitted previously as a dissertation or thesis for any degree at any other University.



25th day of June 1999

University of the Witwatersrand, 1999

To my mother

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PREFACE

South Africa adopted the principles and procedures of Integrated Environmental Management (IEM) in response to the growth in public awareness of the potential adverse environmental consequences of development. IEM aims to integrate environmental assessment into the planning and decision making process, so ensuring that the impact of development proposals on the biophysical and socio-economic environment is understood and adequately considered. In terms of the recently published *White Paper on Environmental Management Policy for South Africa* (15 May 1998) IEM is considered a prerequisite for government approval of all activities with potentially adverse environmental impacts.

In practice, the implementation of the IEM code of practice has been hindered by the non-mandatory nature of integrated environmental assessments, and the unavailability of comprehensive data bases and scientific procedures. Recently passed amendments (September 1997) to the Environmental Conservation Act (Act No. 73 of 1989) have rendered the environmental scoping and impact assessment mandatory for a wide range of activities. This development has served to highlight the remaining obstacle to effective IEM implementation, viz. the need for easily accessible data bases and scientific procedures to facilitate effective environmental scoping and impact assessments.

Air pollution studies in South Africa are particularly affected by methodological and data constraints. Attempts at identifying the potential effects of a proposed development on the ambient air quality is currently determined on the basis of a value judgement made by a 'competent party', or on the conclusions of an extensive environmental impact assessment (EIA) conducted by air pollution specialists. *Scoping studies*, aimed at determining the need for, and focus of, impact assessments represent an essential component of IEM and the new EIA regulations. The use of impact scoping in South African air pollution studies has been restricted by the absence of objective scoping criteria and a readily accessible dispersion climatology data base. There is a clear need for a methodological framework which would facilitate screening and scoping studies within the field of air pollution. The generation of various data bases to provide the information required by such a framework would offset the need for extensive data collection and collation during the decision making process.

The aim of this study is the development of a *conceptual methodological framework*, within which industrial planners may assess whether proposed developments will impact significantly on the air quality of the receiving environment. The primary functions of the conceptual framework are the identification of pertinent data, and the integration of such data into the decision making process.

The methodological framework is designed to achieve the following objectives, applicable to the proposed industry and location:

- Development of an emissions inventory;
- Assessment of emissions against emission limits promulgated for the industry;
- Evaluation of available abatement and mitigation measures;
- Review of the legislative context within which the industry will operate;
- Parameterisation of the atmospheric dispersion potential of the proposed site;
- Collection and collation of relevant site-specific environmental information, including existing ambient air pollution concentrations and receiving environment sensitivities; and
- Development of a decision making framework to ascertain the need for an in depth impact assessment.

The approach adopted for the establishment of the methodological framework entails the generation of a series of data bases, model bases and user interfaces. The various data bases would provide the bulk of information required for application of the methodological framework, so minimising the need for data collection by the decision maker. Based on calculations, coefficients and computational procedures contained within the various data bases, and on information supplied by the user, the model bases are able to facilitate the following functions: development of an emission inventory for the proposed industry, evaluation of existing ambient pollution concentrations and atmospheric dispersion potentials at the proposed site, assessment of the sensitivity of the receiving atmospheric and biophysical environment and finally, characterisation of the total impact of the proposed plant on its receiving environment and evaluation of whether further, more detailed impact studies are necessary. The user interface structures data acquisition from the user regarding the proposed industry and the receiving environment, and facilitates interaction between the user and the data base.

The current dissertation, which serves to document the formation and final configuration of the data base, the model base, and the user interface, comprises nine chapters. An outline of each chapter is given below.

Chapter 1 - Introduction

The rationale for undertaking the study is presented in this chapter. The aims, objectives, procedure and scope are outlined and a brief overview is given of each of the data- and model-bases, viz. the industrial, ambient air quality, atmospheric dispersion potential and environmental risk identification data- and model-bases.

Chapter 2 - Data Requirements and Literature Review

Developments and debates within the fields of industrial engineering, air pollution meteorology, atmospheric chemistry, environmental toxicology, risk assessment, and air pollution legislation are pertinent to the establishment of the data and model bases. A review of the literature and data relevant to develop the data and model bases, user interfaces and final decision making framework is presented in this chapter. Topics which are reviewed include: industrial processes and emissions, macro-scale atmospheric systems affecting South Africa, meso-scale circulation systems, and environmental risk assessment.

Chapter 3 - Air Pollution Legislation

A synopsis of the current state of, and anticipated future developments in, air pollution control in South Africa is presented. The chapter includes: an assessment of the nature of air quality management systems in various developed countries, the identification of international trends in air quality management, and an account of current debates regarding the functional and organisational structure of future air quality management in South Africa.

Chapter 4 - Industrial Data and Model Base

A detailed industrial data base and a model base was compiled for the integrated iron and steel industry so as to demonstrate the utility of the conceptual framework. In this chapter aims and objectives for the creation of the data base, model base and user interface are discussed, and the structure of each component outlined. The actual data base, user interface and model base are presented in Appendix A which is contained in electronic format on the accompanying computer disk. An example is, however, provided to illustrate the structure of the data base and user interface, and the application of the model base.

Chapter 5 - Ambient Air Quality Data and Model Base

Air quality indices for approximately 160 sites across South Africa are presented in the data base. Indices are based on the relationship between monitored levels of pollutants (including sulphur dioxide and total suspended particulates) and local and international air quality guidelines and standards. The procedure developed for the calculation of air quality indices is described in the air quality data base.

Chapter 6 - Dispersion Climatology Data and Model Base

A macro- and meso-ventilation data base and model base are compiled, so as to facilitate the qualitative estimation of site-specific dispersion potentials. The chapter includes a detailed data and literature review, the generation of missing data where possible, and the estimation of macro- and meso-scale ventilation potentials for inclusion in the dispersion climatology data base. The user interface is structured so as to acquire the site specific information needed for the estimation of the dispersion potential. The model base

incorporates ventilation coefficients which are designed to determine site specific meso-ventilation potentials, and to integrate such meso-ventilation potentials with the macro-ventilation potentials contained within the data base.

Chapter 7 - Environmental Risk Identification Data and Model Base
The environmental risk assessment data base contains the "list of environments" identified by the DEAT as necessitating a full-scale environmental impact assessment, a general list of environmental components (e.g. human health and welfare, fauna, flora and the built environment) which may potentially be sensitive to particular pollutants, and information about the human health implications of criteria pollutants. The user interface, outlined in section 7.5 facilitates the determination of the proximity of sensitive environmental components to the proposed site. The model base serves to classify the receiving environment according to its sensitivity to emissions from the proposed development.

Chapter 8 - Environmental Decision Making Framework
The theoretical and contextual basis for the creation of the decision making framework is discussed. The model base incorporates several criteria which determine the manner in which the findings of earlier stages are integrated into the final decision making analysis, so as to evaluate the suitability of the proposed site and the need for further assessments.

Chapter 9 - Recommendations and Conclusions
The practical applicability of the methodological framework is evaluated, based on the review of the assumptions of the framework, and the impacts of model-output inaccuracies arising from the unavailability or insufficiency of data on the decision making capacity of the framework. Possible improvements to the model base and extensions of the data base which may be made to improve the proposed scoping framework are also discussed in this chapter.

Due to the need to include extensive data in the dissertation several appendices are included. The content of each of the appendices are as follows:

Appendix A –Iron and steel data base, model base and user interface.
Appendix B - Tables of air quality indices for various sites within South Africa.
Appendix C - Results of three year air mass-based seasonal synoptic climatology.

Appendix A is included in electronic format on the accompanying computer disk.

LIST OF ABBREVIATIONS

BACT	-	Best Available Control Technology
BPM	-	Best Practicable Means
BPEO	-	Best Practicable Environmental Option
CAPCO	-	Chief Air Pollution Control Officer
DEAT	-	Department of Environmental Affairs and Tourism, South Africa
EAL	-	Environmental Assessment Levels
EC	-	European Council
ECMWF	-	European Centre for Medium Range Weather Forecasting
EIA	-	Environmental Impact Assessment
EIR	-	Environmental Impact Report
EPA	-	United States Environmental Protection Agency
EQS	-	Environmental Quality Standards
EU	-	European Union
HMIP	-	Her Majesty's Inspectorate of Pollution
HP	-	High Pressure system
IDZ	-	Industrial Development Zone
IEM	-	Integrated Environmental Management
IPC	-	Integrated Pollution Control
NAAQS	-	National Ambient Air Quality Standards
PCA	-	Principle Component Analysis
PM2.5	-	Particulate Matter with an aerodynamic diameter of less than 2.5 μm
PM10	-	Particulate Matter with an aerodynamic diameter of less than 10 μm
PSD	-	Prevention of Significant Decline
RA	-	Ridging Anticyclone
RDP	-	Reconstruction and Development Programme
SAWB	-	South African Weather Bureau
SIP	-	State Implementation Plan
TSP	-	Total Suspended Particulates
VAWS	-	Vertically Averaged Wind Speeds
WHO	-	World Health Organisation

TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION 1-1

1.1 BACKGROUND 1-1
1.2 PROBLEM STATEMENT 1-3
1.3 AIMS AND OBJECTIVES OF THE CURRENT STUDY 1-4
1.4 PROCEDURE FOR ESTABLISHMENT OF METHODOLOGICAL FRAMEWORK 1-5
1.5 SCOPE OF THE STUDY 1-10

CHAPTER 2 - DATA REQUIREMENTS AND LITERATURE REVIEW 2-1

2.1 INTRODUCTION 2-1
2.2 INDUSTRIAL PROCESSES AND EMISSIONS 2-1
2.3 MACRO-SCALE ATMOSPHERIC SYSTEMS AFFECTING SOUTH AFRICA 2-9
2.4 MESO-SCALE ATMOSPHERIC SYSTEMS 2-19
2.5 AIR POLLUTION METEOROLOGY AND ATMOSPHERIC DISPERSION CLIMATOLOGY .. 2-30
2.6 ENVIRONMENTAL RISK ASSESSMENT 2-32

CHAPTER 3 - AIR POLLUTION LEGISLATION 3-1

3.1 INTRODUCTION 3-1
3.2 EXISTING AIR POLLUTION LEGISLATION AND CONTROL IN SOUTH AFRICA 3-1
3.3 PROBLEMS WITH EXISTING AIR POLLUTION CONTROL IN SOUTH AFRICA 3-3
3.4 INTERNATIONAL TRENDS IN AIR QUALITY MANAGEMENT 3-4
3.5 CURRENT LOCAL THINKING ON ENVIRONMENTAL ISSUES 3-10
3.6 FUTURE AIR QUALITY MANAGEMENT IN SOUTH AFRICA 3-12
3.7 RECOMMENDATIONS AND CONCLUSIONS 3-23

CHAPTER 4 - INDUSTRIAL DATA AND MODEL BASE 4-1

4.1 INTRODUCTION 4-1
4.2 AIMS AND OBJECTIVES OF THE CURRENT SECTION 4-2
4.3 STRUCTURE OF IRON AND STEEL DATA BASE, MODEL BASE AND USER INTERFACE 4-3
4.4 EXAMPLE 1 OF INDUSTRIAL MODEL APPLICATION – SINTER PRODUCTION 4-7
4.5 INDUSTRIAL MODEL OUTPUTS 4-12
4.6 CONCLUSION 4-13

CHAPTER 5 - AMBIENT AIR QUALITY DATA AND MODEL BASE 5-1

5.1 INTRODUCTION 5-1
5.2 AIMS AND OBJECTIVES OF THE CURRENT STUDY 5-1
5.3 AMBIENT AIR QUALITY DATA BASE 5-2
5.4 USER INTERFACE AND MODEL BASE FOR AIR QUALITY ASSESSMENT 5-11
5.5 CONCLUSION 5-13

CHAPTER 6 - DISPERSION CLIMATOLOGY DATA AND MODEL BASE 6-1

6.1 INTRODUCTION 6-1
6.2 ESTABLISHMENT OF AN AUTOMATED AIR MASS-BASED SYNOPTIC CLIMATOLOGY 6-2
6.3 DISPERSION CLIMATOLOGY DATA BASE 6-19
6.4 USER INTERFACE – ESTIMATION OF SITE-SPECIFIC DISPERSION POTENTIAL 6-33
6.5 MODEL BASE – ESTIMATION OF DISPERSION POTENTIAL 6-36
6.6 CONCLUSION 6-41

CHAPTER 7 - ENVIRONMENTAL RISK IDENTIFICATION 7-1

7.1 INTRODUCTION 7-1
7.2 AIMS AND OBJECTIVES OF THE CURRENT SECTION 7-1
7.3 STRUCTURE OF RISK IDENTIFICATION DATA BASE AND MODEL BASE 7-2
7.4 RISK IDENTIFICATION DATA BASE 7-3
7.5 USER INTERFACE – RISK IDENTIFICATION 7-11
7.6 MODEL BASE – CLASSIFICATION OF ENVIRONMENTAL SENSITIVITY 7-12
7.7 CONCLUSION 7-13

CHAPTER 8 - DECISION MAKING FRAMEWORK FOR AIR POLLUTION IMPACT SCOPING 8-1

8.1 INTRODUCTION 8-1
8.2 DECISION MAKING FRAMEWORK MODEL BASE 8-2

CHAPTER 9 - RECOMMENDATIONS AND CONCLUSIONS 9-1

9.1 INTRODUCTION 9-1
9.2 STRUCTURE OF METHODOLOGICAL FRAMEWORK 9-1
9.3 ACCEPTABILITY OF PREDICTED EMISSIONS FROM PROPOSED DEVELOPMENT 9-2
9.4 INCREMENTAL IMPACTS ON AMBIENT AIR QUALITY 9-3
9.5 CHARACTERISATION OF ATMOSPHERIC DISPERSION POTENTIALS 9-5
9.6 SENSITIVITY OF RECEIVING ENVIRONMENTS 9-8
9.7 STRENGTHS AND LIMITATIONS OF PROPOSED DECISION MAKING FRAMEWORK 9-9

APPENDIX A A-1

APPENDIX B B-1

APPENDIX C C-1

REFERENCES R-1

LIST OF TABLES

Table 2.1 Frequency of occurrence (percentage) of synoptic systems and weather pertubations (after Preston-Whyte and Tyson, 1988). 2-12
Table 5.1 DEAT guideline values for ground-level concentrations of air pollutants. 5-3
Table 5.2 Secondary National Air Quality Standards of the US EPA 5-4
Table 5.3 Primary National Air Quality Standards of the US EPA 5-4
Table 5.4 EU Mandatory Environmental Quality Standards for Air Pollutants 5-5
Table 5.5 Air quality guidelines used in calculation of AQI-I 5-7
Table 5.6 Air quality guidelines and standards used in calculation of AQI-II 5-7
Table 5.7 Air quality guidelines and standards used in calculation of the AQI-III 5-7
Table 5.8 Criteria for classification of sampling sites into Air Quality Classes, and definition of classes 5-8
Table 5.9 Air quality classes(a) for each pollutant over each averaging period for sampling sites within Mpumalanga. Letters A to G represent the pollutant and averaging period and are defined below the table. Classes generated for all three air quality indices (AQI) are given 5-10
Table 5.10 Final air quality indices(a) for each of the sampling sites within Mpumalanga 5-11
Table 6.1 Criteria for classification of non-precipitation synoptic types into stagnating (S), ventilating (V) and neutral (N) systems, based on vertically averaged wind speed (VAWS) and mixing depth 6-17
Table 6.2 Classification of Winter Synoptic Types for Central Plateau into stagnating (S), ventilating (V) and neutral (N) systems. 6-18
Table 6.3 Frequency of Occurrence and Persistence of Winter Synoptic Types over the Central Plateau 6-18
Table 6.4 Classification of the dispersion potential of within-valley sources 6-40
Table 6.5 Dispersion classes based on meso- and macro-scale ventilation potentials 6-41
Table 7.1 Environmental components sensitive to presence of criteria pollutants 7-5
Table 7.2 Environmental sensitivity to synergistic impacts of criteria pollutants 7-6
Table 7.3 Symptoms related to various concentrations of carbon monoxide 7-9
Table 7.4 Symptoms related to various dosages of NO_2 7-9
Table 7.5 Symptoms related to various concentrations of PM10 7-9
Table 7.6 Symptoms related to various dosages of SO_2 7-10
Table 7.7 Symptoms resulting from exposure to concentrations of ozone 7-10
Table 7.8 Symptoms related to human blood lead levels 7-11
Table 7.9 Symptoms related to dosages of total suspended particulates (TSP) 7-11

LIST OF FIGURES

Figure 1.1 Analytical stages of the proposed conceptual framework. 1-4
Figure 1.2 Structure of the industrial data base, model base and user interface. 1-7
Figure 1.3 Structure of ambient air quality data base, model base and user interface. 1-8
Figure 1.4 Structure of dispersion potential data base, model base and user interface. 1-9
Figure 1.5 Structure of environmental risk data base, model base and user interface. 1-10
Figure 5.1 Outline of interaction between model base and user interface in characterisation of air quality for proposed site. 5-12
Figure 6.1 Deviation of average surface pressure for each cluster identified for Irene from the winter-time mean surface pressure for this station (1989-1992). 6-12
Figure 6.2 Deviation of average temperature (at various pressure levels) for each cluster identified for Irene from the winter-time mean temperature for this station (1989-1992). 6-12
Figure 6.3 Deviation of average dew point temperature (at various pressure levels) for each cluster identified for Irene from the winter mean dew point temperature. 6-13
Figure 6.4 Average zonal wind component (at various pressure levels) for each of the clusters identified at Irene (1989-1992). 6-13
Figure 6.5 Average meridional wind component (at various pressure levels) for each of the clusters identified at Irene (1989-1992). 6-14
Figure 6.6 Winter-time ventilation potentials (VPs), expressed as a ratio of the percentage of episode days to the percentage of days on which ventilating systems predominated. An episode is given as a period in which stagnating systems persisted for four or more days. Where VPs $\geq$ 2.0 represent poor dispersion conditions; VPs between 1.0 and 2.0 median dispersion potentials; and VPs $\leq$ 1.0 are indicative of good dispersion.. 6-20
Figure 6.7 Summer-time ventilation potentials (VPs), expressed as a ratio of the percentage of episode days to the percentage of days on which ventilating systems predominated. An episode is defined as a period in which stagnating systems persisted for four or more days. Where VPs $\geq$ 2.0 represent poor dispersion conditions; VPs between 1.0 and 2.0 median dispersion potentials; and VPs $\leq$ 1.0 are indicative of good dispersion. 6-21
Figure 6.8 Designation of meso-ventilation potentials (VPs) based on: hill slope angle (HS) (level 1), source location with regard to horizontal recirculation zones (level 2), and source height with regard to inner layer depth (level 3). 6-37
Figure 8.1 Outline of proposed decision making framework for air pollution scoping studies. 6-21

CHAPTER 1 - INTRODUCTION

1.1 Background

The twentieth century has been beset by growing conflicts between the environment and development (Porritt, 1990; Gower, 1992; Palmer, 1992; Desjardins, 1993). In South Africa, as in other developing nations, escalating concentrations of dangerous and unaesthetic pollutants attest to rapid industrial expansion and urbanisation (Huntley *et al.*, 1989; Cock and Koch, 1991; Fuggle and Rabie, 1992).

During the 1980s, growth in public awareness of the adverse environmental consequences of development demonstrated a need for the incorporation of environmental considerations into development strategies. The South African Government responded to the heightened public concern by adopting the principles and procedures of *Integrated Environmental Management (IEM)*. Formalised by the Department of Environmental Affairs (currently named the Department of Environmental Affairs and Tourism, DEAT) IEM aims to integrate environmental assessment into the planning and decision making process (Council for the Environment, 1989a, 1989b, 1989c; Department of Environmental Affairs, 1992a). Informed decision making, accountability for decisions taken, an interdisciplinary approach to problems, and a broad understanding of the term 'environment' form the foundation of IEM. IEM is thus theoretically designed to ensure that the impact of development proposals on the biophysical and socio-economic environment is understood and adequately considered in the planning process (Russell, 1986; Department of Environmental Affairs, 1992a; Fuggle and Rabie, 1992).

The continued commitment of the DEAT to the principles of IEM is evident in the recently published *White Paper on Environmental Management Policy for South Africa* (15 May 1998). Cradle to grave responsibility, full cost accounting, open information, custodianship, environmental justice, polluter pays, and a precautionary approach represent the main principles underpinning the new environmental legislation (DEAT, 1998a). In terms of the new legislation, IEM is considered a prerequisite for government approval of all activities with potentially adverse environmental impacts.

Despite the continued commitment to, and obvious benefits of integrated environmental management, the effective implementation of IEM has to date been undermined by two main factors:

- non-mandatory nature of integrated environmental assessment in the planning process (Quinlan, 1993); and
- unavailability of comprehensive data bases and scientific procedures.

Attempts during the 1990s to render integrated environmental impact assessment mandatory, under the Environmental Conservation Act (Act No. 73 of 1989), have resulted in the removal of the first obstacle to effective IEM implementation. The Act makes provision for the Minister of Environmental Affairs and Tourism to identify activities which will probably have a detrimental effect on the environment (section 21 of the Act). Directly coupled with section 21 is the provision in section 26 of the Act to make regulations for environmental impact reports (EIRs) with regard to any activity identified in terms of section 21. The DEAT has recently drafted regulations (Amendments No. R. 1182 and No. R. 1183 of 5 September 1997) to implement the Act's provisions, so enforcing the compilation of EIRs for various activities (DEAT 1997a, 1997b). Such activities include power generation and supply facilities, transportation routes and structures, nuclear installations, harbours, sewage treatment works, waste disposal plants, and all scheduled processes (as listed in the Second Schedule to the Atmospheric Pollution Prevention Act, Act No. 45 of 1965).

Recent international and local trends towards new systems of air quality management, based on the principle of integrated pollution control, have emphasised the importance of mandatory integrated environmental management within the planning process (O'Riordan and Weale, 1989; Allott, 1994; Department of the Environment, 1994a, 1994b, 1995; HMIP, 1994; Marjanovic, 1995). *Integrated pollution control (IPC)* is a system of cross-media pollution control which seeks to prevent or minimise environmental degradation due to the release of substances into any environmental medium.

IPC is closely related to the concept of 'best practicable environmental option' (BPEO). BPEO represents the option which, in the context of releases from prescribed processes, provides the most benefit or least damage to the environment as a whole, at an acceptable cost. The introduction of IPC thus reinforced the shift from pollution control based on source-based controls, to air quality management using an effects-based approach. Effects-based controls include multiple levels of ambient air quality standards which define satisfactory air quality and identify the impact of various levels of a contaminant. Although the effects-based approach does not dispense with source-based controls, it ensures that environmental policy is focused on objectives rather than means, consequently providing an effective frame of reference by which source-based controls may be measured and judged (Department of Environment, 1990, 1994a, 1995; Allott, 1994; HMIP, 1994).

In South Africa, new approaches to air pollution control, amenable to integrated pollution control, have been investigated (Department of Environmental Affairs and Tourism, 1995a, 1995b; L & W Environmental, 1995; Marjanovic, 1995). References to such approaches are made within the *Draft White Paper on Integrated Pollution Control and Waste Management,* published in August 1998 (DEAT, 1998b). The guiding principles of IPC are anticipated to result in a profound shift from air pollution control based solely on source-

based controls to an air quality management approach incorporating effects-based controls (Air Work Team, 1995; L & W Environmental, 1995). The adoption of an effects-based approach to air quality management would render the effective compilation of environmental impact assessments for proposed industries imperative, so as to ensure the maintenance of ambient standards.

The introduction of *mandatory environmental impact assessments*, and the growing importance of such assessments in terms of recent and anticipated future environmental legislation, have served to highlight the second obstacle to effective IEM implementation. The need for easily accessible data bases and scientific procedures to facilitate the mandatory environmental scoping and impact assessments is clearly evident.

1.2 Problem Statement

Air pollution studies in South Africa are particularly affected by methodological and data constraints. Attempts at identifying the potential effects of a proposed development on the ambient air quality are currently determined on the basis of a value judgement made by a 'competent party', or on the conclusions of an extensive environmental impact assessment conducted by air pollution specialists (Department of Environmental Affairs, 1992a). The course adopted depends on the nature and scale of the proposed development and on the environment affected.

To date, both value judgements and impact assessments have demonstrated an inability to respond to the needs of decision makers. Value judgements are difficult to defend, their validity being largely dependent on the personal experience of the consultant and the quality of the information available (Holcomb Research Institute, 1976; Bowonder, 1987). Full-scale impact assessments are considered more valuable as planning and decision making tools since the conclusions of such assessment are more likely to withstand the rigours of litigation in disputes over development projects (Duinker, 1986; Robinson, 1989). The time-, finance-, expertise-, and data-intensive nature of impact assessments, however, undermine their practical usefulness due to the temporal, financial and institutional constraints placed on decision makers. In addition to which, the lack of focus of many impact assessments results in voluminous and exhaustive conclusions which frequently bear little relationship to the information needs of the decision makers (Wathern, 1988; Kennedy and Ross, 1992). Current air pollution studies conducted in South Africa are thus seldom conducive to informed decision making, a fundamental principle underpinning IEM.

Initial assessment and *scoping studies*, aimed at determining the need for, and focus of, impact assessments represents an essential component of IEM, IPC and the new regulations regarding EIAs (Department of Environmental Affairs, 1992a, 1992b; Kennedy and Ross, 1992; HMIP, 1994; Marjanovic, 1995). According to Amendment No. R. 1183 to the

Environmental Conservation Act, scoping reports need to include a brief description of how the environment may be affected, and a synopsis of all environmental issues identified (DEAT, 1997b).

The use of impact scoping in South African air pollution studies has been restricted by the absence of objective scoping criteria and a readily accessible dispersion climatology data base. What is needed is a methodological framework which would facilitate screening and scoping studies within the field of air pollution. The generation of various data bases to provide the information required by such a framework would offset the need for extensive data collection and collation during the decision making process. The conceptual framework and supporting data bases should be contained within a PC-based software-package. Such a software-package would comprise a data base, a model base, and an interface to permit the user to access the models and data and to perform 'scenario analysis' as an aid to decision making.

1.3 Aims and Objectives of the Current Study

The development of a *conceptual methodological framework*, within which industrial planners may assess whether proposed developments will impact significantly on the air quality of the receiving environment, forms the focus of the current research. The conceptual framework incorporates five analytical stages (Figure 1.1).

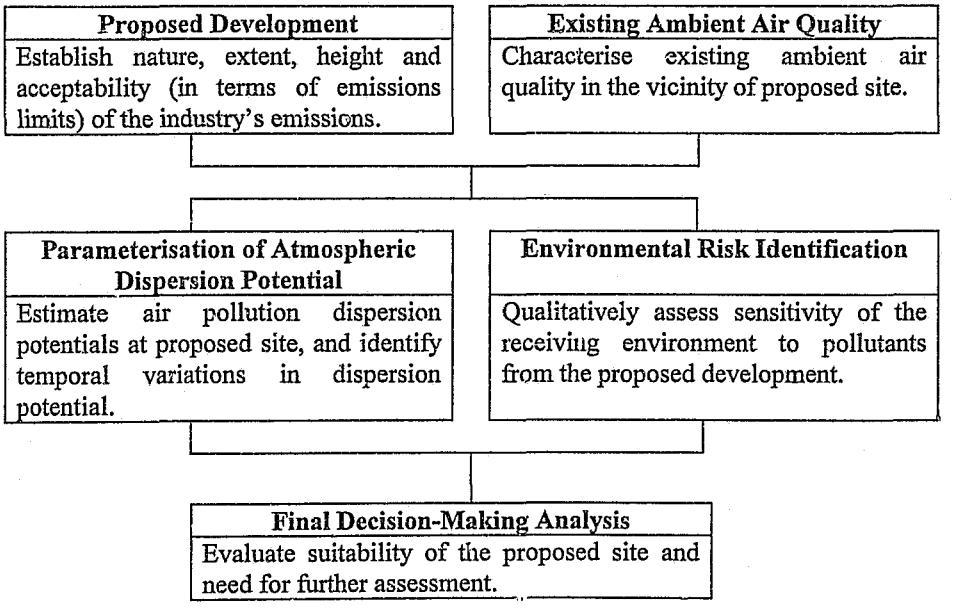


Figure 1.1 Analytical stages of the proposed conceptual framework.

Stage 1 requires establishing the character and magnitude of emissions from the proposed development; Stage 2, the analysis of existing ambient air pollutant concentrations at the planned site. In Stages 3 and 4, the air pollution dispersion potential at the location, and the sensitivity of the receiving environment to the estimated emissions are established. The final stage provides an integrated structure for informed decision making regarding the necessity of conducting an intensive air pollution impact assessment for the development, based on findings of the initial four stages.

The methodological framework for air pollution scoping studies to be developed needs to achieve the following objectives, applicable to the proposed industry and location:

- Development of an emissions inventory to identify species, quantity and release height of atmospheric pollutants.
- Assessment of these emissions against emission limits promulgated by the Chief Air Pollution Control Officer (CAPCO).
- Evaluation of available abatement and mitigation measures.
- Review the legislative context within which the industry will operate, and evaluate the acceptability of the industry's impact in light of such legislation.
- Atmospheric dispersion potential assessment, including both the macro- and meso-ventilation characteristics.
- Collection and collation of relevant site-specific environmental information, including existing ambient air pollution concentrations and receiving environment sensitivities.
- Development of a decision making framework to ascertain the need for in depth evaluation. The framework would rank the influence of the various factors, listed above, affecting the environmental impacts.

The primary functions of the conceptual framework are the identification of pertinent data, and the integration of such data into the decision making process. The effective integration of the data into the decision making process would ensure concise resolutions despite the magnitude and complexity of the data employed.

1.4 Procedure for Establishment of Methodological Framework

The approach adopted for the establishment of a methodological framework entails the generation of a series of data bases, model bases and user interfaces (Figures 1.2 to 1.5). Once established, the various data bases would provide the bulk of information required for application of the methodological framework, so minimising the need for data collection by the decision maker. Information on existing national ambient air pollution concentration levels, industrial processes and emission factors for such processes, macro- and meso-

dispersion characteristics, and the effects of pollutants on various environmental components are included in the *data bases*. Use is made of the best available data in the generation of the data bases. In instances where data are unavailable or insufficient, the resultant implications for the decision making capacity of the framework are examined.

Based on calculations, coefficients and computational procedures contained within the various data bases, and on information supplied by the user, the *model bases* are able to fulfil a number of functions. Such functions include: development of an emission inventory for the proposed industry, evaluation of existing ambient pollution concentrations and atmospheric dispersion potentials at the proposed site, assessment of the sensitivity of the receiving atmospheric and biophysical environment, and finally characterisation of the total impact of the proposed plant on its receiving environment and evaluation of whether further, more detailed impact studies are necessary. The *user interface* structures data acquisition from the user regarding the proposed industry and the receiving environment, and facilitates interaction between the user and the data base.

The current dissertation will comprehensively document the formation and final configuration of the data base, the model base, and the user interface, hence elucidating the conceptual basis, assumptions, and limitations of the framework. Although the generation of an interactive software package is beyond the scope of the proposed research, the dissertation will be structured so as to direct the decision maker through the various analytical procedures of the framework. A brief description of the nature of the various model and data base components which constitute the methodological framework is given in the subsections below.

1.4.1 Industrial Data and Model Bases

The industrial model base identifies and quantifies industrial emissions through the application of appropriate emission factors issued by the United States Environmental Protection Agency (EPA). Data required for emission estimation are drawn from the detailed industrial data base and from information provided by the user on industrial processes, production rates, air pollution control measures, and emission limits (Figure 1.2). The anticipated magnitude of emissions is then compared to emission limits promulgated by the Chief Air Pollution Control Officer (CAPCO). Emission limits are not included in the data base and need to be provided by the user following consultation with CAPCO. Emission coefficients included in the industrial data base facilitate the comparison of the predicted releases with the emission limits. Emission limits are not set for all possible sources of emission. No emission limits are presently set for fugitive emissions arising from materials handling, dust entrainment from paved and unpaved roadways, and emissions from the aeolian or mechanical disturbance of open areas and stockpiles.

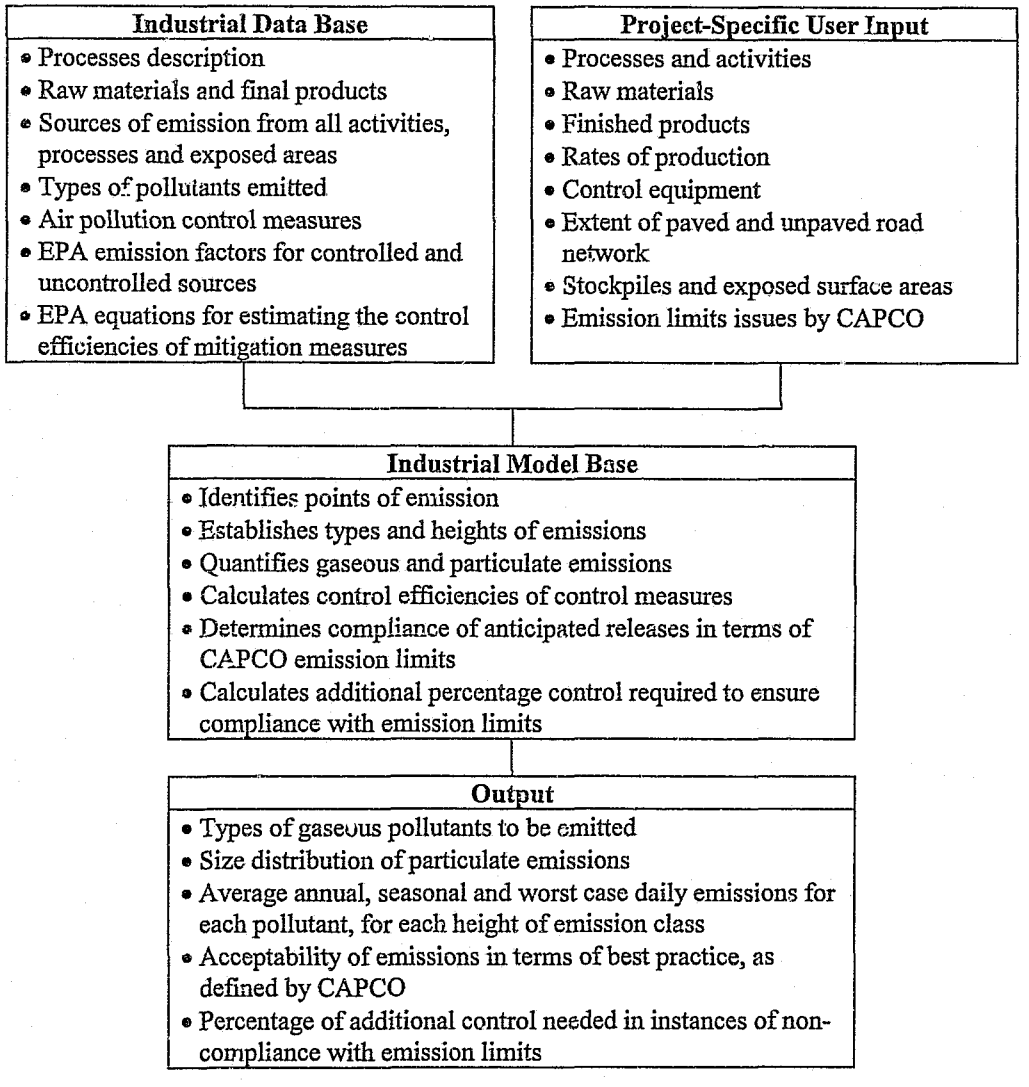


Figure 1.2 Structure of the industrial data base, model base and user interface.

1.4.2 Ambient Air Quality Data and Model Bases

Ambient concentrations of sulphur dioxide and smoke are currently monitored at a network of sites throughout South Africa. Data on regional ambient sulphur dioxide and smoke levels will be used in the current study to characterise the ambient air quality in the vicinity of the proposed site, through the calculation of air quality indices. Such air quality indices will be designed to reflect the relationship between existing levels of pollutants and relevant local and international air quality standards and guidelines (Figure 1.3).

The model base facilitates the identification of an appropriate air quality index for the proposed site, based on the user's definition of the nature of the area. In instances where no monitoring data are available in the data base, or where the user has access to more current data, the model base is designed to compute air quality indices based on monitored levels of air pollutants input by the user, through the application of the procedure contained in the air quality data base.

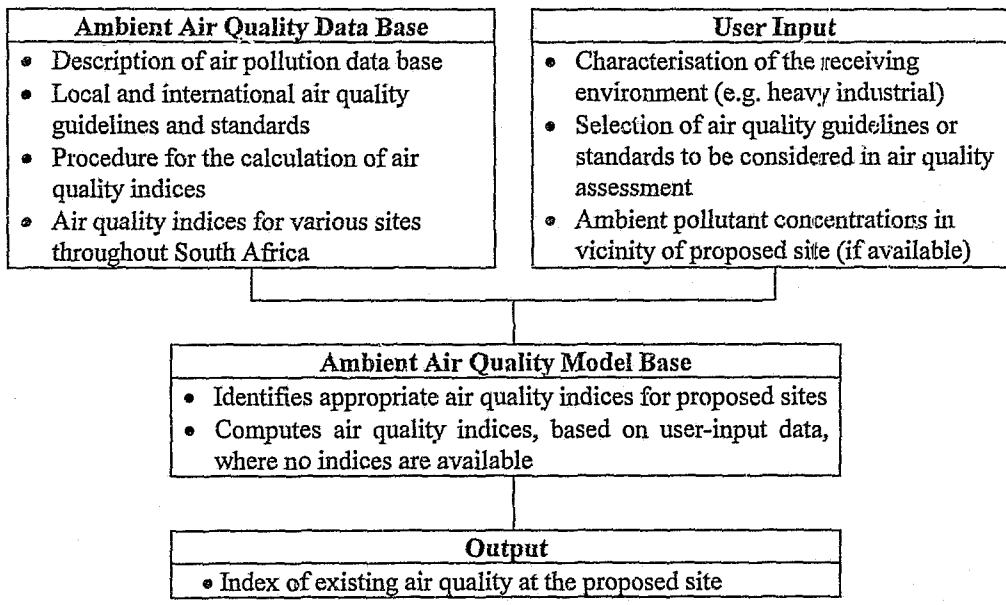


Figure 1.3 Structure of ambient air quality data base, model base and user interface.

1.4.3 Atmospheric Dispersion Potential Data and Model Bases

The atmospheric dispersion potential at a site is estimated based on ventilation coefficients which reconcile the macro- and meso-ventilation potentials of the site. The macro- and meso-ventilation potentials and ventilation coefficients are contained within the dispersion climatology data base. The manner in which such ventilation characteristics are reconciled will be determined on the basis of a limited number of parameters input by the user, viz. site location, height(s) of emission, and description of the relief. In instances where the industrial model base is used, the height(s) of emission output by the industrial model will be used as input for the computation of ventilation potentials (Figure 1.4).

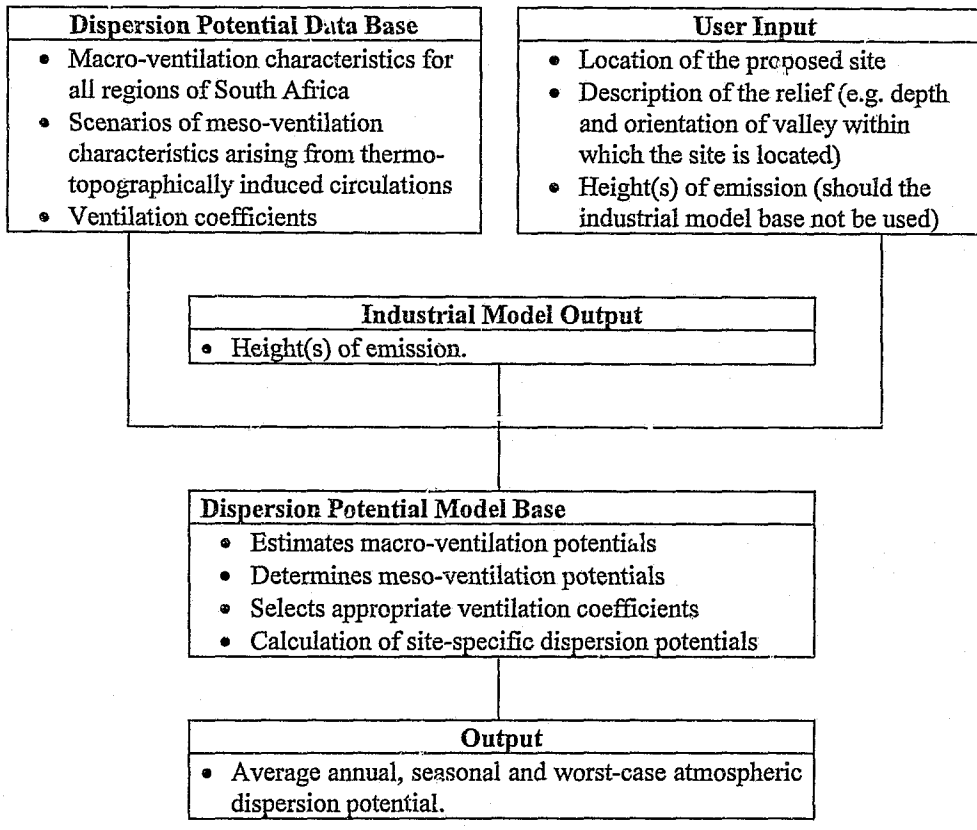


Figure 1.4 Structure of dispersion potential data base, model base and user interface.

1.4.4 Environmental Risk Identification Data and Model Bases

The environmental risk identification model draws on information provided by the user regarding the proximity of sensitive environmental components to the proposed site, and on industrial and dispersion potential model outputs, to classify the sensitivity of the receiving environment (Figure 1.5). Ecotoxicological and epidemiological data contained within the data base will be designed to assist the user in the identification of sensitive environmental components.

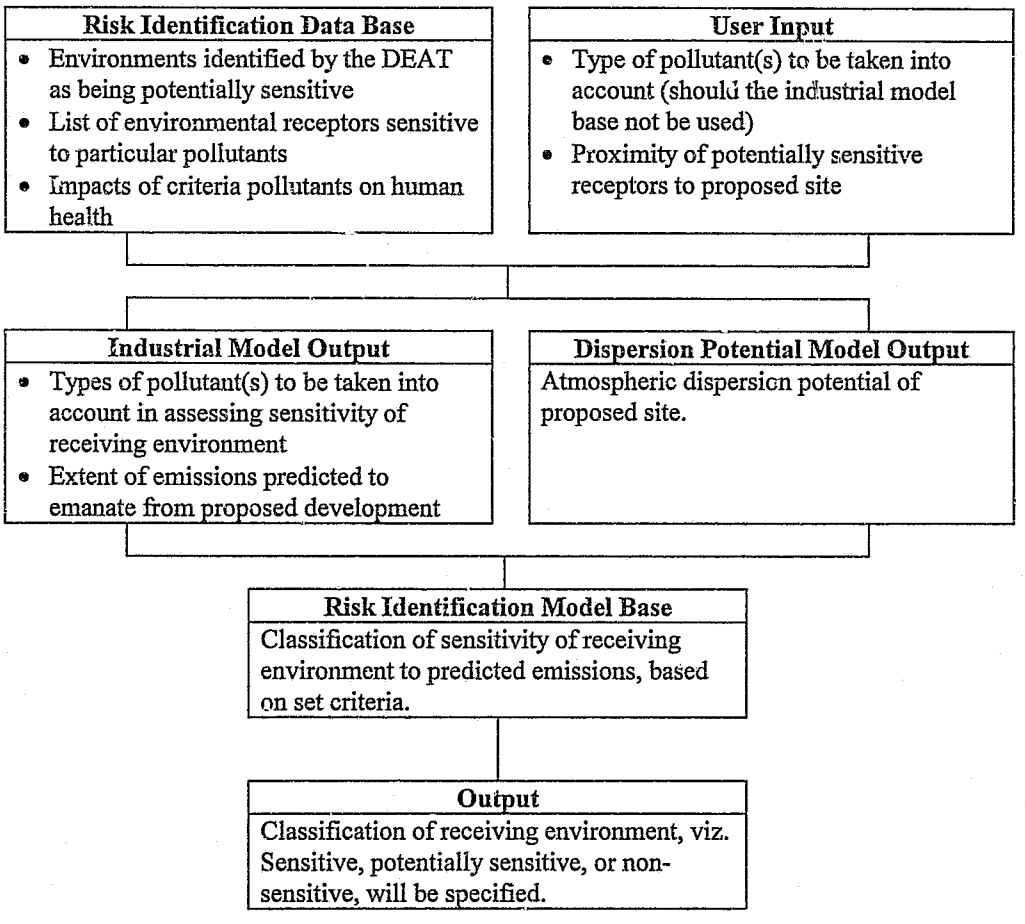


Figure 1.5 Structure of environmental risk data base, model base and user interface.

1.5 Scope of the Study

The computation of industrial emission rates within the proposed framework will require a detailed industrial data base. One type of industry has been selected for inclusion in the data base to demonstrate the utility of the framework, viz. the iron and steel industry. The processes carried out in iron and steel industries are included in the Second Schedule of the Atmospheric Pollution Prevention Act (45) of 1965. Scheduled processes are generally regarded as the cause of industrial pollution in South Africa. In 1994, 131 plants were recorded as operating scheduled iron and steel processes. Iron and steel industries are also referred to in the "List of Activities" cited in South African IEM documentation as the most likely threat to the environment (Department of Environmental Affairs, 1992a).

For the purpose of the current study only environmental components which are potentially sensitive to atmospheric concentrations of criteria pollutants will be indicated in the risk assessment data base (Chapter 7). Criteria pollutants include sulphur dioxide, nitrogen oxides, lead, ozone, and particulate matter. The risk assessment model base will incorporate neither dose-response analysis nor exposure assessment. The estimation of dose size and nature of the exposure would involve an unacceptable level of data collection and entry on the part of the user. The framework will encompass only the hazard assessment stage of Environmental Risk Assessment, thus providing a qualitative estimate of the adverse impact of a proposed industry's atmospheric emissions on the receiving environment. Dose-response information provided in the data base to facilitate such qualitative hazard assessment will be restricted to the potential impacts of criteria pollutants on human health.

The proposed dispersion climatology will be designed to provide a realistic qualitative description of the air pollution dispersion potential of a specific site. The dispersion climatology data base will contain information on the macro-ventilation characteristics of regions within South Africa and ventilation potentials of generalised meso-scale circulation systems. The construction of meso-scale generalisations necessitates a clear understanding of the factors within each type of environment (e.g. urban areas, land-sea interfaces, valleys) which govern the airflow near the ground and the thermal structure of the boundary layer. Due to the complexity of establishing such generalisations, meso-scale systems related to uneven terrain were selected for the development of the generalisations to be included in the data base. No generalisations will be formulated for surface temperature inversions, urban boundary layer modifications and circulations due to land-sea interfaces. Air pollution dispersion potentials for particular areas will be ascertained through the reconciliation of the macro- and meso-ventilation potentials of the proposed site.

Quantifying the impact of a planned industry's emissions on existing ambient pollution concentrations is beyond the scope of the proposed framework. The quantification of anticipated ambient concentrations would require complex air pollution dispersion modelling based on detailed site-specific meteorological data and a comprehensive inventory of the existing emissions in the vicinity of the proposed site. In South Africa such data are rarely readily available. The time-consuming and costly nature of data collection and collation thus renders dispersion modelling infeasible for air pollution scoping studies.

Prior to the generation of the various data and model bases, the legislative context is reviewed. The current state of, and anticipated future developments in, air quality management in South Africa provide the rationale for air pollution scoping studies, and determine the stringency of the decision making criteria.

CHAPTER 2 - DATA REQUIREMENTS AND LITERATURE REVIEW

2.1 Introduction

The multi-disciplinary nature of air pollution warrants the analysis of a wide range of pertinent literature. Particularly relevant to the establishment of the data and model bases are developments and debates within the fields of industrial engineering, air pollution meteorology, atmospheric chemistry, environmental toxicology, risk assessment, and air pollution legislation. This chapter provides a review of the literature and data relevant in developing data and model bases, user interfaces and the final decision making framework. Where information from the literature is incorporated into the data bases, detailed reviews of the pertinent material are included in the relevant chapters. Assessment of the impacts of unavailable or insufficient data on the accuracy of model outputs is similarly undertaken within appropriate chapters. The four topics which will be reviewed in the current section include: industrial processes and emissions, macro-scale atmospheric systems affecting South Africa, meso-scale circulation systems, and environmental risk assessment.

2.2 Industrial Processes and Emissions

2.2.1 Identification and Quantification of Industrial Emissions

Anthropogenic sources may be categorised as point, mobile and area sources (Hammerle, 1976; EPA, 1981a, 1981b; Godish, 1991). Initially, industrial emissions were predominantly considered to comprise point sources exclusively. Recently greater emphasis has been placed on the mobile and fugitive dust emissions resulting from industrial activities. Emissions arising from increased vehicular traffic, and the generation of fugitive dust, including particulates produced during process operations and wind-blown dust from stock-piles, constitute an important part of industrial emissions (Bromberg *et al.*, 1982; Mukerjee and Biswas, 1993; Raasch, 1993). The assessment of possible mobile and fugitive dust emissions, in addition to the potential pollutants generated from the stacks of proposed projects, renders scoping studies far more complex.

An understanding of the nature and extent of an industry's emissions requires detailed knowledge of a range of factors, including: industrial processes conducted, nature and quantity of the raw materials used, projected rates of production and temporal variations in such rates, and finally, types of control measures adopted and the expected efficiency of such measures. In-depth analyses of various industrial activities have been conducted, producing an extensive body of literature on these factors (Stern, 1976; Bond *et al.*, 1972;

Godish, 1991; Paul, 1992; Pinkerton, 1992). The knowledge generated by such studies has facilitated the compilation of a range of air pollution emission factors. The use of emission factors enables the quantification of emissions from various categories of sources. The emission factors presented in the US Environmental Protection Agency (EPA) publication, *Compilation of Air Pollution Emission Factors, AP*-42 are the most widely used (EPA, 1995a).

A notable paucity of South African literature on industrial processes, production rates and air pollution control measures is evident. Documentation on local industrial activities and emissions is restricted to confidential reports which relay the findings of specialist studies conducted for specific industries. Locally derived emission factors are similarly unavailable (van Nierop and Annegarn, 1993, van Nierop, 1995). International literature on industrial processes and production rates, and emission factors generated from foreign experience, thus provides essential information for South African air pollution studies. Caution should, however, be adopted when using such information since international experience and literature may not always be directly relevant to the South African situation. Recent research has shown that certain EPA emission factors may not be directly applicable to local sources, and that the compilation of more appropriate emission factors should be made a priority (van Nierop and Annegarn, 1993).

The subsequent subsections provide the theoretical and contextual basis for the creation of the iron and steel data base, model base and user interface. The first subsection deals with the integrated iron and steel industry, and includes the rationale for selecting this industry for the compilation of the data base, current developments within the industry both locally and internationally, and the future of integrated iron and steel plants. In the second subsection the type of pollutants emitted from iron and steel plants, and the availability of emission factors to quantify such pollutants is discussed. The third subsection contains a description of the nature of emission factors and gives examples for their application.

2.2.2 The Integrated Iron and Steel Industry

Several interrelated processes are undertaken at an integrated iron and steel plant. The major operations are: (1) coke production, (2) sinter production, (3) iron production, (4) iron preparation, (5) steel production, (6) semi-finished product preparation, (7) finished product preparation, (8) heat and electricity supply, and (9) handling and transport of raw, intermediate and waste materials. Various processes within these major operations may result in the generation of gaseous or particulate emissions (Fisher, 1992; EPA, 1995a; Pocklington, 1995).

Coke ovens, sintering plants, blast furnaces, and steelmaking furnaces are major point sources of gaseous and particulate emissions in iron and steel industries. Considerable fugitive dust emissions are generated from vehicle traffic on paved and unpaved roads, raw

material handling, and wind erosion from stockpiles and exposed areas (Fisher, 1992; EPA, 1995a; Pocklington, 1995). On a global basis, iron and steel industries are estimated to emit approximately nine million tons of particulate per annum. Various processes within iron and steel industries may also generate gaseous emissions. Coal combustion, for example, results in emissions of sulphur oxides (SO_x), oxides of nitrogen (NO_x), carbon monoxide (CO), and various organic compounds (Fisher, 1992).

Many of the processes carried out in iron and steel industries are included in the Second Schedule of the Atmospheric Pollution Prevention Act (45) of 1965. Such scheduled processes are generally regarded as major sources of industrial pollution in South Africa. Iron and steel industries are also referred to in the "List of Activities" cited in South African IEM documentation as the most likely threat to the environment (Department of Environmental Affairs, 1992a).

Integrated iron and steel industries are generally bigger polluters than are secondary steel mills. In secondary steel plants emissions are usually confined to individual operations. In integrated iron and steel plants, not only are the individual operations larger and more numerous, but the multiple linkages between each unit operation provide additional risks of emission (Chatterjee, 1995).

2.2.2.1 Local and International Developments in the Iron and Steel Sector

Various measures aimed at reducing emissions from individual operations are currently being investigated. Measures aimed at reducing emissions from coking include more effective coke oven battery design, more efficient operating practices, jumbo coking reactors, and non-recovery coking. Coke saving and coal substitution methods reduce coke consumption in the ironmaking process. Pulverised coal injection (PCI) is currently being used both locally and abroad as a means of substituting the feed of coke to blast furnaces (Pengelly, 1992; Barnaba, 1995). Currently, over 100 blast furnaces world-wide are equipped with coal injection facilities. It is believed that this trend will increase until all operating blast furnaces inject coal, mostly in pulverised form (Chatterjee, 1995).

Research is underway to identify ways in which to reduce the number of processing steps involved in iron- and steel-making (Fisher, 1992; Pengelly, 1992). Minimising the number of processing steps would both enhance productivity and reduce the burden of air pollution control for the multiple linkages in integrated plants. Various techniques have been developed aimed at ironmaking without employing the traditional blast furnace route. The blast furnace route, which includes coke- and sinter-making, represents a significant source of emissions. In the 1970s and 1980s considerable research was undertaken into potential alternatives, including smelting reduction, direct steelmaking, and direct reduction (Chatterjee, 1995).

(a) Smelting Reduction

The Corex process, a smelting reduction technology used in South Africa to replace the blast furnace, has achieved considerable success (Delport, 1992). There is a fully operational 1kt/day Corex plant at Iscor's works in Pretoria, and a similar unit is planned for the proposed Saldanha Steel plant (Engineering News, 1995a, 1995b). In the Corex plant, iron ore or pellets, coal, oxygen, and fluxing materials are fed into a furnace to obtain molten hot metal and some excess reducing gas. Since the Corex system involves a single, continuous sealed process which eliminates the need for cokemaking and sintering, it is able to reduce atmospheric emissions substantially during the ironmaking process (Fuggle and Rabie, 1992; Chatterjee, 1995; Delport, 1992).

Despite the usefulness of the Corex system as a good additional source of molten hot metal (300-750 kt per year), it is believed that at present the Corex operation cannot replace the vastly bigger output of most blast furnaces (Chatterjee, 1995). It appears therefore that blast furnace ironmaking, and therefore cokemaking, will continue for at least the next few decades in the integrated iron and steel industry. The extent of coking will, however, increasingly be reduced with increases in the rate of PCI into the blast furnace.

In South Africa, the blast furnace route may be phased out more quickly than elsewhere. The production cost of the small Corex unit has been found to compare favourably with that of the conventional coke oven/blast furnace route, due to the availability of relatively inexpensive primary raw materials, such as iron ore, coal and electricity (Delport, 1992).

(b) Direct Steelmaking

Research is currently being undertaken to develop direct steelmaking technology that would not require the use of coke as a raw material. The technology is expected to involve the feeding of carbon-containing iron oxides into the top of a reactor, and the feeding of combustion oxygen into the bottom, to refine the charge directly into crude liquid steel. This process would eliminate air pollution from the manufacture of metallurgical coke, as well as reducing emissions from steelmaking (Chatterjee, 1995; EPA, 1995b).

(c) Direct Reduction

Direct-reduced iron (DRI), or sponge iron, is produced in rotary kilns and may be melted with steel scrap and molten iron in electric arc furnaces and basic oxygen furnaces for the manufacture of steel (Chatterjee, 1995). Various Iscor plants, including Pretoria and Vanderbijlpark works, employ DRI as an input into steelmaking furnaces. Sponge iron will also be used as a feed material for the steelmaking process at the proposed Saldanha Steel plant. The direct reduction of iron ore has made local steel producers less dependent on scrap iron and steel (Engineering News, 1995a, 1995b, 1995c; van den Bon, 1996).

Due to the relatively recent development of smelting reduction, direct steelmaking and direct reduction, no emission factors are available for such operations.

2.2.2.2 Future of Integrated Iron and Steel Plants

The use of integrated iron and steel plants, as opposed to mini steel mills, is largely dependent on the scale of demand for, and price of steel. At present integrated steel production employing the blast furnace route appears therefore to still have an appeal in South Africa, as in other developing countries which need to add large capacity to meet demands. Once the demand for steel decreases the role of integrated steel plants is likely to diminish. In Europe, where the market for steel products is unlikely to expand and may even shrink, a reduction in integrated steel production and a further growth in mini mills is envisaged (Chatterjee, 1995).

Despite the continued demand for steel, there was a softening of market prices for steel in 1995, making it less profitable for the some steelworks to compete. In the South African iron and steel industry various attempts have been made to improve profits through rationalisation, modernisation and efficiency improvement programs. Fundamental changes are currently being made in various Iscor steelworks, including Newcastle, Pretoria, and Vanderbijlpark works (Engineering News, 1995a, 1995b, 1995c; Iscor, 1996).

Pretoria Works has been converted from a small integrated carbon steel plant to one of the largest stainless steel operations in the world. As a carbon steel plant Pretoria Works did not have benefit of scale, and the volumes which were produced were such that it would have been difficult to cope in the increasingly competitive carbon steel market. The conversion undertaken at Pretoria works necessitated the conversion of Vanderbijlpark's process. Vanderbijlpark Steel has always relied on Pretoria Works for carbon steel to produce its value added product. The rationalisation of the Vanderbijlpark plant includes plans to convert the entire works to continuous casting, the introduction of pulverised coal injection (PCI) technology for use in the blast furnaces, and the reduction in the number of coke ovens and blast furnaces (Engineering News, 1995a, 1995c; Iscor, 1996; van den Bon, 1996). At the Newcastle works a blast furnace was relined, and the rod mills modernised and upgraded to achieve higher outputs and better yield resulting in a capacity increase from 420 000 tons per year to 620 000 tons a year.

The gradual shift in the United States and Europe from large integrated iron and steel plants to mini mills is reflected in the proposed construction of a mini steel mill at Saldanha. This mini steel mill will be one of the lowest-cost producers in the worlds with a capacity of 1,2 million tons of hot-rolled steel a year, 26 percent of which will be dedicated to the premium-priced ultra-thin market (Engineering News, 1995b).

2.2.3 Emissions from Integrated Iron and Steel Industries

2.2.3.1 Nature of Pollutants Emitted

Gaseous and particulate pollutants are emitted from various operations within the iron and steel production process. Gaseous pollutants emitted include several of the criteria air pollutants for which air quality standards and guidelines have been promulgated, such as carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and lead. Various hazardous air pollutants (HAPs), such as benzene, toluene, xylene, nephthalene, and polycyclic organic matter (POM) may be emitted from sources within the metallurgical coking process (Gschwandtner *et al.*, 1991; EPA, 1995a).

Particulate matter consists of liquid and/or solid particles which can vary considerably in size (0.005 to 500 microns), geometry, chemical composition and other physical properties. The behaviour of particulates released into the atmosphere, and consequently the effect of such particulates on human health and the environment, is largely dependent on particle size. Particulates are therefore classified according to their size, which is most often expressed in terms of aerodynamic diameter. PM10 (particles with an aerodynamic diameter of less than 10 microns), and PM2.5 (particles with an aerodynamic diameter of less than 2.5 microns) represent the most commonly defined classes (Baron and Willeke, 1993; Cooper, 1993). The US EPA air quality standard for total suspended particulates (TSP) was changed to a PM10 standard in 1987 after is was realised that particles with a diameter of greater than 10 microns do not represent a significant health hazard. The US EPA has recently also promulgated a standard for PM2.5, i.e. particulate matter with an aerodynamic diameter of less than 2.5 microns. South African guidelines are only available for PM10 and TSP size fractions.

2.2.3.2 Availability of Emission Factors

At present, available emission factors do not adequately represent the possible range of emissions and plant operation conditions in the iron and steel industry. The AirCHIEF data base, which represents the most current and comprehensive emissions data base available for industrial process operations, facilitates the identification of major pollutants emitted within a plant (EPA, 1995a). This data base does not, however provide for the quantification of the range of pollutants referenced, nor does it mention all the organic and inorganic compounds which may be emitted from ironmaking and steelmaking processes. In the case of gaseous pollutants, information on emission rates is currently sparse and uncertain, and consequently emission factors are generally unavailable for such pollutants. Numerous measurements and tests are currently being undertaken by the EPA to provide a better indication of the emission rates of criteria pollutants, and to increase the availability and validity of emission factors (EPA, 1995a).

The best emission factors are for particulate matter, since particulates are fairly easy to collect and quantify. Particulate emissions from different plants exhibit significant ranges in emissions. This range is due to the variability in operating rates, the quality of raw materials used, and air pollution control efficiencies.

2.2.4 Emission Factors

An emission factor is a representative value which relates the quantity of a pollutant released to the atmosphere, with an activity associated with the release of that pollutant (Hammerle, 1976; EPA, 1995a). Such factors are usually expressed as the weight of the pollutant divided by the unit weight, volume, distance, or duration of the activity emitting the pollutants. The emission factor for coal combustion, for instance, is expressed in kilograms of particulate emitted per tonne of coal burned.

Due to the absence of locally generated emission factors, use will be made of the comprehensive set of emission factors published by the US EPA in its AP-42 document, in the establishment of the industrial database. Easy access to the AP-42 report is made possible through the use of the AirCHIEF CD-ROM database. The AirCHIEF (AIR Clearinghouse for Inventories and Emission Factors) CD-ROM (Compact Disc Read Only Memory) contains various data from US EPA emission estimation reports and databases including AP-42. AirCHIEF is updated annually and allows for easy retrieval of relevant emission factors (EPA, 1995a).

2.2.4.1 US EPA AP-42 Emission Factors

AP-42 contains information on various types of sources including stationary point, mobile, and area sources. Such information includes general process descriptions, identification of points of emission, and criteria and toxic pollutant emission factors for controlled and uncontrolled processes (EPA, 1995a). The following sections of the AP-42 database are relevant to the development of the iron and steel emission data base:

12. Metallurgical Industry
    - 12.2. Coke Production
    - 12.5. Iron and Steel Production

13. Miscellaneous Sources
    - 13.2. Fugitive Dust Sources
        - 13.2.1. Paved Roads
        - 13.2.2. Unpaved Roads
        - 13.2.4. Aggregate Handling and Storage Piles
        - 13.2.5. Industrial Wind Erosion

AP-42 emission factors are averages of all available data of acceptable quality. Such data have been gathered from material balance studies, source tests, modelling and engineering estimates. In order to indicate the reliability and accuracy of AP-42 emission factors, each factor is given a rating from A through E, with A being best. The emission factor rating reflects both the amount, and the representative characteristics, of those data on which the factor is based. AP-42 factor ratings are subjective and do not provide statistical error bounds or confidence intervals about each emission factor. Such ratings, based on the professional judgement of AP-42 authors, simply provide an indication of the accuracy and precision of a given factor being used to estimate emissions from a large number of emission sources (EPA, 1995a). Emission factor ratings will be given with all AP-42 emission factors included in the iron and steel data base. The iron and steel data base will also include the definitions assigned each AP-42 emission factor rating.

The general equation for emission estimation is:

$$E = A \times EF \times (1\text{-}ER/100) \qquad (2.1)$$

where,

E	=	emissions,
A	=	activity rate,
EF	=	emission factor, and
ER	=	overall emission reduction efficiency

ER is defined as the product of the control device removal efficiency and the capture efficiency of the control system. When estimating emissions for long term periods, both the device and the capture efficiency terms should account for upset periods as well as routine operations (EPA, 1995a).

For certain processes, emission factors may be available for processes being controlled by particular air pollution control equipment. Such factors influenced by control technology do not necessarily represent the best available or state-of-the-art controls, but rather reflect the level of typical control for which data were available.

The use of emission factors in emission estimation studies is particularly important in the case of proposed industries, where emissions cannot be monitored, and so cannot be quantified directly. Knowledge of the quantity of emissions likely to result from a project prior to the construction may be used in both the design and operational phases. In the design phase, actions may be taken to reduce emissions by altering the nature of the processes, raw material usage, production rates, and air quality control equipment. Alternatively, changes could be made in operational and management practices during the operational phase of the industry.

2.2.4.2 *Variability of Emissions*

Average emissions differ significantly from source to source, therefore emission factors may not provide adequate estimates of the average emissions for a specific source. The extent of variability between sources is dependent on the process, control system, and pollutant.

Variations in process operations may result in large differences in emissions. Small increases in the amount of pulverised coal injection into the blast furnace may, for example, substantially reduce particulate emissions. Air pollution control devices may also cause differences in emission characteristics, since the specific design criteria of control equipment affects the resulting emissions. Since design criteria are often not included in emission test reports they may not be accounted for in the resulting factors (EPA, 1995a).

Potential errors in emission estimation due to variability between sources should be taken into account when applying emission factors generated for sources within the US to the estimation of emissions from South African sources. Certain of the process operations and air pollution control equipment are unique to South Africa. In the South African iron and steel industry, for example, use is made of directly reduced iron (sponge iron) as a partial feed for the electric arc furnace in place of only using scrap metal and hot molten iron. The implications of such unique process practices and control technology for the estimation of emissions for local industries, based on the use of AP-42 emission factors, will be included in the data and model base.

2.3 Macro-scale Atmospheric Systems Affecting South Africa

Past research has effectively elucidated the meteorological characteristics, spatial distributions, and temporal trends of the synoptic systems and weather pertubations affecting the circulation over southern Africa (Jackson, 1947, 1952; Taljaard, 1953, 1981; Harrison, 1986; Schulze, 1986; Goldreich and Tyson, 1988; Preston-Whyte and Tyson, 1988). The frequency and sequence of occurrence, and persistence of such systems have been studied on a *national* scale (Vowinckel, 1955; Taljaard, 1981; Preston-Whyte and Tyson, 1988), and the general implications of the systems on the dispersion potential of the atmosphere investigated (Diab, 1975, 1977a, 1977b, 1978a, 1978b; Preston-Whyte *et al.*, 1977; Preston-Whyte and Tyson, 1988; Annegarn *et al.*, 1993; Held *et al.*, 1994; Garstang *et al.*, 1995). A synopsis of the findings of the research is presented below.

2.3.1 General Atmospheric Circulation over Southern Africa

Situated in the subtropical high pressure belt, southern Africa is influenced by several high pressure cells, in addition to various circulation systems prevailing in the adjacent tropical and temperate latitudes. The mean circulation of the atmosphere over southern Africa is anticyclonic throughout the year (except near the surface) due to the dominance of three high pressure cells, viz. the South Atlantic High Pressure (HP) off the west coast, the South Indian HP off the east coast, and the continental HP over the interior (Jackson, 1947, 1952; Taljaard, 1953; Schulze, 1986; Preston-Whyte and Tyson, 1988).

Seasonal variations in the position and intensity of the HP cells determine the extent to which the tropical easterlies and the circumpolar westerlies impact on the atmosphere over the subcontinent. The tropical easterlies, and the occurrence of easterly waves and lows, affect most of southern Africa throughout the year. In winter, the high pressure belt intensifies and moves northward, the upper level circumpolar westerlies expand and displace the upper tropical easterlies equatorward. The winter weather of South Africa is, therefore, largely dominated by pertubations in the westerly circulation. Such pertubations take the form of a succession of cyclones or anticyclones moving eastwards around the coast or across the country. During summer months, the anticyclonic belt weakens and shifts southwards, allowing the tropical easterly flow to resume its influence over South Africa. A weak heat low characterises the near surface summer circulation over the interior, replacing the strongly anticyclonic winter-time circulation (Jackson, 1947, 1952; Taljaard, 1953; Schulze, 1986; Preston-Whyte and Tyson, 1988).

2.3.2 Synoptic Systems and Weather Pertubations Affection South Africa

2.3.2.1 Subtropical Systems and Disturbances

(a) Anticyclones

Anticyclones situated over the subcontinent are associated with convergence in the upper levels of the troposphere, strong subsidence throughout the troposphere, and divergence in the near-surface wind field. Subsidence inversions, fine conditions with little or no rainfall, and light variable winds occur as a result of such widespread anticyclonic subsidence (Jackson, 1947, 1952; Taljaard, 1953, 1955; Diab, 1975; Preston-Whyte and Tyson, 1988). Anticyclones occur most frequently over the interior during winter months, with a maximum frequency of occurrence of 79 percent in June and July (Table 2.1). During December such anticyclones only occur 11 percent of the time. Although widespread subsidence dominates the winter months, weather occurs as a result of uplift produced by localized systems, e.g. storms which occur due to the interaction of two high pressure systems (Vowinckel, 1955; Preston-Whyte and Tyson, 1988). The persistence of

strong continental anticyclones are associated with heat waves and the occurrence of Berg winds over coastal regions (Taljaard, 1953; Preston-Whyte and Tyson, 1988).

(b) Berg Winds

Berg winds occur as a result of large-scale prefrontal divergence and adiabatic warming of subsiding offshore airflow with anticyclonic curvature, and are associated with high pressure systems over the interior and depressions along the coast. Bergwinds have been linked to the pre-frontal divergence generated ahead of coastal lows, westerly waves, and cold fronts. Berg winds occur predominantly in late winter and early spring, and may vary in duration from a few hours to several days. Such winds are responsible for almost all sharp increases in temperature experienced in coastal areas. Spectacular day-to-day variations in temperature, from hot conditions due to pre-frontal Berg winds, to cold post-coastal low or post-frontal conditions, have been recorded for coastal regions (Tyson, 1964, 1965; Schulze, 1986; Preston-Whyte and Tyson, 1988). Along the west coast, strong offshore Berg winds have been linked to the occurrence of extensive dust plumes extending out over the South Atlantic Ocean (Diab, 1978a).

(c) Coastal Lows

Coastal lows, which owe their existence to topography and the local generation of cyclonic vorticity, are common features of the circulation of coastal regions. The descent of air over the Escarpment from the high plateau to the coast results in an increase in the depth of the airstream, and consequently, the airstream acquires cyclonic vorticity and curvature. The generation of such cyclonic vorticity facilitates the formation of a coastal low. Coastal lows may form anywhere along the coast between Namibia and northern Natal, provided that strong offshore gradient winds prevail. Coastal lows usually develop along the west coast, propagate southward to Cape Town, and eventually move eastward and north-eastward around the coast (Diab, 1975; Schulze, 1986; Preston-Whyte and Tyson, 1988).

Coastal lows are fairly shallow systems (seldom deeper than 850 hPa, or 1 500 m), being trapped vertically beneath a strong low-level subsidence inversion. These low pressure systems are confined to coastal regions, their horizontal movement being impeded on the landward side by the Escarpment (Preston-Whyte and Tyson, 1988).

Warm offshore airflow occurs ahead of the coastal low, and cool onshore airflow behind the system. Coastal lows are characterised by abrupt pressure, temperature, humidity and wind fluctuations, similar to those of cold fronts, and may therefore be mistaken as such. Due to their shallow nature, however, coastal lows do not represent major rain-producing systems, and are only responsible for localized precipitation in the form of mist and fine drizzle (Diab, 1975; Preston-Whyte, 1974; Preston-Whyte and Tyson, 1988).

Table 2.1 Frequency of occurrence (percentage) of synoptic systems and weather pertubations (after Preston-Whyte and Tyson, 1988).

SYNOPTIC SYSTEMS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Spt	Oct	Nov	Dec
Subtropical Systems:												
Continental High Pressures	18	17	19	25	38	79	79	72	65	38	19	11
Tropical Disturbances:												
Easterly waves	19	16	17	18	14	6	6	10	7	9	12	14
Easterly lows	27	35	37	26	19	7	3	1	5	15	25	35
Easterly wave and low	35	39	23	0	0	0	0	0	7	0	6	19
Westerly Disturbances:												
Ridging anticyclones	7	9	6	8	8	2	2	0	2	11	9	9
Cold snaps	0	0	0	3	4	4	5	8	6	3	3	1
Westerly low	19	11	26	10	3	3	3	3	10	16	13	3
Cut-off low	3	11	16	27	29	17	13	30	33	26	32	26

2.3.2.2 Tropical Disturbances in the Easterlies - Easterly Waves and Lows

The tropical easterly air stream is associated with the warm humid easterly winds between the Inter-Tropical Convergence Zone and the subtropical high pressure belt. Pertubations within the easterlies take the form of open waves and closed lows which are semi-stationary and barotropic in character. Although easterly waves and lows are clearly evident in the lower troposphere below 700 hPa, they are weakly developed at 500 hPa, and usually absent in the upper troposphere where high pressure ridges dominate (Jackson, 1952; Taljaard, 1953, 1981; Harrison, 1986; Schulze, 1986; Tyson *et al.*, 1988).

Surface convergence and upper air (500 hPa) divergence occurs to the east of the wave resulting in strong uplift, instability and the potential for precipitation. To the west of the wave, surface divergence and upper-level convergence produces subsidence, and consequently fine clear conditions with no precipitation. Easterly lows are usually deeper systems than are easterly waves, with upper-level divergence to the east of the low occurring at higher levels resulting in strong uplift through the 500 hPa level and the occurrence of copious rains (Jackson, 1952; Taljaard, 1953, 1981; Harrison, 1986; Schulze, 1986; Preston-Whyte and Tyson, 1988). Easterly waves and lows occur almost exclusively during summer months, and are largely responsible for the summer rainfall pattern and the northerly wind component which occurs over the interior (Table 2.1).

2.3.2.3 Temperate Disturbances in the Westerlies

(a) Westerly waves

Baroclinic in nature, westerly waves are characterised by concomitant surface convergence and upper-level divergence which produce sustained uplift, cloud and the potential for precipitation to the rear of the trough. Ahead of the trough, subsidence and stable conditions with fine clear conditions prevail. A semi-annual cycle is evident in the frequencies of occurrence of westerly waves, with high frequencies occurring between October and April, and low incidences between May and September (Table 2.1) (Jackson, 1952; Taljaard, 1953; Harrison, 1986; Schulze, 1986; Preston-Whyte and Tyson, 1988).

(b) Cut-off Lows

Cut-off lows begin as westerly troughs and deepen into closed circulations which are displaced northward out of the mean westerly air stream. Associated with strong surface convergence and intense uplift to a level higher than 500 hPa, cut-off lows produce heavy, occasionally flood-producing, rains (Harrison, 1986; Taljaard, 1985; Preston-Whyte and Tyson, 1988). Semi-annual variations are evident in the frequency of occurrence of cut-off

lows, with peaks occurring between March and May, and September and November. Low incidences occur between December and February (Table 2.1) (Preston-Whyte and Tyson, 1988).

(c) West Coast Troughs

The occurrence of a surface trough over the west coast, and an upper-tropospheric westerly wave to the west of the subcontinent, results in surface convergence, strong uplift and upper-level divergence. The coincidence of such systems are associated with widespread rains over western parts of South Africa (Harrison, 1986; Preston-Whyte and Tyson, 1988).

(d) Cold Fronts

Cold fronts are associated with westerly waves, west coast troughs and cut-off lows, and occur predominantly during winter when the amplitude of such disturbances is greatest. Cold fronts represent the northward movement of cold air from the south and south-west which are responsible for the occurrence of cold snaps. Such cold snaps persist for two days on 50 percent of occasions, and for four days on 10 percent of occasions (Taljaard, 1981; Harrison, 1986; Preston-Whyte and Tyson, 1988).

Low-level convergence in the southerly airflow occurs to the rear of the front producing favourable conditions for convection. Airflow ahead of the front has a distinct northerly component, and stable and generally cloud-free conditions prevail as a result of subsidence and low-level divergence (Diab, 1975; Taljaard, 1981; Harrison, 1986; Preston-Whyte and Tyson, 1988). The passage of a cold front is therefore characterised by distinctive cloud bands and pronounced variations in wind direction, wind speeds, temperature, humidity, and surface pressure. Following the passage of the cold front, the northerly wind is replaced by winds with a distinct southerly component. Temperature decreases immediately after the passage of the front, with minimum temperatures being experienced on the first morning after the cloud associated with the front clears. Strong radiational cooling due to the absence of cloud cover, and the advection of cold southerly air combine to produce the lowest temperatures (Harrison, 1986; Preston-Whyte and Tyson, 1988).

(e) Ridging Anticyclones

Ridging anticyclones develop when the extended eastward ridging of the South Atlantic HP results in the breaking off of a separate high. Such ridging anticyclones drift eastward into the Indian Ocean and are eventually subsumed into the South Indian HP (Harrison, 1986; Preston-Whyte and Tyson, 1988).

Ridging anticyclones usually follow the passage of a westerly trough. Strong pressure gradients between the ridging anticyclone and the westerly trough promote the onshore advection of moist, unstable air, giving rise to widespread general rains or thunderstorm activity over the southern and eastern coastal and adjacent inland areas. Rainfall resulting from ridging anticyclonic activity occurs throughout the summer rainfall season from October to May (Table 2.1). Coincident with the occurrence of rainfall over the eastern parts of the country, the south-western Cape experiences fine, clear, hot conditions and south easterly airflow as a result of the anticyclonic activity over the region (Diab, 1975; Harrison, 1986; Preston-Whyte and Tyson, 1988).

(f) Southerly Meridional Flow

Southerly meridional airflow occurs over the ocean to the south of the subcontinent, and as onshore airflow over the adjacent land. This airflow pattern occurs as a result of the strong zonal pressure gradient which develops between eastward propagating westerly depressions and the ridging anticyclones which follow such systems. Southerly meridional flow is responsible for light spring rainfall over the southern regions, and with sharp decreases in temperature over most of Southern Africa, particularly in the southern parts (Harrison, 1986; Preston-Whyte and Tyson, 1988).

2.3.3 Patterns of Synoptic Circulation over Southern Africa

Typical sequences in the occurrence of synoptic systems have been distinguished for southern Africa (Harrison, 1986; Lindesay, 1987; Preston-Whyte and Tyson, 1988). A typical 6-day sequence appears to occur in the passage of disturbances to the south of the subcontinent. Subtropical high pressures dominate the circulation over southern Africa on day 1, producing fine, clear conditions with no rainfall. On day 2, a westerly wave moves eastward, and by day 3 the cold front associated with the westerly wave passes over the southern parts of the country and an easterly wave develops simultaneously to the north. The circulation over the subcontinent on day 3 is characterised by an extensive trough of low pressure. By day 4 the westerly low has moved off the east coast, and the Atlantic HP begins to ridge eastward towards Cape Town. Strong southerly meridional flow develops between the low (to the east) and the ridging Atlantic HP (to the west). The ridging anticyclone has broken free of its parent Atlantic HP by day 5, and moves eastwards into the Indian Ocean. By day 6, the ridging anticyclone has been subsumed into the South Indian high, and a synoptic pattern similar to day 1 is established (Preston-Whyte and Tyson, 1988).

2.3.4 Impact of Synoptic Systems on Atmospheric Dispersion Potential

The impact of various synoptic systems and weather disturbances on the dispersion potential of the atmosphere largely depends on the effect of such systems on the height and persistence of elevated inversions (Holzworth, 1967; Diab, 1975, 1978b; Preston-Whyte *et al.*, 1977; Kallos *et al.*, 1993). Elevated inversions suppress the diffusion and vertical dispersion of pollutants by reducing the height to which such pollutants are able to mix, and consequently result in the concentration of pollutants below their bases. Such inversions therefore play an important role in controlling the long-range transport, and recirculation of pollution (Tyson, 1963; Diab, 1975; Preston-Whyte *et al.*, 1977; Annegarn *et al.*, 1993; Harrison, 1993; Held *et al.*, 1994; Garstang *et al.*, 1995).

Subsidence inversions, which represent the predominant type of elevated inversion occurring over South Africa, result from the large-scale anticyclonic activity which dominates the synoptic circulation of the subcontinent. Subsiding air warms adiabatically to temperatures in excess of those in the mixed boundary layer. The interface between the subsiding air and the mixed boundary layer is thus characterised by a marked elevated inversion. Protracted periods of anticyclonic weather, such as characterise the plateau during winter, result in subsidence inversions which are persistent in time, and continuous over considerable distances. The fairly constant afternoon mixing depths, with little diurnal variation, associated with the persistence of subsidence inversions, are believed to greatly reduce the dispersion potential of the atmosphere over the plateau, resulting in the accumulation of pollutants over the region (Diab, 1975, 1977a, 1978b; Preston-Whyte *et al.*, 1977; Held *et al.*, 1994).

In contrast to anticyclonic circulation, convective activity associated with westerly and easterly wave disturbances hinders the formation of inversions. Cyclonic disturbances, which are associated with strong winds and upward vertical air motion, either destroy, weaken, or increase the altitude of elevated inversions (Taljaard, 1955; Holzworth, 1962, 1964, 1967; Diab, 1975, 1977b; Preston-Whyte and Tyson, 1988). Easterly and westerly wave disturbances therefore facilitate the dispersion and dilution of accumulated atmospheric pollution. The frequent passage of cyclonic disturbances at coastal regions precludes the establishment of anticyclonic circulations for any length of time, ensuring frequent fluctuations in the mixing height (Diab, 1975, 1977b; Preston-Whyte and Tyson, 1988).

The nature of the impact of cold frontal passage on the mixing depth varies between the plateau and coastal regions (Preston-Whyte and Tyson, 1988). Preceding the arrival of the cold front during pre-frontal warming, when the lowest surface pressure occurs, the base of the subsidence inversion is lowered and the mixing depth falls at the coast. Immediately following the passage of the front, however, a dramatic rise in mixing depth occurs at coastal stations. Although a drop in the mixing depth also occurs over the interior due to

the passage of a cold front, there is a tendency for the lowest mixing depths to coincide with the coldest air temperatures and rising pressure. Such minimum temperatures and increases in pressure occur in the wake of the front, rather than at the time of minimum pressure as at coastal stations. Stations on the plateau also experience a gradual rise in mixing depth, not a sudden increase as at coastal stations.

The passage of coastal lows are associated with increased atmospheric stability and reduced ventilation in the lower layers of the atmosphere. The restriction of the dispersion potential results in marked increases in atmospheric pollution over urban areas which persists until the arrival of the characteristic squall front.

Subsidence inversions over coastal regions may also be affected by the occurrence of bergwinds and coastal lows (Diab, 1975; Preston-Whyte and Tyson, 1988). The movement of a coastal low along the coast appears to coincide with the lowering of the base of the elevated inversion, thus increasing the potential for the accumulation of pollutants. Berg wind conditions, however, may result in the dissipation of subsidence inversions and the diffusion of pollutants.

2.3.4.1 Spatial Distribution of Elevated Inversions

Multiple elevated inversions occur in the middle to upper troposphere as a result of large-scale anticyclonic subsidence. Three distinct elevated inversions, situated at altitudes of approximately 700 hPa (~3 km), 500 hPa (~5 km) and 300 hPa (~7 km), were identified over southern Africa (Preston-Whyte *et al.*, 1977; Cosijn, 1995). The height and persistence of such elevated inversions vary with latitudinal and longitudinal position. During winter months the first elevated inversion is located at an altitude of 0.5 km over Alexander Bay, 1 km over Cape Town, Durban and Maputo, and around 3 km over the plateau. In summer this inversion decreased in altitude over the west coast to 0.5 km, but rises to 1.2 to 2 km over Durban and Maputo, and to 4 to 5 km over the plateau (Diab, 1975, Preston-Whyte *et al.*, 1977; Cosijn, 1995).

2.3.4.2 Temporal Trends in Elevated Inversions

Seasonal cycles are evident in the frequency of occurrence of elevated inversions (Diab, 1975; Harrison, 1986; Preston-Whyte *et al.*, 1977). The west coast experiences a maximum frequency of elevated inversions during summer and a minimum during winter. In comparison to the west coast, the south coast has lower frequencies of occurrence of elevated inversions, but does not experience as great an annual variation in such frequencies. Over the east coast, the highest inversion frequencies occur during summer months, with the lowest incidences occurring in autumn to early winter. The greatest seasonal variation in elevated inversion frequencies occurs over the interior; with very high

frequencies characterising winter months, and very low frequencies occurring during summer (Diab, 1975; Harrison, 1986; Preston-Whyte *et al.*, 1977; Preston-Whyte and Tyson, 1988).

The extent of the seasonal variation in inversion frequencies is dependent on the mechanisms controlling the development of such inversions. Whereas elevated inversions over the plateau occur primarily as a result of subsidence, elevated inversions over coastal regions represent composites of various types of inversions, including subsistence, frontal and coastal-low inversions. This accounts for the high frequencies of inversions over coastal regions throughout the year (Diab, 1975; Preston-Whyte *et al.*, 1977; Preston-Whyte and Tyson, 1988).

2.3.5 Weather Map Classifications and Synoptic Climatologies for South Africa

An air mass-based synoptic climatology has been developed as part of the current study in an attempt to generate the macro-ventilation potential information needed for the dispersion climatology data base outlined in Chapter 6. A brief review of past work aimed at the establishment of a synoptic climatology for South Africa provides the context within which this component of study has been undertaken.

The work of Longley (1976) represented a first attempt to classify South African weather maps objectively. Use was made of Lund's (1962) correlation method for identifying the most frequently recurring 850 hPa level pressure patterns; the study focusing on summer and winter conditions for the south-west, south-east, east and north-east parts of South Africa. Despite the considerable calculation necessitated by Longley's approach, the lack of treatment of upper-air data was found to represent the main drawback of his work (Taljaard, 1995). During the 1980s the classification of synoptic systems continued with the work of Steyn (1984). Steyn also used Lund's correlation method but based his classification of summer circulation patterns over South Africa on patterns evident at the 300 hPa level.

Harrison's work during the 1980s was not aimed at producing a comprehensive classification of South African weather systems or circulation types, but rather at identifying the occurrence of summer-rain producing circulation types based on the use of principal component analysis of monthly district rainfalls in South Africa. Seven circulation types were identified by Harrison (1986), viz. tropical temperate troughs, tropical depressions, sub-tropical cyclones, west-coast cyclones, east coast troughs, coastal depressions and frontal bands.

Preston-Whyte and Tyson (1988) classified southern African synoptic systems under three main headings, viz. fine and mildly disturbed conditions, tropical disturbances in the easterlies and temperate disturbances in the westerlies. Other systems were also

recognised, including tropical cyclones, composite systems, and the summer rain-producing systems defined by Harrison (1986). Although Preston-Whyte and Tyson's classifications were made subjectively, upper air (500 hPa level) circulations were used along with surface circulations in the classification. Discriminant analysis was applied by Diab *et al.* (1991) in an attempt to formulate an objective classification of the rain-producing systems for Natal. Although upper-air circulations were noted in the classification, attention was focused on surface pressure patterns.

Taljaard (1995) has recently proposed a new classification of atmospheric circulation types over South Africa, based on the analysis of the most characteristic flow patterns at 300 - 200 hPa, sea-level and 850 hPa level in January and July (as representative of summer and winter, respectively). These flow patterns are drawn from the European Centre for Medium Range Weather Forecasting (ECMWF) analyses, and the classification represents a subjective attempt at synoptic classification.

2.4 Meso-scale Atmospheric Systems

The dispersion potential of pollutants is not only dependent on the occurrence and persistence of synoptic systems and large-scale weather disturbances, but also on meso-scale phenomena. Meso-scale perturbance of the low-level wind field and atmospheric stability regime is mainly due to topography and ground-level temperature anomalies which occur at land/sea interfaces or as a result of urban heat islands. In southern Africa the importance of local and regional thermo-topographically induced circulations has long been recognised, and the meteorological characteristics, spatial distributions and temporal trends of such circulations well documented (Jackson, 1954; Tyson, 1968a, 1968b; Preston-Whyte, 1969; Tyson and Preston-Whyte, 1972; Diab and Garstang, 1984; Held, 1985; Jury and Guastella, 1987, Preston-Whyte and Tyson, 1988; Tyson *et al.*, 1988; Jury and Diab, 1989; Schumann and Martin, 1991). The formation, frequency of occurrence and characteristics of surface and local elevated inversions has also been the focus of considerable research (Onesta, 1964; Keen, 1969; Hart, 1971; Diab, 1975; Anfossi *et al.*, 1977; Tyson *et al.*, 1976; Tyson *et al.*, 1980; Surridge, 1986; Surridge and Swanepoel, 1987; Preston-Whyte and Tyson, 1988; Oke, 1990). Recent research into meso-scale wind variability has concluded that over the whole of the subcontinent and for all times of the year, the diurnal meso-scale wind variability is dominant over inter-diurnal synoptic scale variability (Goldreich and Tyson, 1988).

It is clearly beyond the scope of the current study to model the meso-scale wind field for each site within South Africa. In order to facilitate the parameterisation of site-specific meso-ventilation potentials it is, therefore, necessary to construct *generalisations* regarding the nature of the airflow and attendant stability regime under various circumstances. Such circumstances could include proximity to water bodies, and location within valleys and

urban areas. The meso-scale generalisations need be based on a clear understanding of factors within each environments which govern the airflow near the ground and the thermal structure of the boundary layer. Due to the complexity of establishing such generalisations, meso-scale systems related to *uneven terrain* were selected for the development of the generalisations to be included in the data base. No generalisations will be formulated for surface temperature inversions, urban boundary layer modifications and circulations due to land-sea interfaces.

The establishment of quantitative theories of terrain-induced motion as part of the dispersion climatology data base (Chapter 6) necessitates a review of the general nature of such systems. A synopsis of the information available on modifications in meso-scale airflow and the atmospheric stability regime due to complex terrain, specifically with regard to valleys and hills, is presented below.

2.4.1 Circulation Systems within Valleys

Slopes are subject to greater amounts of insolation during the day, and experience greater radiational cooling during the night, than does the adjacent free air. Such differential heating and cooling of the air on slopes and the adjacent free air results in the development of horizontal pressure gradients and the creation of local baroclinic fields on the slopes. The deformation of the isobars and isotherms is opposite by day and night. The solenoidal circulations generated in the baroclinic field produces low-level, up-slope anabatic flow of air during the day, and down-slope katabatic flow at night (Atkinson, 1991; Pielke, 1984).

Similar circulations develop within individual valleys due to uneven heating between the head of the valley and the entrance at a lower altitude. The resulting pressure gradient induces up-valley winds during the day and down-valley winds at night. Despite the close attention of many eminent meteorologists over the last century, no fully three-dimensional, time-dependent model which realistically simulates the structure and diurnal changes of the slope/valley wind circulation has been produced (Atkinson, 1981; Allwine, 1993). It is of course true that valleys comprise slopes, but it is precisely the complicated combination of individual slopes within valleys that hinders the development of a comprehensive model of the valley wind system.

Several observational, numerical and theoretical studies have investigated the dynamic and dispersive behaviour of valley atmospheres. Such studies have resulted in a more complete understanding of dispersion and the processes governing dispersion within valleys. Further work is required, however, on the applicability of the findings to other valleys (Allwine, 1993).

2.4.1.1 Structure of the Circulation within Valleys

The circulation within valleys ise the result of both slope and valley wind systems. Various studies have shown that in most cases three layers clearly exist within the valley circulation: (1) the near-surface up- or down-valley flow, (2) the "anti-wind", and (3) the gradient wind above (Atkinson, 1981; Preston-Whyte and Tyson, 1988). The anti-valley wind represents a compensating return current above the valley wind, completing the circulation pattern.

The depth of the valley wind system is closely related to the relative relief of the valley, i.e. the height difference between valley bottom and ridge top. Evidence suggests that surface winds in both the up- and down-valley wind system are as deep as the valley, dominating the airflow to a height exceeding the bordering ridges. The overlying anti-winds are of a similar depth to the valley winds.

(a) Temperature Profiles and Valley Inversion Development

As cold air accumulates within the valley, the upper reaches of the side slopes remain warm, resulting in a warm layer of air occurring above the cold layer and the development of a valley inversion. The layer of warm air, known as the thermal belt, migrates up-slope until the accumulating cold air fills the valley completely (Keen, 1969). Above the thermal belt the normal adiabatic decrease of temperature with height usually prevails. During the day, as surface heating of the valley results in the development of low-level mixing, thin anabatic flows up the valley sides occur. The anabatic flow removes mass from the core causing the elevated inversion to sink and therefore to warm adiabatically. Eventually the upward movement of the mixed layer and the descent of the valley inversion top combine to eliminate the stable core and a well-mixed atmosphere fills the valley cross-section (Oke, 1990).

(b) Wind Velocities within Valleys

Marked variations in vertical profile of wind velocities have been noted. The valley and anti-wind layers are characterised by maximum wind velocities ranging from 3 to 5 m/s. Much higher wind speeds may be found above the anti-wind layer where gradient winds predominate. During the period between the dissipation of the up-valley wind and the development of the down-slope wind, during which time ground and air temperatures are approximately equal, a brief interval of calm variable winds occur.

In a comparison of two differently shaped valleys, both of which were about 1200-1300 metres deep the following was noted. In "U" shaped valleys a maximum up-valley flow of 3-4 m/s occurs at 600-700 m above the ground, whereas maximum down-valley speeds of 4 m/s occur at a height of 250 m. In a "V" shaped valley the maximum down-wind

velocity lay at 400 m above the ground. Valley shape thus influences the vertical velocity profile.

An important relationship has been found between the depth of the up- or down-valley wind and the height at which maximum velocities occur. This relationship is often expressed in terms of the Prandtl formula. According to the Prandtl formula, the vertical profile the ratio h^*/H should equal about 0.25, where h^* is the height of maximum wind speed, and H is the depth of the valley wind. This means that, for example, for a valley wind which is about 100 metres deep (considering the depth of the valley to be about 100 m) the maximum wind speed would occur at about 25 metres. Tyson (1968b) showed that 39% of down-valley winds near Pietermaritzburg had an h^*/H value between 0.20 and 0.29, i.e. effectively in accord with the Prandtl profile. In an earlier study by Tyson (1968a) the mean value of the h^*/H in a Drakensburg valley was found to be 0.36 with a standard deviation of 0.20. According to such studies by Tyson down-valley winds appear to accord with the Prandtl profile. Tyson's observations of up-valley winds similarly showed good agreement with the Prandtl equation (1968a). The Prandtl profile only holds for slopes with gradients larger than 8 degrees (Atkinson, 1981)

Within-valley winds accelerate with increasing distance from the head of the valley to its mouth. In the case of a narrow gorge with a floor sloping at some 8 degrees the wind speed increased from virtually zero at the valley head, to 3 m/s at about 5 km down-valley, and to 5.4 m/s at about 7 km down-valley (Atkinson, 1981).

2.4.1.2 Factors Affecting Valley Circulation

(a) Orientation of Valley

The exact nature of wind circulations depend on the orientation and geometry of the valley. The most developed and most symmetric wind systems occur predominantly in deep, straight valleys with north-south axes. Valleys with other orientations, or with complex geometries, such as bends or constrictions, are generally characterised by asymmetric or incomplete flow patterns.

For valleys which are east-west aligned, sunrise and sunset heating and cooling will be reasonable uniform on each slope. Equal heating of both slopes results in the initiation of a double helical circulation. During the early morning anabatic up-slope winds characterise both slopes, while subsidence occurs over the central valley. Later on in the day, as a strong temperature gradient begins to develop between the mouth and head of the valley, the up-slope winds begin to weaken and an up-valley wind develops. Above the up-valley wind, an anti-valley wind develops to complete the circulation. By early afternoon, the up-valley wind has increased in strength and depth, dominating the airflow to a height exceeding the bordering ridgelines (Atkinson, 1981; Preston-Whyte and Tyson, 1988).

During the late afternoon the slopes begin to cool and the valley wind weakens, resulting in the development of a double helical circulation in the opposite direction to that of the early morning. Katabatic flow occurs down the valley slopes, whereas ascending airflow occurs over the central valley. This final phase is of short duration, being quickly replaced by down-valley flow which blows in response to the now-reversed temperature gradient between the cooler head and the warmer mouth of the valley. An anti-valley wind characterises the upper airflow representing the compensating return current.

North-south aligned valleys experience distinctly different sunrise and sunset heating and cooling effects between different slopes. Eastward facing slopes receive greater amounts of insolation than do westward facing slopes during the early morning, resulting in the development of a uni-cellular circulation. The shallow, unstable upslope flow exhibits speeds of 2 to 4 m/s with a maximum velocity at about 20 to 40 metres above the surface. During the late afternoon, however, the westward facing slope continues to receive insolation and remains warmer than the eastward facing slope. A reversed uni-cellular circulation thus dominates the valley during the late afternoon. These katabatic winds usually have wind speeds of about 2-3 m/s, with greater speeds occurring where the cold layer is thicker and the slope steeper. For the rest of the day and night the circulation within the valley will be the same as that of east-west aligned valleys. The up-slope valley wind fills the entire valley with maximum wind speeds occurring as close to the ground as surface friction allows since the maximum pressure gradient is near the surface. The down-valley flow generally occurs as intermittent surges rather than continuous flows. North-south valleys experience some asymmetric flow due to diurnal variations of solar radiation input to west- and east-facing slopes (Atkinson, 1981; Preston-Whyte and Tyson, 1988; Oke, 1990).

(b) Degree of insolation

Valley circulations are strongly developed on days with marked horizontal temperature gradients. Such marked gradients occur primarily during cloudless days. Valley winds also reflect the seasonal variations in the extent of insolation. Up-valley winds dominate and are strongest in summer when heating effects are greatest, whereas down-valley winds dominate and are strongest during winter months during which cooling effects are most pronounced.

(c) Gradient winds

Strong gradient winds may hinder the development of strong valley circulations. Anti-valley winds are, however, more prone to obliteration by gradient winds than are valley winds due to their being located above the level of the ridges bordering the valley. Strong

cross-valley gradient winds may also restrict the depth of the down-valley wind. Gradient winds with speeds above 10 m/s prohibit the development of such local winds.

With clear skies and reasonably steady wind direction, slope and valley winds could develop in gradient winds of 5 m/s. Valley circulations are best developed in anticyclonic weather in summer (Oke, 1990). Under such anticyclonic summer conditions, with almost cloudless skies and weak large scale motion, differential warming or cooling of different facets of the landscape gives rise to horizontal temperature and pressure gradients which promote such airflow.

Whiteman and Doran (1993) identified four mechanisms which may produce distinct relationships between winds above and within valleys. Above-valley winds refer to geostrophic or ambient winds:

(1) **Thermal forcing** represents the first process. According to this mechanism the with-in valley winds do not depend on above-valley wind directions, but are rather generated by locally developed along-valley pressure gradients. Such thermally-induced wind systems, which consist of up-valley winds during the daytime and nocturnal down-valley winds, are common in areas with large diurnal cycles in surface sensible heat fluxes, particularly under weak upper-level wind conditions.

Thermally driven down-valley flows are predominantly evident when above-valley winds are weak. Such flow is unlikely to develop in flat-bottomed valleys with low sidewalls, and channelling along the valley sidewalls would be relatively ineffective.

(2) The second mechanism involves strong **downward transport of horizontal momentum** resulting in wind directions within the valley that are similar to the geostrophic wind directions above. Downward transport of momentum may be due to vertical turbulent mixing or gravity waves. Due to friction, the geostrophic wind would turn slightly toward lower pressure as the ground is approached.

Downward momentum transport becomes important when above-valley winds are strong, particularly under conditions of weak stability. Downward turbulent transport of momentum is most likely to occur during unstable or neutrally stratified conditions in wide flat-bottomed valleys with low sidewalls. Channelling would be relatively ineffective and thermally driven winds are unlikely to develop in such valleys. In a very wide valley downward momentum transport could affect wind directions without forced channelling.

(3) The third mechanism involves the **forced channelling** of geostrophic winds within the valley. Above-valley winds are channelled by the valley sidewalls so that within the valley the winds are aligned with the valley axis. Depending on the direction of the geostrophic wind relative to the axis of the valley, the winds will blow up or down the valley. Sudden

shifts in direction occur when geostrophic winds shift across the line normal to the valley axis. Forced channelling is more likely to occur in a narrow valley and would require strong downward momentum transport.

(4) The fourth process is that of **pressure-driven channelling**, in which within-valley winds are driven by the component of the above-valley winds along the valley's length. Such channelling is produced as a column of air passes across a valley and expands vertically. The wind velocity of the geostrophic wind decreases and the wind turns left in the direction of the imposed large-scale pressure gradient. Within the valley, only the along-valley component of the large-scale pressure gradient can be effective since the air is forced to flow parallel to the valley sidewalls. Within-valley winds thus shift from up-valley to down-valley winds as the geostrophic wind direction shifts across the valley axis. Although pressure-driven channelling results in predominantly along-valley flow, as in the case of forced channelling, the wind reversals occur for geostrophic wind directions 90 degrees different from those characteristic of the forced channelling mechanism. Pressure-driven channelling may result in countercurrents, since the geostrophic winds above the valley blow parallel to the isobars, whereas the winds in the valley are constrained to blow along the valley's axis across the isobars.

Pressure-driven channelling is anticipated to be a dominant mechanism in valleys where the influence of downward momentum transport and thermal wind mechanisms are minimal. This occurs for shallow, but well-channelled linear valleys in a climatological regime with slight or moderately stable atmospheres. It seldom occurs in wide, deep valleys.

In both forced and pressure-driven channelling the within-valley winds have a nearly equal probability of flowing up or down the valley during both daytime and night-time. In practice, all four mechanisms may contribute to the flow regime within a single valley.

2.4.1.3 Implications of Valley Circulations and Inversions for Dispersion

(a) Implications of Valley Circulation

Clearly valley circulations are major determinants of the low-level flow field, particularly at night and in winter, and to a large extent control the transport of ground- and low-level emissions (Broder *et al.*, 1981; Jakeman *et al.*, 1992). During the day the warm ground promotes convective motion and the boundary layer may be extended to depths of several hundred metres, whereas at night turbulence and mixing are suppressed by the development of highly stable air near the ground as a result of the negative heat flux. Up-slope and up-valley winds are therefore associated with greater levels of atmospheric instability than are down-slope and down-valley winds. Due to their non-turbulent nature, down-valley winds are able to transport pollutants tens of kilometres without much

dispersion or dilution. Given the regular occurrence of thermo-topographical circulations over suitable terrain, such winds represent important factors in the determination of air pollution dispersion potentials.

Egan and Schiermeier (1986) identified the impact of various valley configurations, including shallow valleys and deep draining valleys, on the atmospheric dispersion potential. In shallow valleys, the pollution plume is significantly higher than the valley sidewalls. Under stable atmospheric conditions, the plume does not interact with the valley topography except that the plume trajectory may be channelled along the valley axis. In the deep, draining valleys pollutants are released within valleys. The dispersion of such pollutants is dependent on the behaviour of the valley atmosphere and its interaction with the underlying valley topography.

In order to understand fully the implications of valley circulation systems for the dispersion of pollutants it is necessary to consider not only the nature of individual winds, but also the impact of diurnal reversals in airflow. Meso-scale circulations often represent highly adverse pollution conditions due to such diurnal flow reversals. Fumigation episodes are often associated with the early-morning decay of nocturnal winds and the onset of advancing up-valley winds. The dissipation of one wind system, and onset of another may also provide for the recirculation of pollutants. Pollution advected towards the mouth of the valley by a down-valley wind may be recirculated by the up-valley wind.

(b) Implications of Valley Inversion

Ground-level air pollution maximas within valleys occur during the early morning and in the evening largely as a result of the development and dissipation of the valley inversion. Valley inversions develop from the ground upward resulting in the replacement of the turbulent mixing layer with low-level atmospheric stability. Under highly stable conditions vertical dispersion is suppressed, the dissipation of pollution taking place largely by laminar diffusion. The dissipation of the valley inversion from the base upwards, and the gradual development of an effective mixing layer beneath the inversion frequently results in fumigation conditions. During fumigation the inversion acts as a 'lid' above the pollution plume, preventing upward dispersion and the concentration of pollutants within the confined mixing layer.

(c) Interaction of Valley Systems with Synoptic Circulations

The interaction between valley flows and above-valley flows are important in estimating the consequences of the regional transport of pollutants (Allwine, 1993). This interaction needs to be taken into account when assessing the dispersive characteristics of valleys and estimating the valley ventilation rate (Ulrickson and Mass, 1990).

2.4.2 Orographically-induced Meso-circulations

The practical evaluation of the wind field in complex terrain is of great interest in air quality evaluation (Finardi *et al.*, 1993, Walmsley *et al.*, 1990; Taylor *et al.*, 1987; Walmsley *et al.*, 1982; Hunt, 1980; Pielke *et al.*, 1983). In 1975 Jackson and Hunt observed that there had, until that time, been few attempts to relate measurements of wind velocity and turbulence on hills to the local topography. The work of Jackson and Hunt represented the beginning of a modern approach to the study of boundary-layer flow over hills. In the subsequent twenty years substantial research effort has been undertaken aimed at rectifying this omission (Taylor *et al.*, 1987). The studies of Mason and Sykes (1979), Sacre (1979) and Bradley (1980) provided the first useful data from field experiments over low hills. Subsequent work aimed at the extension and refinement of the analytical, linear and asymptotic approach of Jackson and Hunt in order to cope with the increasingly detailed description emerging from the growing body of field experiments. A close relationship developed between field experiments and theoretical advances (Mason and Sykes, 1979; Taylor *et al.*, 1983; Zeman and Jensen, 1987). More recently wind-tunnel models have increasingly been used in the development of theory (Finnigan *et al.*, 1990; Gong and Ibbetson, 1989; Britter *et al.*, 1981; Pearse *et al.*, 1981)

The first analytical model, proposed by Jackson and Hunt (1975), aimed to provide an approximate theory of non-separating flow over a low, two dimensional hill. Numerous models were subsequently based on the theories of Jackson and Hunt, most models assuming neutral thermal stratification, a uniform surface roughness, and an isolated feature in an otherwise flat plain (Taylor *et al.*, 1987; Walmsley *et al.*, 1986; Mason and King, 1985).

Jackson and Hunt (1975) postulated a two-layer structure for the flow over a gentle hill, consisting of an inner and an outer layer. The outer layer is assumed to be essentially inviscid while turbulent transfer processes are dynamically significant only within the inner layer. Jackson and Hunt introduced turbulent transport by means of a mixing-length model to obtain an analytic inner-layer solution in which the flow pertubations increase with height.

Several laboratory and field experiments (Britter *et al.*, 1981; Bradley, 1980; Mason and Sykes, 1979) have shown that the Jackson and Hunt's linear theory can predict the mean flow perturbation reasonably well, even for hills of moderate slope (Gong and Ibbetson, 1989). Further tests and applications proved the linearised theory to give reasonably good results on the upstream side and on the top of hills with $h/L <$ or $=$ 0.3-0.4 (16.7 to 21.8 degrees)(Taylor *et al.*, 1987), and for $h/L <$ or $=$ 0.58 (or 30 degrees); where h is the height of the hill in metres, and L is the horizontal length expressed as the half-length at half-height (Finardi *et al.*, 1993). Due to the use of simple mixing-layer closure by linearised models, the inner layer is always modelled as being in local equilibrium and wake effects

are underestimated. The study of Gong and Ibbetson (1989) concludes that these types of linear model are quite adequate on the upwind side and the top of the hill, even when the slope is moderate, but that it fails on the lee side where there exists a distinct wake region.

Following the work of Jackson and Hunt, several studies have aimed at elucidating the role of separation bubbles in pollutant trapping and so considered steep hills by developing more sophisticated closures (Ying *et al.*, 1994; Zeman and Jensen, 1987). More recent work has also attempted to improve on past theoretical and numerical analyses which have largely been restricted to the modelling of airflow over two-dimensional topographic features. Jackson and Hunt's linear theory for terrain-induced mean flow perturbations above two-dimensional low hills was extended to three-dimensional terrain features by Mason and Sykes (1979), and has formed the basis for a series of models developed by Walmsley *et al.*, (1986, 1982), Taylor *et al.* (1983) and Mason and King (1984). The latter two references introduce terrain wavelength dependency modifications which are particularly useful for real terrain applications, and are frequently referred to as the 'modified Jackson-Hunt (JH) theory'. This theory takes into account spatial variations in both surface roughness and surface elevation.

During the past few decades considerable research has aimed to improve the understanding of flow and dispersion characteristics under topographic influences. Field measurements, in conjunction with theoretical, numerical and wind tunnel studies and tracer experiments currently provide a good basis for a preliminary description of neutrally stratified boundary-layer flow over low hills. To date, the alterations in the mean wind field and turbulence profiles resulting from airflow over uneven terrain, and the implications of such flow convergence-divergence and turbulence for pollution dispersion are qualitatively well understood. A qualitative relationship has also been established between the downwash resulting from the flow separation in the lee of hills, the location of sources in relation to hills, and significant changes in ground-level concentrations. A comprehensive quantitative understanding of the relationship between flow and dispersion over complex terrain has, however, not yet been established.

2.4.2.1 Characteristics of Airflow over Hills and Implications for Dispersion

Airflow may become separated from the surface if it passes over a hill, and a low pressure region created to the lee of the hill which sucks part of the fluid towards it often generating turbulent vortices in the hills wake. Gradual slopes of varying elevation usually allow the boundary layer to adjust without separation. The airflow normally accelerates as it nears the hill due to the flow being constricted vertically, and decelerates after the hill due to the increase in depth.

A simple rule-of-thumb has been developed in recent years for estimating the degree of speed-up in mean velocity over the ridge. This is given as:

$$\Delta S_{max} \approx 2\, h/L \qquad (2.2)$$

where

ΔS_{max} = maximum fractional speed-up
h = height of the hill (m)
L = length of the hill (defined as the half-length at half-height) (m)

Taylor and Lee (1984) have revised the maximum fractional speed up for 3D axially-symmetric hills to $\Delta S_{max} \approx 1.6\, h/L$. Knowledge of localised areas of wind speed-up is important to the siting of emission sources to maximize pollution dispersal.

Steep hills result in flow separation and the development of bolster and lee eddies. As the flow approaches the steep ridge a pressure build-up occurs, resulting in the development of a pressure maximum in the middle to upper part of the face. The major portion of the flow moves upwards and squeezes over the ridge. Some of the flow is deflected and drawn downwards (towards the lower pressure) and forms a bolster eddy or roll vortex along the base. At the base of the face winds are therefore weak, unsteady and turbulent. The flow which streams over the ridge separates and a lee eddy forms . The winds on the leeward slope are thus counter to mean flow, weak and unsteady, and the area is sheltered in the mean but subject to short-term gustiness. The turbulent wake of the hill, shaped like a horseshoe in plan, extends downstream for a considerable distance. The horizontal extent of bolster and lee eddy circulations is related to the size of the forcing obstacle, and the prevailing atmospheric conditions, particularly wind and vertical stability.

On smooth, symmetrical, two-dimensional ridges, the critical slope angle for flow separation is around 17 to 20 degrees. Separation on less steep hills will occur if the surface is rough (Finnigan *et al.*, 1990). Intermittent flow separation has been found to occur on rugged hills with maximum slope angles as low as 12.5 degrees (Britter *et al.*, 1981). Intermittent separation bubbles have been observed for a number of gentle (9°, 12.5° and 16°) vegetated and or rugged hills (Finnigan *et al.*, 1990; Britter *et al.*, 1981). Such observations accord well with the increased turbulence in the wake noted behind both steeper ridges (Arya *et al.*, 1987).

The depth of the inner layer is important in evaluating the dispersion of pollutants from a source. The height of a source located on a hilltop is, for instance, compared to the depth of the inner layer in order to determine whether the source is within the turbulent layer, and consequently whether the potential exists for entrainment of its emissions into the cavity region on the lee of the hill (Beljaars and Taylor, 1989). Jackson and Hunt's *l* is probably best considered as a scale height for the inner layer.

The ability to predict the area of shelter resulting from the presence of a hill is useful to avoid the siting of sources in areas conducive to fumigation conditions. Lee eddies are semi-enclosed circulation systems and are therefore poor locations for a pollution source. If the source is build very close to, or on the leeward slope, pollutants are trapped in the lee eddy and recirculated towards the source. Sources built at small distances away from the leeward slope may be affected by the altered flow, with plumes being forced to ground-level by downwash.

Dispersion experiments have been conducted over two-dimensional ridges with various source locations (Gong, 1991; Arya *et al.*, 1981, 1987). and over three-dimensional hills under both neutral (Gong and Ibbetson *et al.*, 1989) and stable stratified conditions (Snyder and Hunt, 1984). A parameter termed the 'terrain amplification factor', defined as the ratio of maximum ground-level concentration in the presence and absence of hills, was introduced to study spatial variations in magnitude and location of maximum ground-level concentrations resulting from topographic influences.

For the purpose of the current study the onset of flow separation will be predicted based on the dimensions of the hill. The conclusions reached in the above mentioned dispersion experiments are useful in quantifying the horizontal extent of bolster and lee eddy circulations, and will be used in the establishment of the meso-scale scenarios for the current investigation (see Chapter 6).

2.5 Air Pollution Meteorology and Atmospheric Dispersion Climatologies

Meteorological mechanisms govern the dispersion, transformation and eventual removal of pollutants from the atmosphere (Shaw and Munn, 1971; Stern, 1976; Twomey, 1977; Dobbins, 1979; Pasquill and Smith, 1983; Godish, 1991). The extent to which pollution will accumulate or disperse in the atmosphere is dependent on the degree of thermal and mechanical turbulence within the earth's boundary layer (Diab, 1975; Martin, 1979; Pasquill and Smith, 1983; Preston-Whyte and Tyson, 1988; Oke, 1990).

Dispersion comprises vertical and horizontal components of motion. The vertical component is defined by the temperature profile of the atmosphere which controls the intensity of thermal turbulence and the depth of the surface mixing layer. Since ambient air pollution concentrations are largely a function of the altitude to which pollutants are able to mix, the mixing depth provides a useful indication of the air quality which may be expected (Diab, 1975; Dobbins, 1979; Pasquill and Smith, 1983; Godish, 1991). Temperature inversions represent extreme forms of atmospheric stability and thus present the most adverse conditions for air pollution dispersion. Research into the formation, frequency of occurrence and characteristics of surface and elevated inversions have proved

fundamental to the understanding of air pollution dynamics (Backer *et al.*, 1969; Diab, 1975; Tyson *et al.*, 1976; Preston-Whyte *et al*,, 1977; Surridge, 1986).

The horizontal dispersion of pollution in the boundary layer is primarily a function of the wind field. The wind speed determines both the distance of downwind transport and the rate of dilution as a result of plume 'stretching'. The generation of mechanical turbulence is similarly a function of the wind speed, in combination with the surface roughness. The wind direction, and the variability in wind direction, determine the general path pollutants will follow, and the extent of cross-wind spreading (Shaw and Munn, 1971; Pasquill and Smith, 1983; Oke, 1990).

Pollution concentration levels therefore fluctuate in response to changes in atmospheric stability, to concurrent variations in the mixing depth, and to shifts in the wind field. Spatial variations, and diurnal and seasonal changes, in the wind field and stability regime are functions of atmospheric processes operating at various temporal and spatial scales, as described in Sections 2.2 and 2.3 for macro- and meso-scale processes. Atmospheric processes at each of these scales need therefore to be taken into account in order to parameterise accurately the atmospheric dispersion potential of a particular area (Niemeyer, 1960; Miller and Niemeyer, 1963; Holzworth, 1964; 1967; Diab, 1975; Tyson *et al.*, 1988; Oke, 1990).

Substantial research has been directed towards the establishment of dispersion climatologies for various areas, both locally and abroad (Holzworth, 1962; Onesta, 1963; Williams, 1964; Langenberg, 1974; van As *et al.*, 1974; Tyson *et al.*, 1988; Viswanadham and Santosh, 1989; Kallos *et al.*, 1993). Dispersion climatologies attempt to describe the atmospheric dispersion potential of areas, and the temporal variations in such potentials, as a function of the macro-, meso- and, where appropriate, micro-scales of ventilation which characterise the area. Consequently, such dispersion climatologies provide the basis for the assessment of both long-term accumulations of background pollution concentrations, and short-term worst-cases of pollution dispersion potential, which may be expected for a particular region.

The macro-ventilation characteristics of a region are determined by the nature of the synoptic systems which dominate the circulation of the region, and the nature and frequency of occurrence of alternative systems and weather perturbations over the region. Meso-scale processes affecting the dispersion potential include thermo-topographically induced circulations, the development and dissipation of surface inversions, and the modification of the low-level wind field and stability regime by urban areas. Micro-scale processes, such as the effect of buildings and surface roughness on low-level airflow patterns, contributes to the complexity of establishing the dispersion potential of a specific site (Orlanski, 1975). The development of dispersion climatologies thus requires substantial information on the general climate and topography of regions, in addition to

detailed knowledge of factors affecting the local wind field and stability regime over such regions.

An atmospheric dispersion climatology data base provides the cornerstone for effective air pollution scoping studies. No readily accessible dispersion climatology data base is available for the assessment of regional dispersion potentials within South Africa. The generation of such a data base would be costly, data-intensive, and time-consuming, and hence unsuitable for scoping studies.

2.6 Environmental Risk Assessment

Environmental risk is no longer defined solely in terms of human health. Potential harm to the biophysical environment, the economic system and the quality of human life is increasingly being incorporated into the concept (Lipton *et al.*, 1993; Forbes and Forbes, 1994; Harris *et al.*, 1994). During the past two decades, the assessment of environmental risk has become an important tool for providing qualitative and quantitative estimates of the adverse impacts of pollutants on various environmental components (Russel and Gruber, 1987). Environmental risk assessment incorporates four distinct stages, namely, hazard assessment, dose-response analysis, exposure assessment, and risk characterisation.

The process of hazard assessment is aimed at determining whether particular substances cause adverse impacts on various aspects of the environment. The process results in a qualitative description of the impact of pollutants based on predicted ambient concentrations and knowledge of the biological effects of pollutants. The quantification of these adverse impacts is made possible through dose-response analysis and exposure assessment. By combining information generated through hazard assessment, dose-response analysis and exposure assessment, the overall risk posed by a particular pollutant to the environment may be characterised (Ott, 1990; Paustenbach *et al.*, 1990; Lipton *et al.*, 1993). As a comparatively new discipline, many of the methodologies employed in the various stages of environmental risk assessment are currently the subject of debate and change.

Concern over the environmental effects of air pollution has resulted in the development of new area of study. Whereas environmental epidemiology and toxicology are concerned with the harmful effects of chemicals encountered by people through air pollution, ecotoxicology studies the effects of pollutants on the structure and function of intact ecosystems and communities (Forbes and Forbes, 1994). These fields reflect the interests of toxicologists, epidemiologists and ecologists in the biological effects of natural and synthetic pollutants. Although substantial progress has been made in understanding the relationship between air pollution and environmental effects, the field still appears to be a mixture of facts and suppositions. Three areas of research have complicated the detection

of pollution-caused effects, namely: the differentiation between natural and pollution-caused changes, the determination of the synergistic effects of pollutants, and the identification and correlation of cause and effects (Masters, 1971; Lynn, 1976; Forbes and Forbes, 1994).

Despite the methodological problems associated with environmental epidemiological studies, it is well established that air pollution causes both acute health effects during major air pollution episodes, and chronic effects associated with relatively low levels of pollution (Masters, 1971; Lynn, 1976; Dassen *et al.*, 1986; Stevens and Swackhamer, 1989). In South Africa epidemiological research into the impact of industrial pollution on the health of populations situated near emission sources is becoming increasingly important. To date studies have been conducted in Sasolburg, the eastern Transvaal highveld area, the East Rand and in the Vaal Triangle (Coetzee, 1984; Zwi *et al.*, 1990; Opperman *et al.*, 1993; Terblanche *et al.*, 1993). International investigations into air pollution injury to vegetation have also made considerable progress (Linzon, 1971; Lynn, 1976; Forbes and Forbes, 1994). Environmental epidemiological and toxicological studies have produced a range of associative evidence for the relationship between air pollution and environmental change. Inadequate knowledge exists, however, on dose-response relationships and on the intensity, frequency and duration of human exposure (Ferris, 1978; Stevens and Swackhamer, 1989; Paustenbach *et al.*, 1990; Lipton *et al.*, 1993; Forbes and Forbes, 1994).

To date, few attempts have been made to incorporate the analytical techniques of risk assessment into environmental impact assessment (EIA) studies. EIA studies typically predict only the environmental fate of contaminants, rather than the effects of such contaminants on the environment. Consequently, EIAs generally exhibit crude and simplistic estimates of the magnitude, likelihood and time distribution of impacts (Andrews, 1988). The integration of environmental impact and risk assessments into a unified analytical process would clearly improve the effectiveness of environmental management.

CHAPTER 3 - AIR POLLUTION LEGISLATION

3.1 Introduction

An evaluation of the need for air quality scoping studies and the determination of the criteria for environmental decision making, necessitates an understanding of the legislative context. Air quality management, like other aspects of environmental management, is currently in a state of transition. Substantial changes in the approach to, and organisational and functional structures responsible for air quality management is anticipated in the near future. A synopsis of the current state of, and anticipated future development in air pollution control in South Africa is presented in this chapter. The synopsis includes a review of the following factors:

- Existing air pollution control structures and legislation in South Africa.
- Problems with current air pollution control in South Africa.
- Current local thinking on, and international trends in, air quality management.
- Most likely approach to be adopted for future air quality management in South Africa.
- Anticipated future organisational and functional structures to facilitate local air quality management.

3.2 Existing Air Pollution Legislation and Control in South Africa

3.2.1 Current Air Pollution Legislation and Control Structures

Air pollution control is administered at a national level by the Department of Environmental Affairs and Tourism according to the Atmospheric Pollution Prevention Act No. 45 of 1965 as amended. The Department of Health, formerly the Department of National Health and Population Development, was responsible for air pollution control prior to April of 1996. The Air Pollution Prevention Act regulated the control of noxious and offensive gases emitted by industrial processes, the control of smoke and wind borne dust pollution, and emissions from diesel vehicles. The implementation of the act is charged to the Chief Air Pollution Control Officer (CAPCO).

All industries undertaking scheduled processes are controlled by CAPCO through Best Practicable Means (BPM) using permits. Scheduled processes, referred to in the Act, are processes which emit more than a defined quantity of pollutants per year. Such processes include large combustion sources, smelting and inherently dusty industries. BPM represents an attempt to restrict emissions while having regard to local conditions, the prevailing extent of technical knowledge, the available control options, and the cost of abatement.

Although emission limits and ambient concentration guidelines are published by the Department of Environmental Affairs and Tourism (DEAT), no provision is made in the current legislation for ambient air quality standards or emission standards. The decision as to what constitutes the best practicable means for each case is reached following discussions with the industry. A registration certificate, containing maximum emission limits specific to the industry, is then issued.

CAPCO is responsible for the control of dust from industry and waste dumps. Dust control from mine dumps is the result of consultation between the Government Mining Engineer and CAPCO. The control of dust is undertaken using BPM through notice in writing.

Local authorities are responsible for the regulation of emissions from vehicles and domestic fuel combustion under the powers conferred by the Minister of the DEAT. Emissions from domestic fuel combustion are controlled through smoke control zone orders, and through the regulation of fuel-burning appliances installed in the local authorities' areas of jurisdiction. Provincial tiers of government are currently not involved in air pollution control.

3.2.2 Existing Approach to Air Pollution Control

It is evident from the previous section that air pollution management in South Africa is currently based entirely on source-based controls, and is focused primarily on controlling the emissions from the industrial sector. Proposed industries are permitted to go ahead if compliance with emissions limits set by CAPCO is demonstrated. Project proposers are not currently required to prove - through, for example, dispersion modelling - that the proposed development will comply with ambient air quality guidelines. Emission limits imposed by the Chief Officer on the proposed industry also tend to reflect the prevailing extent of technical knowledge, and the availability of control options which do not exceed "excessive costs", rather than measures to ensure the maintenance of acceptable air quality.

3.3 Problems with Existing Air Pollution Control in South Africa

3.3.1 Weaknesses in Current Control Structures

As a result of the current legislation, the administration of air pollution control in South Africa is highly fragmented. At a national level, various departments are responsible for implementing the existing legislation, including the Department of Health, the Department of Environment and Tourism, and the Department of Minerals and Energy. Comprehensive control of air pollution at a local level is hindered due to the division of responsibilities for implementing regulations between national and local authorities.

Air pollution control within metropolitan areas is similarly impeded due to the absence of a single authority able to undertake the day-to-day tasks required for implementing control. Each metropolitan area may have several air pollution control officers and town planners each operating within their own municipal boundaries. Since air pollution does not adhere to political boundaries, it is essential that a single authority be established to facilitate the management of air quality within the metropolitan area.

The fragmented organisational structure of air pollution control has several adverse consequences:

- Discrepancies, anomalies and ineffectiveness in air pollution control.
- Air pollution considerations are afforded fairly low priority in planning.
- Answers required for air pollution management decisions can not be obtained quickly.
- Air pollution control personnel do not form a coherent and recognisable body and consequently lack both status and authority and have few prospects for promotion.
- The national authority is not bound in all respects by its own legislation. This provides the potential for inconsistencies and subjectivity in the decision making process.

In addition to the fragmented organisational structure of air pollution control authorities, inadequate staffing has furthermore severely limited the effective enforcement of the existing legislation.

3.3.2 Problems Inherent in the Existing Approach to Air Pollution Control

The nature of the present air pollution legislation similarly has several shortcomings:

- Air pollution control is currently based entirely on source-based controls rather than on the achievement and maintenance of ambient air quality standards.
- It does not deal with all pollution sources. The permit system is applied only to stack emissions. Various sources of fugitive dust emissions, such as roads, open pit mining, construction and demolition and agriculture have been omitted. Emissions from biomass burning, aviation, and toxic substance transport and spills have also been overlooked.
- The cumulative effect of multiple sources at a particular industrial area is not taken into account. Multiple sources may result in unacceptable ambient air quality despite each source remaining in compliance with emission limits.
- Not enough attention has been paid to exposure levels, for example human exposure to domestic coal burning emissions in townships.
- Public participation in the decision-making process is impeded due to the centralisation of the responsibility for air quality management at the national level.

3.4 International Trends in Air Quality Management

Considering that air pollution control in South Africa frequently reflects the nature of foreign air quality legislation, current international trends in air quality management must be taken into account. The need, outlined in the Reconstruction and Development Programme (RDP) document, for the review of, and conformity with, international conventions and agreements on environmental issues, presents further justification for an assessment of international experience.

3.4.1 Trends in the European Community

Current thinking in Europe on air quality management is effectively reflected in the directive on Ambient Air Quality Assessment and Management published by the European Union Environmental Council (June 1995). The main ideas presented in the directive include:

- An integrated approach to the protection of air, water and soil.
- The maintenance of ambient air quality where it is good and the improvement of air in other cases.

- Air quality management through the implementation of multiple levels of ambient air quality standards, including:
  - "Limit values" of pollution concentrations. Such values are based on scientific knowledge, with the aim of avoiding, preventing or reducing harmful effects on human health and the environment as a whole. Limit values are to be attained within a given period and are not to be exceeded once attained.
  - "Target values". In order to avoid harmful long term effects on human health and the environment target levels are to be attained where possible over a given period (long-term acceptable thresholds). Such levels represent a long term goal to be pursued through cost-effective progressive methods. At these levels pollutants are either harmless to health and the environment, or unlikely to be reduced through expending further reasonable cost on abatement due to background sources or other factors.
  - "Alert thresholds" refer to levels beyond which there is a risk to human health from brief exposure. The exceedance of such thresholds necessitates immediate steps.

- The development and implementation of plans for non-attainment areas aimed at attaining the 'limit value' within a specified time limit.
- Mandatory measurement of ambient air quality in agglomerations (i.e. areas in which the number of inhabitants exceed 250 000) and other areas where air pollution levels exceed the limit value.
- The establishment of criteria and techniques to ensure the standardisation of methods and location of ambient air quality monitoring.
- Public accessibility to information on ambient air quality.
- The delegation of various functions to the most appropriate levels of government (national, provincial and local).

Mandatory environmental quality standards (EQS) have been set by the EC for several air pollutants. In instances where no EQS is available, reference is made to the various data sources for the setting of provisional environmental assessment levels (EAL). EALs are derived for both long term and short term exposure to air. In developing such EALs three objectives have been taken into account: (1) the protection of human health, (2) the general protection of ecosystems, and (3) the protection of other sensitive receptors such as buildings or commercial activities requiring a particular environmental quality. Data sources used to derive the EALs include: the World Health Organisation (WHO) air quality guidelines for Europe 1987, other international organisations, relevant national organisations (e.g. US EPA IRIS database), Health and Safety Executive (HSE) occupational exposure standards, and HSE maximum exposure limits. The EC made use of a standardised protocol in the development of EALs so as to ensure that the levels were consistent, reproducible and readily understood (HMIP, 1994).

3.4.2 Trends in the UK

During 1994 and 1995 the United Kingdom developed a new air quality policy and legislation. The legislation, which was enacted in August 1996, reflects an innovative approach to air quality management and could provide valuable guidance for the evolution of policy in South Africa. The British approach is very similar to that of the European Council discussed in the previous section. The most important trends in the air quality legislation of the UK are as follows:

- A shift of focus from a source-based approach to an effects-based approach is evident in the current new legislation.

  An effects-based approach is promoted as a method of ensuring that policy is focused on objectives rather than means, thus encouraging the development of innovative approaches to air quality management. Source-based controls are perceived as one strategy for achieving ambient air quality standards. A variety of other instruments, including economic measures and national policies aimed at progressive movements towards the achievement of standards, are being investigated to ensure that the management of air quality is flexible and cost-effective. An effects-based approach thus does not dispense with technology-based controls but provides an effective frame of reference by which such controls can be measured and judged.

- An effects-based approach based on multiple levels of standards is proposed. Despite the difference in terminology, the standards outlined in the British legislation are essentially the same as those given in the European Union Directive. Levels of ambient standards referred to include:

  ~Alarm thresholds. The level for a pollutant or combination of pollutants where there is a potential risk of immediate serious damage and immediate response is required.

  ~Long-term acceptable thresholds. Such levels represent a long term goal to be pursued through cost-effective progressive methods. At these levels pollutants are either harmless to health and the environment, or unlikely to be reduced through expending further reasonable cost on abatement due to background sources or other factors.

  ~Background thresholds. Background levels reflects the impact of background, non-anthropogenic sources of pollutants.

- The identification of, and focus of air quality management on, "hotspots". Hotspots refer to areas in which air quality standards are, or may potentially be, exceeded.
- The provision of technical guidance documents for air quality monitoring and source inventory preparation.

- The decentralisation of air pollution control and support of local air quality management so as to gear programmes to suit local circumstances.
- The integration of air quality considerations into land use and development planning.
- Emphasis on even-handed (proportionate) and cost-effective management strategies though control of contributions by all types of sources (industrial, domestic, transport).
- The encouragement of public participation through facilitating the involvement of the public in the permitting system.

3.4.3 Trends in the USA

The Environmental Protection Agency (EPA) is responsible for air pollution control in the United States. Recently the EPA has placed increasing emphasis on the achievement of ambient standards through the adoption of an integrated cross-media, place-driven approach. Multiple levels of standards are set. In addition to primary and secondary National Ambient Air Quality Standards (NAAQS), Prevention of Significant Decline (PSD) increments have been determined to protect pristine environments. Place-driven approaches, which refer to the tailoring programmes to suit local context, are believed to gives rise to innovative and flexible ways of achieving goals (Preston-Whyte, 1989; Schulze, 1993).

The decentralisation of air quality management and the development of programs and plans to achieve and maintain compliance are currently undertaken in the US. Metropolitan air quality planning is enforced at the state level. State or regional governments are required to submit plans for areas not in compliance with NAAQS. Such state implementation plans (SIPs) need to outline management strategies which would ensure the attainment of air quality standards over a specified time span.

The EPA issues extensive guidance documents on the development of SIPs and provides technical advice on air pollution control measures which may be adopted to attain compliance. Such guidance reflects two important trends in US air quality management:

- the establishment of federal-state partnerships so as to achieve objectives.
- the shift of the EPA from traditional "command and control" style regulation towards a partnership approach with industry.

Source-based controls, including New Source Performance Standards (NSPS), Best Available Control Technology (BACT) for new sources, and Reasonably Available Control Technology (RACT) for existing sources, continue to be used as tools to achiev maintain standards. Increasing use is, however, being made of market force

environmental goals. Economic incentives are perceived to provide effective alternatives to command-and-control measures in certain instances.

Further trends in air quality management in the US include:

- the integration of environmental equity issues into environmental management considerations.
- information-based motivations for environmental improvement, i.e. making information freely available to the public in order to place pressure on polluters.
- public participation in the decision-making process and the empowerment of communities through education.

3.4.4 Trends in Germany

Air pollution legislation in Germany emphasises the attainment and maintenance of ambient standards, through source-based controls, such as emission limits. One of the most important foundations underlying the legislation is the precautionary principle which provides for instances where environmental tolerances are unknown.

3.4.5 Trends in Switzerland

Maximum emission levels and ambient air quality impact thresholds are imposed by federal law. The success of air quality management in Switzerland is believed to be largely due to mandatory monitoring programmes, the severe penalties given for non-compliance with ambient standards, and the decentralised nature of air quality management. Swiss cantons are empowered to enact their own regulations and to produce their own clean air strategy to meet and maintain ambient standards.

3.4.6 United Nation's Agenda 21 Initiative

According to the UN's Agenda 21 initiative cities are designated as key areas for action, and local governments provided with a special mandate for air quality management. This initiative is primarily designed to ensure that practical policies and programmes are tailored to the local context, and allow for the implementation of sustainable development at city level. Considerable emphasis is placed on consultation with local communities.

3.4.7 Recent International Trends in Air Pollution Management

A review of recent developments in various countries reveals several common trends in air pollution control and management:

- An integrated approach to pollution control planning so as to ensure the effective protection of all media.
- Decentralised management of air quality. Emphasis is placed on the division of functions between national, provincial and metropolitan levels.
- An effects-based approach based on multiple levels of ambient standards.

  The various standards outlined in the European Union directive and the UK legislation explicitly link air pollution concentrations to appropriate remedial action over suitable time scales. Such multiple levels serve to emphasise that changes in ambient air quality take place over extensive periods, and that long term planning is more effective than corrective action aimed at instantaneous improvements in air quality.

- Air quality management planning is given priority.

  Planning is increasingly perceived as the means of achieving and maintaining acceptable levels of air quality, as opposed to an enforcement approach. Such planning promotes the identification of control measures available and the assessment of the cost of such measures and the likely pollution reductions arising from their implementation.

  Formalised planning is further perceived to be a means of facilitating public participation. In the US public hearings are held, and public comments are integrated into the development and evaluation of plans.

- Air quality management planning is more explicitly linked to land-use and transportation planning.

  The greater emphasis placed on the relationship between air quality management and land-use and transportation planning reflects the broader shift towards long term planning and the attainment of 'target values' or 'long-term acceptable thresholds'. Although land-use planning can not ensure immediate improvements in air quality such planning may prove fundamental to the maintenance of acceptable urban air quality levels.

- Place-driven approach to air quality management. This approach refers to the tailoring of measures to suit the local environment so as to ensure innovative and flexible actions to secure ambient standards.
- Employment of a host of measures to achieve and maintain ambient standards, including source-based controls, economic incentives, national policies, and the integration of air quality considerations into land use and development planning.
- Management of all types of sources to ensure proportionate, cost-effective approach.

- Mandatory assessment of ambient air quality in non-attainment areas.
- Provision of technical assistance on air quality monitoring, modelling and source inventory preparation.
- Standardisation of procedures for ambient air quality monitoring.
- Public participation in the management process.
- Public accessibility to environmental information, including right of information to environmentally harmful practices.

3.5 Current Local Thinking on Environmental Issues

In order to present a realistic account of the most probable configuration of future air quality management, a review of current local thinking on, and developments in the realm of air quality management and of the national context within which legislation will be implemented, must be undertaken. The effect of market forces on the evolving policy need also be considered. Current initiatives reflect many of the international trends discussed in the previous section.

3.5.1 Integrated Pollution Control

New approaches to air pollution control, amenable to integrated pollution control (IPC), have recently been investigated in South Africa (Department of Environmental Affairs and Tourism, 1995a, 1995b; L & W Environmental, 1995; Marjanovic, 1995; DEAT, 1998b). The *Draft White Paper on Integrated Pollution Control and Waste Management* was published in August 1998 (DEAT, 1998b). The following guiding principles form the basis for the proposed IPC regulatory system:

- **Equity.** The equal right to a safe environment protected by the regulatory system and proportionate payment for prevention or remediation of adverse environmental conditions.
- **Freedom of Information.** Access to all environmental and safety information, discharges and releases to the environment, decision making documents and process documents generated in the regulatory system.
- **Polluter pays.** The cost of prevention and/or remediation of pollution effects shall be linked as closely to the polluter as possible.
- **Precautionary principle.** In the absence of quantifiable risk, the best available means within the control principle adopted shall be used to protect public health and the environment from exposure to pollutants.

- **Public participation.** The regulatory system should be designed to provide for participation in decision-making by people and communities who may be affected by such decisions.
- **Subsidiarity.** Control of pollution shall be exercised at the lowest effective level of regulatory authority, with appropriate mechanisms to avoid inconsistency of control.
- **Sustainability.** The regulatory system should be consistent, and should contribute directly and indirectly to sustainable development in South Africa.

The guiding principles set out for IPC will form the basis for the new air pollution legislation, underpinning both goals and actions.

3.5.2 Issues Recognised by the Constitution and the RDP

Future air quality management needs to address the following needs, as outlined in the Constitution and RDP Document:

- Safe living and working environments
- Responsibility for environmental matters placed at provincial level, except for aspects which can only be realistically undertaken at central government level
- Environmental considerations must be built into every decision (including development planning)
- Compulsory EIAs for large scale projects
- Public participation in decision-making around environmental issues (communities to manage their natural environment)
- Education and empowerment of communities
- Access to information on environmentally harmful practices

3.5.3 National Context

South Africa has a diverse range of environments which differ with respect to:

- the socio-economic context, and
- the sensitivity of the natural environment.

Future air quality management should be designed to account for such differences.

3.5.4 Market Forces

Increasing pressure is being placed on South African companies to develop and implement environmental management policies. A growing number of multinational companies and foreign bankers are confining their business associations to concerns which reflect their own environmental ethics (Lennon and Surridge, 1996; Betty, 1993).

3.6 Future Air Quality Management in South Africa

The Integrated Pollution Project was initiated to facilitate a review of present governmental functions and structures concerned with pollution control, and to initiate a process of restructuring the regulatory system to produce a more effective pollution control system. The air work team were responsible for drafting a new approach to air pollution control amenable to Integrated Pollution Control. The new approach to air quality management and the recommended restructuring of authorities responsible for such management put forward by the air work team will briefly be discussed in the subsequent sections.

3.6.1 Recommended Organisational Structures for Air Quality Management

Four tiers of authority are foreseen in the execution of control of air pollution:

- It is recommended that the mandate for the co-ordination of air quality management be given to a single **national agency**. Functions of the national agency would include legislation, transboundary pollution management, international agreements, dispute resolution and the demarcation of Local Air Quality Management Areas.
- **Provincial authorities** will be charged with main executive powers for the implementation of control, which may be delegated to lower tiers where the capacity exists.
- **Metropolitan authorities** will be responsible for Local Air Quality Management Areas as identified by the national agency.
- **Local authorities** outside metropolitan areas may derive certain powers from the provincial authorities commensurate with their abilities.

Air quality management at a metropolitan rather than a national level is proposed for two main reasons:

- Decentralised management of air quality is essential to ensure that strategies aimed at securing ambient standards are tailored to suit the local context. Strategies which are sensitive to local environment would solve the problem of overcontrolling in certain areas and undercontrolling in others which plagues air pollution control at the national level.

- Decentralised management would promote public participation. Local involvement in the pollution control process by all role players is better achieved when control is exercised at the lowest level of authority consistent with effective performance.

Each metropolitan area within South Africa faces unique air quality challenges. Air quality management strategies for the Witwatersrand region need to take into account fugitive emissions arising from mine tailing dams, in addition to vehicle emissions and photochemical smog formation. Fugitive dust emission from roadways, and emissions from domestic coal combustion and waste incineration represent the main sources of pollutants in Soweto. The deterioration of air quality in the Vaal Triangle is similarly due primarily to a smoke from domestic coal combustion and fugitive dust emissions, in addition to extensive industrial emissions. The brown haze problem in Cape Town, and the elevated levels of sulphur dioxide in the Durban Metropolitan area, similarly present regionally specific air quality problems requiring tailored management strategies.

It is advocated that the metropolitan authority be charged with the main executive powers for the implementation of air pollution control rather than local authorities for two main reasons:

- Air pollution control at a local level would be ineffective, as often sources outside of the local area contribute to urban concentrations of particulates. Should standards be exceeded in an urban area, the controlling of local emissions may only have a limited effect on reducing ambient concentrations. Airborne particulate matter is a thus a REGIONAL air pollution problem and requires air quality management on a metropolitan level.
- Effective air pollution management necessitates the utilisation of specialist techniques for monitoring and modelling. The expertise and funds necessary for such management may not be available at local levels.

3.6.1.1 The Metropolitan Air Quality Authority

The Metropolitan Air Quality Authority would be responsible for the preparation and co-ordination of the air quality management plan for the region. The council should work closely with the local government, the provincial authorities, and the national agency concerned with IPC.

The Metropolitan Air Quality Council would ideally be composed of:

- Elected officials from local government;
- Business leaders;
- Clean air advocates and others from the region.

- Officers currently concerned with air quality (current air pollution control officers and health officials).
- Representatives of the transportation planning agencies, and representatives of the land use planning organisations in the region.

It is essential that the Metropolitan Air Quality Authority include a division which is able to perform the technical analysis that serves as the basis for strategy development and attainment demonstration. This division would prepare emission inventories, undertake ambient air quality monitoring and exposure assessment, conduct air quality modelling, analyse air quality data, and provide technical assistance and advice. Where such functions cannot be done internally, consultants would have to be contracted.

3.6.1.2 Collaboration with Land Use and Transportation Planning Authorities

Important relationships exist between air quality management, land use planning, and transportation planning. New land use developments can influence both travel patterns and exposure levels. The siting of a residential area in close proximity to an industrial area would, for example, result in increased levels of human exposure to the emissions generated by the industry. Extended transportation networks and increased traffic flows resulting from such new developments would directly influence air quality through enhanced tailpipe emissions of particulate matter and increased reentrainment of dust on roadways. Unless this relationship is recognised and channels of communication established between local and regional agencies responsible for land use planning, air quality management and transportation planning, air quality management is unlikely to succeed.

It may be necessary to establish a metropolitan transportation planning organisation in order to ensure the success of air quality management strategies. Such an organisation would be responsible for the development of a long-range transportation plan and a transportation improvement plan (TIP) for the region. Close collaboration between the Transport Planning Organisation and the Metropolitan Air Quality Authority would ensure the coordination of air quality and transport planning activities and facilitate the effective integration of the respective planning processes.

The Transportation Planning Organisation would be expected to provide demographic and transportation data that would form the basis for the emission inventory being created and maintained by the Metropolitan Air Quality Authority. The organisation should also assist the Metropolitan Air Quality Authority through its analysis of transportation control measures which may be included in the strategy implementation plan, and its review and comment on draft elements of the plan.

3.6.2 Recommended Functions of Air Quality Management Structures

The responsibilities of the various tiers of authorities depends on the level at which air quality functions can best be realized, and the extent to which a certain level of authority is able to assist another level of authority to realise its goals in the most efficient way possible. A fairly detailed description of the responsibilities recommended for the various tiers of authorities is presented in the subsequent sections.

3.6.2.1 National level

The mandate for the co-ordination of air quality management should be given to a national agency. The agency would be geared towards facilitating the **integration of functions** and initiatives undertaken by various government departments concerned with environmental issues.

One of the main functions of the national agency would be the definition of the nature of areas requiring specialised, localised management (i.e. areas in which ambient standards are exceeded, or in which there is a perceived threat of non-compliance). Metropolitan areas should ideally fall within the defined category, and should be designated as local air quality management areas

The main aim of the national agency is to provide the basis for a progressive movement towards the achievement and maintenance of long-term acceptable air quality standards through:

- the implementation of various national policies aimed at reducing, directly and indirectly, ambient concentrations.
- facilitating and co-ordinating air quality management at provincial, metropolitan and local levels.

Functions of the National Agency would include the following:

1. Setting air quality standards and maximum emission limits. This is undertaken at the national level so as to ensure uniformity and afford equal protection for all human health. Such national functions are also important in bringing national standards into accordance with international standards, and in addressing regional pollution issues.

2. Supervision of programmes adopted by provincial and local authorities to ensure conformity with national laws and regulations, including offering assistance in strategy development and in the establishment of timetables.

3. Provision of information and guidance to provincial metropolitan and local authorities to facilitate the effective implementation of plans of action, including:
   a) scientific and professional knowledge in various fields, including technical, legal and administrative.
   b) definition of methodologies for dispersion modelling, ambient monitoring and emission inventory development.
   c) information on best practicable means and technological innovations.
   d) guidance on the structuring of plans of action.
   e) direction on development of structure of public participation and information dissemination.
   f) guidance on the assessment of effects of direct and indirect control measures on other media (land, water).
   g) information on integration of air quality considerations into land use and development planning.
   h) set out methodology for comprehensive impact assessment and management strategy for large scale developments.
   i) regulate issuance of permits.

4. Research and development into various fields (mentioned above). Every attempt should be made to unite all potential resources to study and resolve potential problems.

5. Coordination of environmental monitoring projects, efforts at establishing emission inventories, and education campaigns.

6. Financing of activities, and the securing of stable long-term financing to ensure long-term planning and implementation of consistent policy.

7. Identification of sensitive environments which may need more stringent ambient standards.

8. Administration of international conventions and protocols, e.g. Framework Convention on Climate Change and related Kyoto Protocol, and the Montreal Protocol.

3.6.2.2 Provincial and Metropolitan Level

Where local air quality management areas have been identified, such as the Coega Industrial Development Zone, a special mandate should be granted to metropolitan or local authorities for the management of air quality. The responsibilities of such authorities would be the same as those of provincial authorities.

Functions of provincial and metropolitan authorities need include:

1. Administration of air quality management - includes activities such as:
   a) setting up air quality monitoring network.
   b) the establishment of emission inventories.
   c) the granting of permits.
   d) inspection and supervision.
   e) emergency strategies to be adopted should alarm thresholds be exceeded.
   f) carrying out environmental impact assessments.
   g) informing public of environmentally harmful practices.
   h) launching environmentally awareness and education campaigns.
   i) incorporating environmental impact of development strategies in the course of planning.
   j) various other activities aimed at addressing emissions from all types of sources (industrial, domestic, transport, agriculture, etc.).

2. Setting of more stringent ambient standards - based on sensitivity of environments or on appeals made by local communities.

3.6.2.3 Description of the Functions of Metropolitan Authorities

(a) Establishment of an Emission Inventory

An emission inventory is a comprehensive, accurate and current account of air pollutant emissions and associated data from specific sources over a specific time period. An emission inventory is a key element in programs aimed at improving and maintaining air quality for several reasons:

- An inventory helps define problems in terms of which pollutants should be considered, which sources are important, and what control measures might be most effective. Appropriate air pollution reduction strategies may thus be selected.
- In addition to containing information on present emission levels from the various source categories, an emission inventory should ideally indicate future levels of emissions in the absence of any intervention strategies. The effectiveness of various intervention strategies may then be evaluated.
- An emission inventory also provides the basis for the planning of the ambient monitoring network.

Two main factors are needed to establish an emission inventory: (1) a set of emission factors, and (2) source data to which the emission factors are applied to estimate emissions. The most commonly used source of emission factors in the US EPA document AP-42, *Compilation of Air Pollutant Emission Factors*. Industrial source data consist of stack and exhaust flow parameters, production levels, throughputs, control device efficiencies (etc.), as well as information on source location and plant layouts. In addition to industrial source data, transportation, demographic and land use planning data are needed for the establishment of the inventory. Information on the location and intensity of future activity will also need to be collected.

Prior to the establishment of an emission inventory careful consideration should be given to the costs, and to the personnel and computer requirements involved. The preparation of the first disaggregate emission inventory would require several person-years of effort and considerable cost. Staff will also be needed to update the inventory in order to keep it comprehensive, accurate and current. Emission inventories should ideally be established and maintained at a local level and coordinated at a regional level.

(b) Ambient Air Quality Modelling

Various methods can be used to estimate the air quality impact of emissions of particulate matter using dispersion and receptor models: (1) use of receptor and dispersion models in combination; (2) use of dispersion models alone; and (3) the use of two receptor models, with control strategy developed using a proportional model. The use of receptor and dispersion models in combination is the preferred method.

Dispersion models calculate ambient air concentrations primarily as functions of source configurations, emission strengths, terrain features, and meteorological characteristics. Such models thus provide useful tools to ascertain the spatial and temporal patterns in ambient concentrations arising from the emissions of various sources.

Dispersion modelling may be used to determine the impact of potential strategies aimed at reducing emissions on ambient concentrations. The effectiveness of various strategies may be evaluated prior to their implementation, so facilitating the process of cost-benefit analysis. It is also possible for a region to demonstrate attainment of ambient air quality standards subsequent to proposed intervention through dispersion modelling.

There are numerous types of dispersion models, including the Industrial Source Complex Model (ISC), CALPUFF, RAM, the Fugitive Dust Model (FDM), the Urban Airshed Model, the Hot Spot Model, Climatological Dispersion Model (CDM), Multiple Point Source Model with Terrain Adjustment (MPTER) and Single Source (CRSTER) Model. Extensive use is currently being made in South Africa of the US EPA's FDM and ISC

models. Dispersion models are generally more reliable for estimating longer time-averaged concentrations (e.g. annual averages) than for estimating shorter-term concentrations (e.g. 24-hour) at specific locations.

A further weakness of using dispersion models to compute ambient particulate concentrations is that such models are currently unable to analyse the impact of particulate precursor emissions on the formation of secondary particles. Receptor models are therefore frequently used to determine the total secondary particulate contribution, which is then apportioned among source categories by a proportion consistent with the inventory of nitrogen oxides and sulphur dioxide emissions.

Dispersion modelling may be done inhouse by the metropolitan authority or private consultants may be contracted. Various environmental consultants currently have technical knowledge of dispersion modelling methodology and software. Even if the modelling is done internally such consultants could provide useful guidance on the identification of a suitable dispersion model, and the selection of appropriate source and meteorological data for use in with the model.

Receptor models infer the relative impact of various sources on ambient air quality by reconciling particle size, shape and chemical composition data of ambient air samples with particle size, shape and chemical composition data for various emission sources in the vicinity of the ambient air measurement site.

There are several types of receptor models including chemical mass balance (CMB), factor analysis (FA), optical microscopy (OM) and automated scanning electron microscopy (ASEM). The selection of a receptor model depends on data availability and source characteristics. The most widely used method is the chemical mass balance. CMB compares the chemical "fingerprints" of emissions from several source categories to the chemical composition of the sample.

(c) Monitoring of Ambient Air Quality

The aim of air quality monitoring is to obtain information on ambient concentrations of pollutants and on the spatial and temporal changes of such concentrations. On-line, real-time monitoring is often used to provide early warnings during pollution episodes. Air quality monitoring monitoring also makes it possible to ascertain whether air pollution reduction strategies undertaken have been successful in reducing ambient concentration levels.

The metropolitan authority should be responsible for:

- planning of ambient monitoring network in region;
- coordination of all ambient monitoring;
- collection and collation of data from all areas within the metropolitan region;
- making regional air quality information public available; and
- annual network reviews.

The following tasks may be undertaken by local authorities:

- maintenance of monitoring site;
- episode monitoring;
- special purpose monitoring;
- quality assurance;
- data compilation and reporting; and
- ensuring public availability of local information.

(d) Personal Monitoring and Exposure Assessment

Monitoring the exposure of individuals is important to identify sources which have the most severe impact on human health and welfare.

Use may also be made of an exposure index to measure the relative importance of an emission with respect to its impact on human health. One example of the development of an exposure index involves multiplying the contribution of a source at a specific time to ambient particulate at ground level, with the number of people living or working at that location at that time. The source with the highest index would have the largest impact on the largest number of people and would be a priority in an air pollution control plan.

Intervention strategies adopted may thus be evaluated on the basis of the ability of such strategies to reduce the exposure levels of individuals.

(e) Development of a Strategy Implementation Plan

A Strategy Implementation Plan is needed, for example for the Coega IDZ, to show how the region will remain in compliance with the adopted ambient air quality standards. The development of such a plan involves the formulation of regulatory policies which allow industrial development to take place, while preventing a cumulative increase towards the

primary standards. The establishment and maintenance of an emission inventory for the region, ambient monitoring, receptor and dispersion modelling and exposure assessment form the basis for the development and evaluation of air quality strategies. The final strategy implementation plan may include various control measures, programs and regulations that provide for necessary emission reductions, or the allocation of emission rights under a permitting system.

Recommended structure for the Strategy Implementation Plan:

1. Identification of pollutants to be controlled.
2. Identification of all sources and potential sources of each pollutant - and for each source determine:
   a) quantity of emissions (including temporal patterns in extent of emissions).
   b) percentage contribution to total emissions of a pollutant.
   c) the height of emission - e.g. ground, medium elevated or high elevated source.
   d) likelihood of human exposure to emissions (exposure index) - e.g. emissions near population concentrations.
3. Identification of air quality management strategies for emission permitting:
   a) list and description of possible control strategies for each source and potential sources. (Much of this information is currently available in the national guidelines for scheduled processes.)
   b) explanation of implementation of each measure.
   c) quantification of ambient concentrations as a result of each additional industrial facility through use of dispersion model analysis.
   d) do cost-benefit analysis of controlling each source with each strategy. Cost-benefit analyses should include the consideration of:
      i. source characteristics (i.e.. percentage contribution, height of emission, and exposure index) - to select the sources to be controlled.
      ii. incremental contribution to ambient concentrations as a result of implementation of each strategy - identify most effective strategies for ambient pollution abatement.
      iii. technical feasibility of each strategy.
      iv. socio-economic impacts of each strategy - determine the feasibility of strategies within the socio-economic context.
4. Following final evaluation of strategies, recommend the most cost-effective strategies which may be adopted to minimise emissions.

5. Demonstrate how and when standards may be attained should the recommended strategies be undertaken through the use of dispersion model analysis.
6. Indicate the effect of future emissions from growth and development (industry, transport, population growth) on ambient air quality and demonstrate how compliance will be maintained.
7. Contingency measures may have to be included in the strategy implementation plan. These measures need only be implemented should the recommended control strategies not be successful in achieving and maintaining compliance within a required time period.
8. The plan may also include a comprehensive long-range air quality management plan.

On each occasion that a major new source is planned or modifications to existing industries proposed, the strategy implementation plan must be revised. The revision should include a new source review permit program to govern the construction and operation of new and modified major stationary sources.

The formulation and adoption of the Strategy Implementation Plan should include the following processes:

- *Community Involvement and Public Participation*

  Throughout the development of the Strategy Implementation Plan the Metropolitan Air Quality Authority should seek input from the public, local governments, and the industrial and business sectors.

  Information and education campaigns are essential to ensure meaningful public participation in the SIP development process. The actual process of public participation may be facilitated through public workshops organised to inform public of developments, answer questions and record public comments.

- *Public Hearing Process*

  Once an SIP has been drafted a public hearing process should be held. Following the public hearing the SIP can be revised and finalised.

  The public hearing process should not signal an end to public involvement in the SIP process. Public participation should be extended to include an opportunity to monitor the implementation of the SIP and the progress made in reaching air quality standards.

- *Authority and Resources*

  It must be ensured that agencies involved in the implementation of the SIP have sufficient personnel, funding and authority to implement the plan efficiently and to undertake SIP commitments, including:

  - ambient monitoring (air quality and meteorological).
  - personal monitoring and exposure assessment.
  - receptor and dispersion modelling.
  - continual review of control strategies.

  Where the necessary abilities do not exist at the local or metropolitan level, capacity building should be undertaken. In the case of the Coega IDZ, it may be appropriate for the major industrial operations in the region to jointly fund and operate the technical infrastructure required in support of the Metropolitan Air Quality Authority.

3.7 Recommendations and Conclusions

The air quality of South Africa is increasingly under threat due to rapid industrial expansion and population growth. Several weaknesses in current air pollution legislation, functional and organisational control structures and control approaches are believed to impede the effective management of future air quality. It is anticipated that future efforts aimed at ensuring acceptable levels of air quality will involve a shift from national air pollution control based on source-based controls to decentralised air quality management through an effects-based approach. Such an effects-based approach requires the setting of multiple levels of standards for ambient air quality. Source-based controls represent *one* important measure which may be adopted to assist in the attainment and maintenance of ambient standards.

The future approach to air quality management will most likely include the following five components:

(1) The principle of equity; the control and management of all sources of air pollution relative to their contributions to ambient concentrations to ensure that improvements in air quality are secured in the most timely, even-handed and cost-effective way.

(2) Place-driven strategies aimed at tailoring solutions to the local environment.

(3) Decentralised air quality management.

(4) Public participation in the decision-making process.

(5) The dissemination of information to the public regarding pollution levels and potentially environmentally harmful practices.

The assessment of the environmental risk resulting from a proposed industry, despite compliance with the emission limits promulgated by CAPCO, reflects the shift from air pollution control based on source-based controls to air quality management based on the consideration of the effects of emissions on the receiving environment. The anticipated shift towards on effects-based approach based on multiple levels of standards is furthermore reflected in the current scoping framework by the inclusion of US EPA primary and secondary National Ambient Air Quality Standards and PSD increments in the air quality data base.

CHAPTER 4 - INDUSTRIAL DATA AND MODEL BASE

4.1 Introduction

An emission inventory identifies sources of emissions and quantifies each source's contribution to ambient air pollution concentrations. It forms the basis for assessing the impact of an industry's emissions on the receiving environment (Hammerle, 1976; EPA, 1981a; Godish, 1991). Such an inventory should provide a comprehensive, accurate and current account of pollutants released to the atmosphere by specific facilities, operations and activities occurring at the industrial site. In addition to the pollutants generated from stacks and vents, emissions from mobile and fugitive dust sources need to be taken into account in the compilation of an emission inventory (Bromberg *et al.*, 1982; Mukerjee and Biswas, 1993; Raasch, 1993; van Nierop, 1995).

Data from source-specific emission tests or continuous emission monitors are particularly suitable for quantifying a source's emissions (EPA, 1995a). However, such data may not be available, as in the case of proposed industries. Appropriate emission data for existing industries may similarly be unavailable since test data may not reflect the variability of actual emissions over time. The use of emission factors are frequently the best or only method available for quantifying emissions. Such emission factors relate the quantity of a pollutant to the activity associated with the release of that pollutant. Due to the absence of local emission factors, use is often made of the comprehensive set of single-valued emission factors and predictive emission factor equations published by the United States Environmental Protection Agency (US-EPA) in its AP-42 document (see Section 2.2). Detailed information on the industrial processes being conducted, the nature and quantity of raw materials used, production rates, and air pollution control measures adopted are needed for the calculation of emissions from emission factors.

Detailed data required for emission quantification, and the need to include point, mobile, and fugitive dust sources, renders the compilation of an emission inventory data intensive and time consuming, and hence seemingly unsuitable for an air pollution scoping study. However, most of the information on industrial processes and activities, raw materials, production rates, and control measures proposed for a planned industry, is generally available prior to the initialization of scoping studies. The feasibility of compiling an emission inventory during the scoping phase thus depends on the availability of a data base containing the necessary emission factors, and a model base to guide the quantification of emissions based on such factors.

Following the development of an emission inventory, the anticipated magnitude of emissions may be compared to the emission limits promulgated by the Chief Air Pollution Control Officer (CAPCO). Emission limits represent the level of emissions achievable

through the application of best practicable means (BPM). The decision as to what constitutes the best practicable means for each industry is reached by CAPCO following discussions with the industry.

4.2 Aims and Objectives of the Current Section

The development of a data and model base which would facilitate the identification and quantification of emissions from *all* types of industries is beyond the scope of this study. The purpose of this section is the compilation of a detailed industrial data base and a model base for one type of industry, viz. the integrated iron and steel industry, so as to demonstrate the utility of the conceptual framework.

The iron and steel industry data and model bases are designed to fulfill the following objectives:

- Identify sources of emission from all activities, processes and exposed areas, including upset and certain accidental releases.
- Quantify average annual and short-term worst-case emissions from uncontrolled sources.
- Identify appropriate control measures which may be adopted for each source.
- Estimate average annual emission reductions afforded by each control measure.
- Compare average cost efficiencies of various control measures which may be used to reduce annual emissions from a specific source.
- Evaluate predicted emissions based on the emission limits for scheduled processes promulgated by CAPCO.
- Calculate the additional control required to ensure compliance with emission limits.

The iron and steel industry data and model bases thus enable the development of an emission inventory for the proposed plant, and facilitate the evaluation of whether or not the plant is in compliance with the emission limits issued by CAPCO. In instances of non-compliance the percentage of control needed to bring the industry into compliance is calculated. The user may then alter the design of the proposed industry in order to reach the level of control needed to achieve compliance. Such alterations may entail:

- changes in the nature or amount of raw materials used;
- changes in process operations aimed at decreasing pollutants emitted;
- implementation of additional abatement techniques; or
- combination of the aforementioned changes.

In instances where the user is unable or unwilling to reduce emissions sufficiently to enable compliance with the emission limits issues by CAPCO, the proposed industry will not be authorized and it will be concluded that the proposed project *requires further evaluation.*

The detailed iron and steel data base, model base and user interface are contained in electronic format on the accompanying computer disk as Appendix A. The structure and content of the data base, model base and user interface are described in Section 4.3, and an example given in Section 4.4 to demonstrate the utility of the industrial component of the methodological framework.

4.3 Structure of Iron and Steel Data Base, Model Base and User Interface

US-EPA AP-42 emission factors relevant to the processes conducted in iron and steel industries will be used to quantify the potential gaseous and particulate emissions generated by the proposed industry (EPA, 1995a). Detailed information on the proposed development needed for the calculation of emissions based on emission factors includes: location and extent of the plant, industrial processes and air pollution control measures to be adopted, projected rates of production, and raw materials to be utilised. An industrial data base has been established to assist the user in the collation and entry of the information required. The creation of the industrial data base involved the compilation of detailed data on the activities of local iron and steel plants. The data were obtained from local and international literature, and through structured communication with specific local iron and steel industries.

The data base lists all potential pollutants which may be emitted during iron- and steel-making processes, and indicates the availability of emission factors to quantify emissions from various process operations. This list is presented in Table A.1 in Appendix A. Although emission factors for particulate emissions are available for most process operations, emission factors for gaseous emissions are rather limited. All available emission factors are included in the data base, and the model base is structured so as to guide the quantification of emissions based on such available factors.

Process requirements and emission limits for iron and steel industries, as outlined in the Department of Environmental Affairs and Tourism's *Guidance Document for Scheduled Processes* are given as follows:

PROCESS 30: IRON AND STEEL PROCESSES

Iron and steel processes: That is to say, processes -

- **in which iron, iron ores, steel or ferro-alloys are produced or processed so as to give rise to noxious or offensive gases; or**
- **involving the cleaning of castings and handling of casting mould materials.**

(a) Basic Information

(i) TLV iron oxide fumes = 5 mg/m^3
(ii) TLV iron particulate = 10 mg/m^3 as iron

(b) Guidelines

(i) Sinter Plants:

- Plants erected before 1975: particulate emissions less than 350 mg/m^3.
- Plants erected after 1975: particulate emissions less than 200 mg/m^3. If $CaCl_2$ or HCl is added: particulate emissions less than 100mg/m^3.

(ii) Arc Furnaces:

- Particulate emissions: less than 120 mg/m^3.
- Roof extraction or snuffbox for 2 x 25 ton or 50 ton furnaces and larger.

(iii) Ferro-alloy Plants:

- High efficiency pre-cleaning cyclones are required for pressure-type bag filters.
- Plant design to provide for the inter-changeability of motors and fans.
- Spare motors and fans to be available.
- New furnaces to provide for the removal of fumes from off-gases from secondary sources such as tap holes, etc.
- Proper monitoring and recording instruments are to be provided.
- Availability of air cleaning apparatus to be more than 96% of the time each month at the prescribed efficiency.
- Proper dust control measures to be implemented where raw materials and products are handled.
- All dust emissions to be less than 120 mg/m^3.

(iv) BOF and AOD furnaces to be supplied with primary and secondary extraction and filtration. Particulate emission: less than 120 mg/m^3.

(v) Cupolas:

- Up to a diameter of 910 mm:
  - Wet closed circuit grit arrestor.
  - 6 mm (One quarter inch) stainless steel hood can also be used. In this case the minimum distance between the top of the loading door and the hood to be 6 m. Provision also to be made for easy maintenance of the hood.
- Larger than 910 mm and up to 1220 mm diameter:
  - A multistage purification system. Equipment to be capable of removing 85% of particles with a size of 10 micron in the case of material with a specific gravity of 2 or more
- With inner diameter of more than 1220 mm:
  - particulate emission of less than 120 mg/m^3.

The exceptions to guidelines (v) to (vii) are -

(a) where any cupola is used for a longer period than one shift per day: control equipment as required for the next higher class to be installed;

(b) in a sensitive area, the next higher class equipment also to be installed;

(c) where cupolas of different classes are installed, equipment as specified for the largest cupola to be installed;

(d) when the percentage of the average particle size of a cupola emission changes by 10% (e.g. previously 50% smaller than a certain size and now 60%), then the cupola is classified one class higher.

(vi) Fettling areas and sand handling erected after 1975: Particulate emissions less than 120 mg/m^3. (This emission is specified because it usually occurs near ground level and because new silica surfaces are exposed). Sandblasting should take place underneath suitable hoods which have been provided with suction.

(vii) Hot blast cupolas: maximum particulate emission of 120 mg/m^3.

(viii) Where castings are cleaned and cut with the aid of oxygen: particulate emission less than 120 mg/m^3.

(ix) Emission from sponge iron plants: particulate emissions less than 120mg/m^3. Recommended minimum number of fields for electrofilters: 3.

(x) All other steel processes where fumes are emitted: particulate emissions less than 120 mg/m^3.

(xi) Any other dust source originating in the process to be investigated and controlled.

(xii) Efforts should be made to use odour-free resins in core-making.

TLV = Threshold Limit Value

Final emission limits for scheduled processes are determined by CAPCO for individual industries following discussions with the industry. Consequently emission limits and process requirements, as specified for the iron and steel industry in the Guidance Document, are not included in the data base. Emission limits need to be provided by the user, following interaction between the proposed industry and CAPCO. Emission coefficients included in the industrial data base facilitate the comparison of the predicted releases with the emission limits.

4.3.1 Iron and Steel Data Base

A description of each of the following operations will be included in the data base: coal briquetting, coke manufacture, sintermaking, blast furnace ironmaking, direct reduction ironmaking, iron preparation and hot metal desulphurisation, basic oxygen furnace steelmaking, electric arc furnace steelmaking, open hearth furnace steelmaking, vacuum degassing of steel, miscellaneous combustion processes, and semifinishing and finishing of steel. Following a general description of fugitive dust emissions, the operations and

processes resulting in such emissions are described, including vehicle traffic on paved and unpaved surfaces, material handling and erosion from open areas and storage operations.

Information contained within the data base includes:

- process descriptions;
- lists of processes within each operation which represent potential sources of emissions;
- types of pollutants emitted;
- US-EPA emission factors relevant to each process;
- potential air pollution control technology;
- possible improvements in operational and management practices;
- information on the current status and future applicability of the process; and
- US-EPA equations designed to estimate the control efficiency of various control measures.

Emission factors are unavailable for coal briquetting, direct reduction ironmaking, corex processes, and for various processes within semi-finishing and finishing steel operations. For processes where emission factors are unavailable, an attempt is made to provide an indication of the nature and extent of emissions, based on a review of the relevant literature and communication with representatives from local industries.

Each AP-42 emission factor has been assigned a quality rating by the US-EPA. The quality ratings are defined and the rating afforded each emission factor given in the iron and steel data base. A description of various air pollution control devises is also presented in the data base.

4.3.2 User Interface for the Iron and Steel Industry

The identification and quantification of potential emissions from a proposed industry necessitates the acquisition of a range of information on the industry. Such information includes data on the nature of processes to be undertaken, projected rates of production, proposed types and amounts of raw materials to be used, the nature of air pollution control techniques to be adopted, the extent of the planned paved and unpaved road network, and the projected area of storage piles. In order to attain the necessary information, and structure the users interaction with the data base, a user interface has been proposed.

The user interface will be structured so as to lead the user through a series of questions. The nature of the user's response to earlier questions will determine the nature of subsequent inquiries. The response of the user may take various forms (toggle, menu, range or open-ended responses) depending on the nature of the question.

4.3.3 Industrial Model Base

The model base will draw on information provided in the data base and on data input by the user, so as to:

- Identify points of emission.
- Establish the type of pollutant emitted.
- Ascertain the height at which emissions occur (e.g. ground-level, medium and high elevation emissions).
- Quantify average annual and short-term worst-case emissions for each source, based on EPA single-valued emission factors and predictive emission factor equations. Both uncontrolled and, where possible, controlled emissions will be estimated.
- Quantify total annual and worst-case emissions for each height category arising from the industry, by summing the emissions from each source relevant to the category.
- Calculate the average control efficiency of various control measures, based on EPA control efficiency equations.
- Determine the acceptability of the predicted emissions in terms of best practice as defined by the emission limits set by CAPCO.
- Calculate the additional percentage of control needed in instances of non-compliance, to ensure compliance with emission limits.

The model base will structure the interaction between the user and the data base, so as to provide users with the information and guidance needed to respond to the questions posed in the user interface.

4.4 Example 1 of Industrial Model Application – Sinter Production Process

4.4.1 Industrial Data Base (Sinter Production Process)

4.4.1.1 Process Description for Sinter Production

During sintering, fine-sized raw materials, including iron ore, coke breeze, limestone, mill scale and flue dust, are converted into an agglomerated product, sinter, which may be charged into the blast furnace. Generally, 2.5 tonnes of raw materials, including water and fuel, are required to produce 1 tonne of product sinter.

The sintering process begins with the raw materials, which may be mixed with water to enhance cohesion, being placed on a continuous, traveling grate or sinter strand. A burner hood positioned over the sinter strand ignites the coke in the mixture. The combustion then becomes self supporting, providing sufficient heat to cause surface melting and agglomeration of the mixture (Peters, 1982; EPA, 1995a, 1995b).

Beneath the sinter strand a series of windboxes draw the combusted air down through the material bed into a common duct, leading to a gas cleaning device. The fused sinter is discharged at the end of the sinter strand, where it is crushed and screened. Undersize sinter is recycled to the mixing mill and back to the strand. The remaining sinter is cooled in open air or in a circular cooler by water sprays or mechanical fans. Once cooled, the sinter is crushed and screened for a final time, the fines recycled, and the product sent to be charged to the blast furnaces (Barnaba, 1995; EPA, 1995a).

4.4.1.2 Particulate Emissions and Controls

Emissions are generated from various operations at the sinter plant including raw material handling, windbox exhausts, sinter crushing and hot screening at the discharge end, and cooling and the use of cold screens. Emission factors for particulates are available for such processes (Table A.6).

The windbox exhaust is the primary source of particulate emissions, mainly iron oxides, sulfur oxides, carbonaceous compounds, aliphatic hydrocarbons, and chlorides. Such windbox emissions are frequently controlled by cyclone cleaners followed by a dry or wet ESP, high pressure drop wet scrubber, or baghouse (EPA, 1995a). At the discharge end, emissions are mainly iron and calcium oxides. The crusher and hot screen emissions represent the second largest source of emissions in the sintering process, and are usually controlled by hooding and a baghouse or scrubber (EPA, 1995a). At some sinter plants emissions generated from other material handling operations are captured and vented to a baghouse (Barnaba, 1995; EPA, 1995a).

4.4.1.3 Gaseous Emissions and Controls

Sinter plant operations may result in various gas emissions in addition to particulate emissions. Potential gaseous emissions include CO and NO_x (EPA, 1995a; Pengelly, 1995). Uncontrolled sinter windboxes may emit large quantities of CO. According to US-EPA emission factors, 22 kg of CO may be released per tonne of finished sinter produced (emission factor rating is C). NO_x is released from sinter strand waste gas (Pengelly, 1995). No emission factors are available for NO_x emissions from the sinter plant.

4.4.1.4 Future Trends in Sintering

Various techniques, including direct reduction, smelting reduction, and direct steelmaking, which will eliminate the need for sintering, have been developed (Chatterjee, 1995). The Corex process (a smelting reduction technology) eliminates the need for cokemaking and sintering. Sinter production does not, however, necessarily end with the introduction of the Corex process. In South Africa, sinter production has continued despite the Corex process having been adopted, since sinter has been used as a feed material in addition to iron ore and pellets (Engineering News, 1995a; Iscor, 1996).

4.4.2 User Interface (Sinter Production Process)

Case-specific information is required to quantify emissions from the proposed process, and to determine temporal variations in such emissions. The nature of the response required for each of the questions given below is indicated by the following symbols: <T> for toggle options, <M> for menu options, <R> for range options, and <O> for open-ended responses.

Production Schedule

- Process seasonal throughput (%) - i.e. the percentage of total sinter which is produced in each season:
  - ◊ December to February **<R>**
  - ◊ March to May **<R>**
  - ◊ June to August **<R>**
  - ◊ September to November **<R>**

Production Rates

- Amount of finished sinter produced per year in tonnes **<O>**
- Maximum amount of finished sinter produced per day in tonnes **<O>**

Air Cleaning Equipment

- Type of air cleaning equipment used to prevent windbox exhaust emissions **<M>**
  Options:
  - ◊ none
  - ◊ coarse particulate removal devices
  - ◊ dry ESP
  - ◊ wet ESP
  - ◊ venturi scrubber
  - ◊ cyclone
  - ◊ baghouse
  - ◊ other

- Control efficiency of cleaning equipment as a percentage <R>
  (only necessary if "other" option selected from the above menu)

- Type of air cleaning equipment used to prevent emissions at discharge end (sinter crushing and hot screening) <M>
  Options:
  - ◊ none
  - ◊ baghouse
  - ◊ venturi scrubber
  - ◊ other
- Control efficiency of cleaning equipment as a percentage <R>
  (only necessary if "other" option selected from the above menu)

Emission Limits Issued by the Chief Air Pollution Control Officer

- Emission limits for particulates emanating from the sinter process in kg/day, as specified by the Chief Air Pollution Control Officer <R>

4.4.3 Industrial Model Base (Sinter Production Process)

4.4.3.1 Production Rates

The amount of finished sinter produced per year (in tonnes) is multiplied by the seasonal process throughput percentages input by the user for sinter production to estimate the amount of sinter produced seasonally. Seasonal emissions may then be calculated. The maximum quantity of finished sinter which could be produced in one day (tonnes) provides the basis for worst-case emissions.

4.4.3.2 Selection or Estimation of Appropriate Emission Factors

Based on the type of air cleaning device to be used, and the control efficiency of the device (as input by the user), an appropriate emission factor is selected. Where no appropriate emission factor is available, an attempt will be made to estimate a suitable emission factor.

- In instances where no air cleaning device is used, the emission factor for uncontrolled particulate emissions included in the data base will be used. Uncontrolled CO emissions from windbox exhausts will be estimated from the US-EPA single-valued emission factor estimate, 22 kg of CO per tonne of finished sinter produced.

- Where specific cleaning devices are selected by the user, the appropriate US-EPA emission factors for controlled particulate emissions will be applied.

- For all "other" cleaning devices, the emission factor for TSP will be calculated by the emission factor equation for controlled emissions given as,

$$E = U - (U*C) \tag{4.1}$$

where

E = emission factor for pollutant controlled by cleaning device (kg/tonne)
U = emission factor for uncontrolled emissions (kg/tonne)
C = control efficiency of cleaning device as a percentage (as specified by user)

U is given as 5.56 kg/tonne and 3.4 kg/tonne for windbox exhausts and discharge end TSP emissions, respectively.

- No emission factors are currently available to facilitate the estimation of CO emissions from controlled sinter operations.

4.4.3.4 Estimation of Particulate and Gaseous Emissions from Sinter Production

Annual emissions will be estimated by multiplying the amount of sinter produced annually (tonnes) by the appropriate emission factor(s) (as selected in the previous section) to generate particulate and CO emissions in kg per annum. Seasonal emission rates will similarly be estimated based on the multiplication of the amounts of coke produced during each season (tonnes) by the appropriate emission factor(s). In the estimation of worst-case emissions the maximum amount of coke which may be produced in one day (tonnes) will be multiplied by the appropriate emission factors to generate particulate and CO emissions in kg per worst-case day.

Results generated for the sinter production process are as follows:

- Total annual, seasonal and worst-case TSP, and if possible PM-10 and PM-2.5 emissions (kg).
- Total annual, seasonal and worst-case CO emissions (kg).

The user will be warned of the absence of emission factors for CO emissions from controlled sinter operations.

4.4.3.5 Evaluation of Compliance of Processes with Emission Limits

The information provided by the user provides the basis for the classification of processes for which emission limits are available into three emission classes. The classification is based on the relationship between modelled emissions and the limits imposed by CAPCO.

- The first emission class represents processes which are in non-compliance with emission limits (i.e. modelled emissions ≥ 100% of emission limits)
- The second class includes processes for which there is a risk of non-compliance, as defined by modelled emissions ≥ 80% of emission limits.
- The third emission class represents processes in which little or no risk of exceeding emission limits exists (i.e. modelled emissions < 80% of emission limit).

The percentage by which emission limits are exceeded by processes in the first emission class is presented as the percentage of additional control required to bring a process into compliance with emission limits. In instances of non-compliance the user may choose to rerun the model based on additional abatement techniques, or alter the nature or extent of the sintering process in order to reach the level of control needed to achieve compliance. Reference may be made to the relevant sections within the industrial data base which documents control measures for the processes which are in non-compliance.

4.5 Industrial Model Outputs

For *each* pollutant, total possible emissions from all operations for the proposed industry are estimated and the results displayed as follows (examples given in italics):

PROCESS	*TSP* EMISSIONS (*tonnes per annum*)		
	Ground Level (0 - 10 m)	Medium Level (10 - 200 m)	High Level (>200 m)
Coke manufacture (underfire combustion)	*18*		
Basic Oxygen Furnace steelmaking		*25*	
Coal crushing	*55*		
TOTAL EMISSIONS	*73*	*25*	

Results are presented for each time period, i.e. annual, seasonal and worst-case daily emissions. Quantitative estimates will be given for TSP, PM-10 and PM-2.5. For all other pollutants, a qualitative estimate of the possible extent of the emission from all processes

within the proposed industry are made. Where emission factors are available for particular operations, quantitative results are included.

If the user is unable or unwilling to reduce emissions sufficiently to enable compliance with the emission limits issues by CAPCO, a list of processes which are in non-compliance are included in the final results. The percentage of additional control required by each process in order to be in compliance is given.

4.6 Conclusion

Following the establishment of an emission inventory for the proposed industry the next stage of modelling may be initiated. The air pollution scoping procedure will not, however, be continued for proposed industries which are not able to demonstrate compliance with the emission limits promulgated by CAPCO, as is evident in the decision making framework outlined in Chapter 8. In instances of non-compliance proposed processes would need to be altered or additional air pollution control equipment adopted. Alternatively the existing emission limits may be renegotiated with the Chief Air Pollution Control Officer.

CHAPTER 5 - AMBIENT AIR QUALITY DATA AND MODEL BASE

5.1 Introduction

The analysis of the impact of a proposed development on the ambient air quality of a region necessitates an understanding of existing ambient air pollution concentrations. In extensive air pollution studies, emission inventories, which identify sources of emissions and quantify each source's contribution to ambient air pollution concentrations, usually form the basis for the assessment of the existing ambient air quality (EPA, 1981; Hammerle, 1976). Although a National Air Pollution Source Inventory has been compiled for South Africa, and has been regularly updated since 1984 by the Directorate Air Pollution Control (Department of Environmental Affairs and Tourism), this data base currently only includes scheduled processes. In addition to which, the latest inventory is as yet incomplete as information from a number of small scheduled emitters is still outstanding.

The compilation of an emission inventory for existing sources and the modelling of dispersion from such sources to establish air quality levels, is time consuming and hence unsuitable for inclusion in an air pollution scoping study. In the absence of a comprehensive and current emission inventory of existing sources it is proposed that the existing ambient air quality be evaluated on the basis of monitored levels of pollutants. The relationship between existing air pollutant concentrations in the vicinity of the proposed site, and ambient air quality standards and/or guidelines would provide an index of ambient air quality.

5.2 Aims and Objectives of the Current Study

The ambient air quality data base, model base and user interface aim to facilitate the characterisation of ambient air quality in the vicinity of the proposed site through the calculation of air quality indices. Such indices are computed on the basis of comparisons between existing levels of pollutants and ambient air quality standards and guidelines. Three steps were undertaken prior to the establishment of the data base:

- Selection and acquisition of ambient air quality data.
- Selection of appropriate local and international ambient air quality guidelines and standards to be used in the assessment of air quality.
- Development of a transparent, reproducible method for reflecting the relationship between monitored levels of pollutants and air quality standards.

A description of the air quality guidelines and standards used, and the methodology applied in the calculation of air quality indices is given in the air quality data base (section 5.3). The air quality indices estimated for various sites within the country are included in Appendix B.

Information on the manner in which the receiving environment should be categorised (i.e. heavy industrial, urban, residential, rural, pristine, other) is obtained from the user via the user interface. The model base facilitates the identification of an appropriate air quality index for the proposed site, based on the user's definition of the nature of the area. In instances where no monitoring data are available in the data base, or where the user has access to more current data, the model base is designed to compute air quality indices based on monitored levels of air pollutants input by the user, through the application of procedures contained in the air quality data base.

5.3 Ambient Air Quality Data Base

5.3.1 Monitored Levels of Ambient Air Pollution Concentrations

Monitored levels of SO_2 and particulates for the year 1992 were used in the estimation of air quality indices for 161 sites across the country (Table B.1 and Table B.2). The ambient SO_2 and particulate data are drawn from the national survey of smoke and SO_2 undertaken by the Department of National Health and Population Development. Smoke concentrations and SO_2 levels are monitored at 150 and 115 sampling sites respectively. Results are presented by the DNHPD as monthly averages and highest concentrations (24-hour average) for each month. Whereas SO_2 concentrations are reported in micrograms per cubic metre ($\mu g/m^3$), smoke concentrations are described by a soiling index (S/m^3) which represents the soiling that occurs on a filter when an air sample is passed through it (van Zyl, 1992). The conversion factor for smoke concentrations (1 S/m^3 = 5 $\mu g/m^3$) is used to convert the soiling index to total suspended particulate (TSP) concentrations in $\mu g/m^3$.

PM10 (particulate matter with an aerodynamic diameter of less than 10 μm) represent particles of a size that would be deposited in, and damaging to, the lower airways and the gas-exchanging portions of the lung (Dockery and Pope, 1994). Due to the adverse effect of PM10 on human health, estimates of PM10 were made based on the calculated concentrations of TSP. Ambient levels of PM10 were assumed to represent 55% of TSP concentrations. The assumption is based on two factors: (1) In a study undertaken for the Vaal Triangle (van Nierop, 1995) it was concluded that PM10 emissions represent approximately 40% of TSP emissions based on the relationship between total PM10 and TSP emissions from all point, line and area sources. The ratio between ambient concentrations of PM10 and TSP is generally higher than that for emissions due to the shorter atmospheric residence times of larger particles. (2) In the US, ambient concentrations of PM10 are calculated as being

approximate to 55% of measured TSP concentrations, since PM10 to TSP ratios are generally between 50% and 60% for all sampling sites.

5.3.2 Air Quality Guidelines and Standards

5.3.2.1 South African Air Quality Guidelines

The air pollution guidelines issued by the Department of Environmental Affairs and Tourism (DEAT) refer to the maximum concentrations of pollutants to which people may be exposed without endangering health (Table 5.1). The pollutants specified in the guidelines, the averaging times and the maximum concentrations allowed are comparable to the National Ambient Air Quality Standards of the US Environmental Protection Agency prior to the introduction of the 1990 Clean Air Act Amendments.

Table 5.1 DEAT guideline values for ground-level concentrations of air pollutants.

Averaging Times	SO_2 (ppb)	NOx (ppb)	NO (ppb)	NO_2 (ppb)	O_3 (ppb)	Pb ($\mu g.m^{-3}$)	TSP ($\mu g.m^{-3}$)
instantaneous peak	600	1 400	900	500	250		
1 hour average	300	800	600	200	120		
24 hour average	100	400	300	100	50		300(a)
1 month average	50	300	220	80		2.5	
annual average	30	200	150	50			150(b)

(a) As measured with a 24 hour high-volume sampler.
(b) Represents the geometric mean.

The DEAT guideline for PM10 is given as 180 $\mu g/m^3$ and 60 $\mu g/m^3$ for highest daily and annual average concentrations, respectively. As for TSP, no guidelines are given for other averaging periods.

Although the DEAT guidelines currently represent the basis on which the acceptability of air quality is determined, various factors justify the evaluation and inclusion of the air quality standards of other countries in the data base. Such factors include: the likelihood of the current guidelines being revised in the near future, increasing public pressure for the implementation of stricter air quality standards, and escalating pressure from multinational corporations and bankers on local concerns to adhere to international standards.

5.3.2.2 International Air Quality Standards

(a) US EPA Air Pollution Legislation

The US EPA define two types of air quality standards: primary standards to protect human health but not necessarily prevent other adverse effects of air pollution, and secondary standards which aim to protect the public welfare from any known or anticipated adverse effects of a pollution (Table 5.2 and Table 5.3). In addition to PM10 standards, the US EPA introduced a supplementary sub-standard for PM2.5 (particulates with an aerodynamic diameter of less than 2.5 μm) in 1997. This fine fraction is able to penetrate the deep lung.

Table 5.2 Secondary National Air Quality Standards of the US EPA

Averaging Times	SO_2 ($\mu g.m^{-3}$)	CO (ppm)	Pb ($\mu g.m^{-3}$)	NO_2 (ppm)	O_3 (ppm)	PM2.5 ($\mu g.m^{-3}$)	PM10 ($\mu g.m^{-3}$)	TSP ($\mu g.m^{-3}$)
1 hour average		35(a)			0.12			
3 hour average	1 30(a)							
8 hour average		9(a)						300(a)
24 hour average						65(e)	150(g)	
3 month average			1.5					
Annual average				0.053(b)		15(f)	50(h)	150(b)

(a) Not to be exceeded more than once per year.
(b) Represents the arithmetic mean.
(c) US EPA standards for TSP prior to introduction of PM10 standards in 1990.
(d) Represents the annual geometric mean.
(e) Three-year average 99th percentile of 24-hour concentrations to be less than this value.
(f) Three-year averages of yearly concentrations to be less than this value.
(g) Three-year average 98th percentile of 24-hour concentrations to be less than this value.
(h) Three year annual averages to be less than this value in populated areas.

Table 5.3 Primary National Air Quality Standards of the US EPA

Averaging Times	SO_2 ($\mu g.m^{-3}$)	CO (ppm)	Pb ($\mu g.m^{-3}$)	NO_2 (ppm)	O_3 (ppm)	PM2.5 ($\mu g.m^{-3}$)	PM10 ($\mu g.m^{-3}$)	TSP(c) ($\mu g.m^{-3}$)
1 hour average		35(a)			0.12(a)			
8 hour average		9(a)						
24 hour average	365(a)					65(e)	150(g)	260(a)
3 months average			1.5(b)					
Annual average	80(b)			0.053(b)		15(f)	50(h)	70(d)

(a) Not to be exceeded more than once per year.
(b) Represents the arithmetic mean.
(c) US EPA standards for TSP prior to introduction of PM10 standards in 1990.
(d) Represents the annual geometric mean.
(e) Three-year average 99th percentile of 24-hour concentrations to be less than this value.
(f) Three-year averages of yearly concentrations to be less than this value.
(g) Three-year average 98th percentile of 24-hour concentrations to be less than this value.
(h) Three year annual averages to be less than this value in populated areas.

Certain standards, such as the ambient standard for PM10, are designated as both primary and secondary standards. The legislation of the US also defines air quality levels that cannot be exceeded in specified geographical areas for "prevention of significant deterioration" (PSD) of the air of those areas. PSD standards are in effect tertiary standards which are set at lower ambient levels than either primary or secondary standards (Harrison, 1990).

PSD standards are termed "increments" over "baseline air quality", and are said to be "consumed" as new sources are given permits that allow pollution to be introduced into these areas. PSD standards play an important role in long-term air quality management strategies.

Areas within the US are subject to primary or secondary standards, or PSD increments, depending on their classification. Three classes are specified. Class 1 areas refer to pristine environments, such as national parks, coastline areas, and natural wilderness areas. Class 2 areas are areas where moderate deterioration of air quality is allowed Class 3 areas are specifically designated as heavy industrial areas. Unless otherwise designated, all areas are categorised as Class 2 areas.

(b) European Union Environmental Quality Standards

The EU defines environmental quality standards (EQS) as the concentration of a substance in the receiving environment which must not be exceeded if the environment is to be suitable for a particular purpose or use, or to achieve a given level of protection for a particular receptor(s) (HMIP, 1994). Mandatory EQSs have been set by the EU for several air pollutants (Table 5.4). The EC air quality standard for SO_2, which is dependent on the level of particulates in the atmosphere, reflects the synergistic effect of pollutants.

Table 5.4 EU Mandatory Environmental Quality Standards for Air Pollutants

Substance	Averaging Period	Limit Value ($\mu g.m^{-3}$)	Suspended Particulates(a) ($\mu g.m^{-3}$)
SO_2 (Directive 80/779/EEC)	annual mean(b)	80 120	> 40 ≤ 40
	winter daily means(c)	130 180	> 60 ≤ 60
	daily means (d)	250(e) 350(e)	> 150 ≤ 150
Suspended Particulates(a) (Directive 80/779/EEC)	annual mean(b)	80(f)	
	winter daily means(c)	130	
	daily means (d)	250(f)	
NO_2 (Directive 85/203/EEC)	1 hour(g)	200	
Pb (Directive 82/884/EEC)	annual mean	2	

(a) Measured by black smoke method.
(b) Calculated from median of daily means for the year.

(c) Median of daily means for the winter period (1 October to 31 March).
(d) Calculated from 98th percentile of daily means for the year.
(e) Not to be exceeded on more than 3 days.
(f) Calculated from 95th percentile.
(g) Calculated from 98th percentile from mean values per hour or lesser period.

(c) WHO Air Quality Guidelines

Reference is made by various countries to the World Health Organisation's air quality guidelines for Europe 1987, which include both annual mean and risk limits. The World Health Organisation (WHO) has recently set a new long term goal for SO_2 concentrations. A guideline value of between 40 and 60 $\mu g/m^3$ has been set for mean annual SO_2 concentrations, with 98% of measurement falling below 100 to 150 $\mu g/m^3$ (HMIP, 1994).

It is anticipated that an effects-based approach to air quality management will be adopted in South Africa in the near future. Such an approach requires the determination of multiple levels of air quality standards, including ambient standards which ensure human health and welfare, standards which protect the natural and built environment, and finally standards aimed at the prevention of significant decline in the air quality of pristine environments. Since such standards are not yet locally available, the air quality guidelines and standards of the EU, the WHO and the US EPA are used, in addition to the DEAT's guidelines, in the estimation of ambient air quality indices.

5.3.3 Procedure for the Calculation of Air Quality Indices

The development of a single air quality index based on various air quality standards, for application in air pollution scoping studies, is problematic since the assessment of air quality in South Africa is currently determined exclusively on the basis of DEAT guidelines. The development of a single air quality index would also not adequately reflect the acceptability of air quality in terms of both human health, and the natural and built environment. Three different air quality indices (AQI-I, AQI-II, AQI-III) have, therefore, been developed for the assessment of ambient air quality:

- **AQI-I** reflects the relationship between monitored levels of pollutants and DEAT guidelines.
- **AQI-II** incorporates a combination of primary local and international guidelines and standards (i.e. standards are aimed primarily at the protection of human health).
- **AQI-III** defines air quality in terms of the relationship of measured levels of pollutants to secondary, more stringent air quality guidelines and standards designed to protect human welfare and the natural and built environment.

Ambient concentrations of TSP and SO_2, over 24-hour, monthly (in the case of SO_2), and annual averaging periods are used in the calculation of the first air quality index. PM10 concentrations are taken into account, in addition to TSP and SO_2 levels, in the computation of the second and third indices. The air quality guidelines and standards applied in the calculation of the indices for each pollutant over each averaging time are given in Tables 5.5, 5.6 and 5.7.

Table 5.5 Air quality guidelines used in calculation of AQI-I

Pollutant	Averaging Period	Air Quality Guideline or Standard	Limit Value of Standard ($\mu g/m^3$)
TSP	24 hours	DEAT Guidelines	300
TSP	annual average	DEAT Guidelines	150
SO_2	24 hours	DEAT Guidelines	260
SO_2	monthly average	DEAT Guidelines	130
SO_2	annual average	DEAT Guidelines	80

Table 5.6 Air quality guidelines and standards used in calculation of AQI-II

Pollutant	Averaging Period	Air Quality Guideline or Standard	Limit Value of Standard ($\mu g/m^3$)
TSP	24 hours	EU Standard	250(a)
TSP	annual average	US Primary NAAQS	70
PM10	24 hour	US Primary/Secondary NAAQS	150(a)
PM10	annual average	US Primary/Secondary NAAQS	50
SO_2	24 hours	EU Standard	250
SO_2	monthly average	DEAT Guidelines	130
SO_2	annual average	DEAT Guidelines; US Primary NAAQS; EU Standard	80

(a) Value not to be exceeded more than once a year.

Table 5.7 Air quality guidelines and standards used in calculation of the AQI-III

Pollutant	Averaging Period	Air Quality Guideline or Standard	Limit Value of Standard ($\mu g/m^3$)
TSP	24 hours	US Secondary NAAQS	150(a)
TSP	annual average	US Secondary NAAQS	60
PM10	24 hour	US Primary/Secondary NAAQS	150(a)
PM10	annual average	US Primary/Secondary NAAQS	50
SO_2	24 hours	EU Standard	250
SO_2	monthly average	DEAT Guidelines	130
SO_2	annual average	WHO Guidelines	60

(a) Value not to be exceeded more than once a year.

Five classes of air quality have been defined for each index. Sampling sites are classified according to the percentages of the selected guideline or standard that monitored pollutant levels represent. The lowest air quality class assigned a particular sampling site for all pollutants over all averaging periods, is defined as the characteristic air quality class for that site.

The definition of each air quality class and the criteria for the classification of sampling sites are presented in Table 5.8. The lower and upper limits of the fourth class and fifth class respectively are dependent on the background concentrations of each pollutant (i.e. concentrations of pollutant typical for pristine environments). Background concentrations vary according to type of pollutant. The value of background concentrations of a pollutant, as percentages of selected guidelines and/or standards, would also vary for each index. The value of background concentrations is, therefore, calculated individually for each pollutant and for each air quality index.

Table 5.8 Criteria for classification of sampling sites into Air Quality Classes, and definition of classes

Air Quality Class	Definition of Class	Ambient Concentrations as % of Standard and/or Guideline
1	non-compliance	≥ 100
2	risk of non-compliance	80 - 100
3	average (urban) air quality	50 - 80
4	relatively good air quality	BC - 50 (a)
5	pristine environment	≤ BC (a)

a) BC represents the background concentration of each pollutant as a percentage of selected guideline or standard.

Background levels for SO_2 are relatively low, approximately 1 ppb (2.62 $\mu g/m^3$) (Brimblecombe, 1996; Godish, 1991). In the evaluation of monthly and annual average concentrations of SO_2, 5 $\mu g/m^3$ was used as the upper limit for pristine environments. A value of 10 $\mu g/m^3$ was used as the upper limit in 24-hour highest concentrations of SO_2. Background levels of TSP vary from 0 to 10 $\mu g/m^3$ in clean environments. In the US, mean annual values of TSP range from 8 $\mu g/m^3$ in pristine environments to 288 $\mu g/m^3$ in polluted environments.

For the purpose of the present study background concentrations of TSP were taken to be 10 $\mu g/m^3$ and 15 $\mu g/m^3$ for the assessment of annual averages and 24-hour highest concentrations respectively. The corresponding upper limit for pristine environments for PM10 were defined as 8 $\mu g/m^3$ and 10 $\mu g/m^3$ for annual average and 24-hour highest concentration averaging periods.

5.3.4 Air Quality Indices Results

Based on the criteria presented (Table 5.8), a sampling site is classified into various air quality classes, following the evaluation of each pollutant over each averaging period considered. The lowest air quality class assigned to the sampling site for all pollutants over all averaging periods represents the final air quality class of the site. Results showing pollutant/averaging period specific air quality classes and final air quality classes for each sampling site according to each air quality index are given in Appendix B. To provide an example of the nature of the output given in Appendix B, the pollutant/averaging period specific classes and final air quality classes assigned to sampling sites within the Mpumalanga Province are given in Tables 5.9 and 5.10, respectively.

It should be noted that for instances where TSP or PM10 concentrations only exceeded 24-hour standards on *one* occasion, the station was placed in the second air quality class and defined as at risk of non-compliance. According to US EPA standards for TSP and PM10 for a 24-hour averaging period, a site would be in non-compliance only if standards were exceeded on more than two days over a three year period.

Table 5.9 Air quality classes(a) for each pollutant over each averaging period for sampling sites within Mpumalanga. Letters A to G represent the pollutant and averaging period and are defined below the table. Classes generated for all three air quality indices (AQI) are given.

Sampling Site (b)	Specific Classes for Air Quality Index I(c)					Final Index	Specific Classes for Air Quality Index II(c)							Final Index	Specific Classes for Air Quality Index III(c)							Final Index
	A	B	E	F	G	AQI-I	A	B	C	D	E	F	G	AQI-II	A	B	C	D	E	F	G	AQI-III
MPUMALANGA																						
Middleburg																						
CBD (C)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
Weber Str (I)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Fontein Str (R)	5	4	3	3	3	3	5	4	4	4	3	3	3	3	5	4	4	4	3	3	2	2
Nelspruit																						
CBD (C)	5	4				4	5	4	4	4				4	5	4	4	4				4
Industrial Area (I)	4	4				4	4	4	4	4				4	4	4	4	4				4
Lowveld High School (R)	4	4				4	4	4	4	4				4	4	4	4	4				4
Witbank																						
CBD (C)	5	4	4	4	4	4	5	4	4	4	4	4	4	4	5	4	4	4	4	4	4	4
Ferrobank (I)	4	4	4	4	4	4	4	3	3	3	4	4	4	3	4	3	3	3	4	4	4	3
Extention 10 (R)	5	4	4	4	4	4	5	4	4	4	4	4	4	4	5	4	4	4	4	4	4	4
Tasbet Park (R)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

(a) Definition of air quality classes assigned: (1) non-compliance; (2) risk of non-compliance; (3) average/urban air quality; (4) relatively good air quality; and (5) pristine environment.

(b) The nature of sampling sites are given by the following letters:

- C Central urban areas
- I Industrial areas
- R Residential areas

(c) Definitions of pollutants and averaging period criteria used for calculation of specific air quality classes:

A. Highest measured TSP concentrations recorded for each month over 24-hour averaging period.
B. Annual average TSP concentrations.
C. Highest PM10 concentrations for each month over 24-hour averaging period (estimated from highest concentrations of TSP sampled).
D. Annual average PM10 concentrations (estimated from monitored annual average levels of TSP).
E. Highest measured SO_2 levels recorded for each month over 24-hour averaging periods.
F. Monthly average SO_2 levels sampled.
G. Annual average SO_2 levels sampled.

Table 5.10 Final air quality indices(a) for each of the sampling sites within Mpumalanga

Sampling Site(b)	Air Quality Index		
	I	II	III
MPUMALANGA			
Middleburg			
CBD (C)	4	4	3
Weber Str (I)	4	4	4
Fontein Str (R)	3	3	2
Nelspruit			
CBD (C)	4	4	4
Industrial Area (I)	4	4	4
Lowveld High School (R)	4	4	4
Witbank			
CBD (C)	4	4	4
Ferrobank (I)	4	3	3
Extention 10 (R)	4	4	4
Tasbet Park (R)	4	4	4

(a) Definition of air quality classes assigned: (1) non-compliance; (2) risk of non-compliance; (3) average/urban air quality; (4) relatively good air quality; and (5) pristine environment.

(b) The nature of sampling sites are given by the following letters: C - Central urban areas; I - Industrial areas; R - Residential areas

5.4 USER INTERFACE AND MODEL BASE FOR AIR QUALITY ASSESSMENT

The interactions between the model base and the user needed for the characterisation of air quality at the proposed site are discussed in this section. A synopsis of such interactions is presented in Figure 5.1.

5.4.1 Selection of Information for the Characterisation of Air Quality

Air quality indices may be estimated from data contained within the air quality data base (note Table B.1) or from user-supplied information (Figure 5.1). Information input by the user would need to include monitored annual average or 24-hour highest concentration levels for at least one of the following pollutants: TSP, PM10 or SO_2. Additional information should be entered if available. For user-input data on air pollution levels the model will compute air quality indices based on the procedure outlined in Section 5.3 of the air quality data base.

In instances where the proposed site is not accounted for in the data base, information on ambient levels of pollutants will need to be input by the user. Alternatively use may be made of a site contained within the data base, which is comparable in terms of air quality to the proposed site.

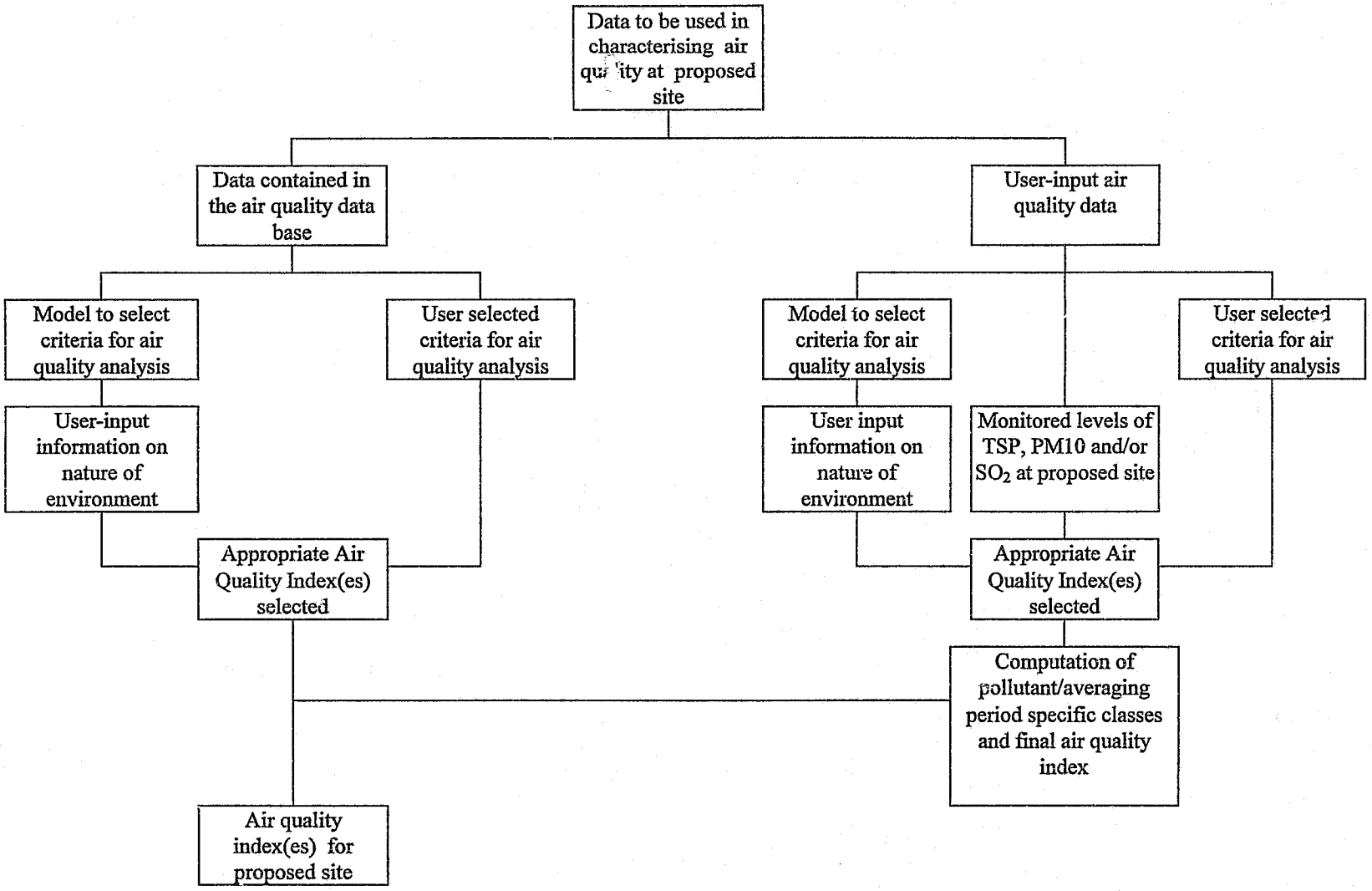


Figure 5.1 Outline of interaction between model base and user interface in characterisation of air quality for proposed site.

5.4.2 Selection of Criteria for Classification of Air Quality

The appropriate air quality index (AQI-I, AQI-II, AQI-III) to be used for the proposed development site may be selected by the user, or may be determined by the model based on the user's classification of the nature of the receiving environment (Figure 5.1). Where the "user selected" option has been chosen, the user is required to specify the air quality index or the combination of indices to be taken into account in the estimation of the air quality at the proposed site, and the potential which exists for further development.

In instances where the "model selected" option has been chosen the user is required to indicate the manner in which the environment in which the proposed site is located should be classified. Possible categories are listed below, with the air quality indices to be selected by the model for each of the categories is given in brackets.

- Heavy Industrial (AQI-II)
- Commercial (AQI-II)
- Residential (AQI-III)
- Rural (AQI-III)
- Pristine (AQI-III)

From the air quality indices assigned various land use categories it is evident that a conservative approach has been adopted. In the case of heavy industrial, industrial and commercial industrial sectors the air quality is classified according to both local and international primary air quality guidelines and standards (AQI-II). For rural and pristine areas, reference is made to more stringent local and international air quality guidelines and standards designed to protect not only human health and welfare. but also the natural and built environment. AQI-I, based exclusively on local guidelines, will only be used if specified directly be the user.

5.5 Conclusion

The existing ambient air quality for the proposed site is characterised by one user-selected or model-recommended index. The air quality class of the receiving environment is incorporated into the final decision-making phase (Chapter 8), and the resultant implications of such indices for recommendations made will be discussed.

CHAPTER 6 - DISPERSION CLIMATOLOGY DATA AND MODEL BASE

6.1 Introduction

Dispersion climatologies attempt to describe atmospheric dispersion potentials, and temporal variations in such potentials, as a function of the macro-, meso- and, where appropriate, micro-scale ventilation characteristics. Such climatologies provide the cornerstone for effective air pollution scoping studies. No readily accessible dispersion climatology data base is available for the assessment of regional dispersion potentials within South Africa. The *quantification* of the dispersion potentials necessitates detailed site-specific meteorological data and extensive dispersion modelling, and is consequently beyond the scope of the current study. The purpose of this section is the development of a data- and model-base which would provide a realistic *qualitative* description of the air pollution dispersion potential of a site within South Africa.

The establishment of macro-ventilation potentials for inclusion in the dispersion data base necessitated an investigation into the frequency of occurrence, persistence and sequence of occurrence of synoptic systems affecting each region of South Africa. The investigation comprised the development of a synoptic climatology for the country. The methodology adopted in the establishment of the synoptic climatology and an example of the nature of the results generated are described in Section 6.2. A comprehensive account of all results is given in Appendix C.

The results of the synoptic climatology form the basis of the macro-ventilation potentials included in the dispersion climatology for each region, as documented in Section 6.3.1. The dispersion climatology data base also comprises a description of the quantitative theories selected from the literature on boundary layer modifications due to uneven terrain (Section 6.3.2). These theories are applied by the meso-scale ventilation model.

The user interface (Section 6.4) and model base (Section 6.5) facilitate the computation of site-specific macro- and meso-ventilation potentials. Macro- and meso-ventilation potentials estimated for the proposed site are reconciled based on various ventilation coefficients (Subsection 6.5.5). The manner in which ventilation characteristics are reconciled is determined on the basis of a limited number of parameters input by the user, viz. site location, height(s) of emission, and description of the relief.

The main objectives of the current chapter may be summarised as follows:

- Parameterization of macro-scale ventilation through the establishment of an automated air-mass based synoptic climatology;

- Establishment of a generic model for the evaluation of modifications in the airflow and atmospheric stability regime within uneven terrain;
- Compilation of a dispersion climatology data base comprising the macro-scale ventilation potentials generated by the synoptic climatology, and a generic meso-scale ventilation model for uneven terrain; and
- Design of a user interface and model base to acquire the site-specific information needed to establish the macro- and meso-scale ventilation potentials for a proposed site, and facilitate the reconciliation of such potential so as to provide a description of the overall dispersion potential of the site.

6.2 Establishment of an Automated Air Mass-based Synoptic Climatology

An understanding of the macro-ventilation characteristics of a region necessitates an analysis of the synoptic systems and weather disturbances which affect the circulation over the region. The following characteristics need be taken into account in the analysis of such systems:

- meteorological properties;
- spatial distribution and temporal trends;
- frequency of occurrence;
- persistence;
- sequence in which systems occur; and
- implications of the occurrence of the system or disturbance for the dispersion potential of the atmosphere.

Each air mass is characterised by typical thermal, moisture and aeolian properties which determine the conversion rates of pollutants, the heights to which pollutants are able to mix, and the rate of horizontal dispersion. Anticyclonic systems are, for example, characterised by reduced wind speeds, elevated inversions which suppress diffusion and vertical dispersion, and prolonged periods of dry weather. Under such meteorological conditions, the capacity of the atmosphere to disperse or remove pollutants is greatly diminished. The weather associated with the passage of a cyclonic system is, however, characterised by strong winds, an unstable atmosphere and the potential for precipitation, all of which favour the dispersion or removal of pollutants.

The persistence for several days of air masses which impede atmospheric dispersion clearly has important implications for air quality studies. An investigation into the persistence of air masses over South Africa would be particularly relevant for regions and periods in which the weather is dominated by a small number of synoptic systems. The South African Highveld, for example, exhibits low synoptic variability in winter months during which anticyclonic circulation systems dominate. The establishment of the regional frequency of occurrence and

persistence of air masses would delineate those areas, and those seasons, in which atmospheric stagnation predominates.

The predominant sequence in which systems occur over the region similarly has important implications for the ventilation potential of the atmosphere. A synoptic system which impedes atmospheric dispersion may, for instance, frequently be preceded and followed by other systems which restrict the ventilation potential of the region. The meteorological properties, frequency of occurrence, persistence, and sequence of occurrence of synoptic systems combine to determine the extent to which such systems will impede or facilitate the dispersion of pollutants.

The frequency and sequence of occurrence, and persistence of synoptic systems and weather disturbances have only been investigated on a *national* scale (Vowinckel, 1955; Taljaard, 1981; Preston-Whyte and Tyson, 1988). Such information is inadequate to facilitate the estimation of the regional dispersion potentials required for the dispersion climatology data base. The annual frequency of occurrence of a synoptic system over southern Africa does not, for instance, accurately reflect the frequency with which the system affects a particular region. Although westerly lows have been shown to affect the circulation over southern Africa 26 percent of the time during March (Table 2.1), only a portion of such westerly lows may affect the central interior.

The establishment of a synoptic climatology for South Africa was undertaken as part of the current study to provide information regarding the frequency of occurrence, persistence and sequence of occurrence of the synoptic systems affecting each region. This information is necessary for the parameterization of macro-ventilation potentials.

In recent years, the synoptic climatological approach has extensively been used as a means of evaluating the air pollution dispersion potential of regions (Kalkstein and Corrigan, 1986; Davis and Kalkstein, 1990a; Davis, 1991; Comrie, 1992; Davis and Walker, 1992; Davis and Gay, 1993; Eder *et al.*, 1994). The underlying assumption of the synoptic climatological approach is that dispersion potentials should be related to the combination of weather elements present within a given synoptic situation, rather than to changes in individual weather elements. The synoptic climatological approach aims therefore to integrate individual weather elements into classes which are representative of the state of the atmosphere at a given time (Barry and Perry, 1973; Davis and Kalkstein, 199b; Key and Crane, 1992; Davis and Gay, 1993). Given that the transport, diffusion and deposition of airborne pollutants are governed by a wide array of weather elements, including the temperature, humidity and predominant flow characteristics of the air mass into which the pollutants are emitted, the adoption of such an approach in the study of air pollution dispersion potentials appears beneficial (Dobbins, 1979; Oke, 1990; Godish, 1991).

The synoptic climatological approach encompasses several distinct techniques. The main techniques were evaluated in the preceding subsection, and an appropriate technique for the task at hand selected. Data requirements of the selected technique and the manner in which results are interpreted and applied are subsequently discussed. An example of the results generated is provided in Section 6.2.6 (i.e. winter-time synoptic types identified for the central plateau). A comprehensive description of all results is, however, given in Appendix C.

6.2.1 Synoptic Climatological Techniques

6.2.1.1 Temporal vs. Spatial Synoptic Climatological Approaches

The classification of weather variables may be carried out in one of two ways. (1) Individual days exhibiting similar meteorological characteristics may be grouped together to establish a *temporal* synoptic index for a particular station (Muller and Jackson, 1985; Kalkstein and Corrigan, 1986; Kalkstein *et al.*, 1987). Alternatively, (2) stations with similar meteorological conditions over a 24 hour period may be categorized to produce a *spatial* synoptic climatology (Davis and Kalkstein, 1990a, 1990b; Puvaneswaran, 1990).

6.2.1.2 Weather-typing vs. Air Mass-based Approaches

Synoptic climatological techniques may be characterised as either weather-typing or air-mass based approaches. In weather-typing, the synoptic classification is developed primarily from airflow data. Surface pressure and upper air height data are commonly used in weather-typing (Muller, 1977; Ladd and Driscoll, 1980; Muller and Jackson, 1985; Faiers, 1988). Since an understanding of regional air quality variations necessitates dynamic and thermodynamic information, the adoption of an air mass-based approach would be more valuable than a weather-typing approach in the establishment of a synoptic climatology.

Air mass-based approaches use both thermodynamic and hydrodynamic variables in the classification of individual days into air mass or synoptic types. Each air mass type is represented by an entire suite of meteorological conditions which covary in a consistent manner (Barry and Perry, 1973; Kalkstein and Corrigan, 1986; Davis and Kalkstein, 1990b; Davis, 1991). Subsequent to the classification of individual days, the meteorological properties, spatial and temporal variations, frequency and sequence of occurrence, and persistence of the resulting categories may be analysed. Following the identification of the synoptic-scale thermal, moisture and flow variations likely to occur in a particular region, the implications of such variations for air pollution dispersion potentials may then be postulated. The development of synoptic climatologies would thus facilitate the establishment of regional dispersion potentials for South Africa, and the detection of temporal variations in such

potentials. An air mass-based synoptic climatology would thus provide the basis for the development of a national dispersion climatology.

6.2.1. 3 Upper-air vs. Surface Approaches

The synoptic classification of days may either be based solely on surface data or on rawinsonde observations taken at several pressure levels (Barry and Perry, 1973; Kalkstein *et al.*, 1987; Davis and Kalkstein, 1990b; Davis and Walker, 1992). A potential disadvantage of using surface data arises due to substantial variations in terrain over relatively short distances. The meso- or micro-scale effects arising from such irregular terrain often mask synoptic-scale features, resulting in the appearance of numerous small weather systems that are unrelated to the synoptic-scale circulation (Atkinson, 1981; Davis and Walker, 1992). This disadvantage is particularly relevant when developing a synoptic climatology for the coastal regions of South Africa. The atmospheric circulation in the dissected topography between the escarpment and the coastline of southern Africa is largely dominated by meso- and local-scale thermo-topographically induced winds. Land and sea breezes, and slope and valley winds govern the airflow near the ground and the thermal structure of the atmosphere (Jackson, 1954; Tyson, 1968a, 1968b; Preston-Whyte, 1969, 1974; Tyson and Preston-Whyte, 1972). Synoptic classifications developed for coastal regions using surface meteorological data would most likely reflect the local thermo-topographical processes, rather than the synoptic-scale circulation patterns or air mass types.

Upper air data reflects the vertical structure of the atmosphere, clearly providing a more appropriate basis for the classification of synoptic-scale circulations. The use of upper air data for the establishment of a synoptic climatology is, however, problematic in that the rawinsonde network is much coarser than the network of first-order stations. Only nine upper air stations are currently in operation in South Africa, viz. Bethlehem, Bloemfontein, Cape Town, Durban, Port Elizabeth, Pretoria (Irene), Springbok, Pietersburg, and Upington. The inclusion of upper air data would therefore only allow for a very broad synoptic categorisation. Despite this disadvantage, it is proposed that upper air data remain the most appropriate basis for the establishment of a synoptic climatology.

Two factors warrant the use of upper air data in synoptic classification. First, the nine rawinsonde stations are strategically located within the major climatic regions of South Africa. Secondly, synoptic classifications based on upper air data are likely to represent the synoptic circulation systems occurring in the region accurately (Barry and Perry, 1973; Davis and Walker, 1992). Due to these two factors, regional generalisations may be made when basing synoptic classifications on upper air data, thus justifying the development of a broad synoptic categorization.

6.2.1.4 Synoptic Climatological Approach Adopted

Following the evaluation of the various synoptic climatological techniques, a temporal air mass-based synoptic climatological approach based on the utilisation of upper-air meteorological data, was selected. Temporal synoptic climatologies are established for each of the nine rawinsonde stations, and the resulting synoptic classifications generalised for each region.

6.2.2 Data Requirements

6.2.2.1 Upper air data

The establishment of the synoptic climatologies is based on meteorological data sampled twice daily (00h00 and 12h00 UCT) at four pressure levels for each of the nine South African Weather Bureau (SAWB) rawisonde stations (Cape Town, Durban, Port Elizabeth, Upington, Springbok, Pretoria-Irene, Pietersburg, Bethlehem, Bloemfontein). The specific pressure levels selected were determined based on the location of the station, and on data availability.

The diurnal variations of meteorological variables provide useful information regarding the specific nature of an air mass. Synoptic classifications based solely on single observations per day inhibits the effective classification of days. In order to incorporate diurnal cycles into the classification, meteorological variables sampled at least twice daily should be used for the establishment of synoptic categories. The synoptic climatologies developed to date have primarily been based on meteorological observations sampled at two (00h00 and 12h00 hours) or four (01h00, 07h00, 13h00 and 19h00 hours) times per day (Kalkstein and Corrigan, 1986; Davis and Kaikstein, 1990b: Davis and Walker, 1992). In South Africa, upper air data is only sampled at 00h00 and 12h00 UCT each day.

6.2.2.2 Weather variable selection

The selection of weather elements to be used in the development of a synoptic climatology is dependent upon the ability of the elements to characterize the temperature and moisture properties and flow characteristics of the air mass, and on the availability of such elements in digital form. In developing a synoptic climatology for South Africa, data availability appears to be the deciding factor. Dew point temperature is frequently selected over other moisture variables due to its conservative nature with respect to changes in temperature and elevation (Barry and Perry, 1973; Kalkstein and Corrigan, 1986; Davis and Walker, 1992). Dew point temperature data sets are, however, incomplete for certain South African upper air stations. Relative humidity, which is highly collinear with dew point, will therefore be used to define

the moisture properties of air masses, in instances where dew point temperature is not available.

Air temperatures, which serve to indicate the thermal properties of air masses, are readily available. Pressure and wind components, indicative of flow patterns, are important elements in the development of synoptic climatologies since flow patterns are often quite distinct among different synoptic situations. Wind direction and wind speed data from which zonal and meridional components are computed, and pressure data are generally available. Wind direction and wind speed data are used to compute zonal and meridional wind components.

The following variables were selected in the development of a synoptic climatology for South Africa: air temperature, dew point temperature and/or relative humidity, pressure, geopotential height, and zonal and meridional wind components. These meteorological variables are the most accessible ones, and provide a maximum of synoptic information.

6.2.3 Scope of the Current Study

The use of six meteorological parameters, measured at four pressure levels twice a day over three years and for nine stations, represents a substantial data set. The classification of such parameters necessitates considerable data preparation and analysis. The establishment of a synoptic climatology for a long-term period is thus beyond the scope of the present study. The aim of the study is the analysis and classification of synoptic types for summer (December, January, February) and winter (June, July, August) months over a three year period, viz. December 1989 to November 1992. Autumn and spring represent transitional periods during which circulation patterns and weather change rapidly. Meteorological variables recorded at twelve hour intervals proved to be inadequate in representing the diurnal cycles present in the synoptic-scale situation during autumn and spring months.

Two benefits arise from the establishment of the three year synoptic climatology for summer and winter months. First, the short-term synoptic climatology will facilitate a general understanding of regional dispersion potentials during summer and winter periods within South Africa, and of the intra-annual variations in such potentials. A sound understanding of the inter-annual variations in ventilation potential necessitates a much longer study period, so as to take above average and below average rainfall years into account. Secondly, the various steps undertaken in the development of the three year seasonal synoptic climatology could provide a useful basis for the potential establishment of longer-term synoptic climatologies in future. Such steps include the selection of a suitable synoptic climatological technique, the assessment of data availability and selection of meteorological variables, the establishment of an efficient classification procedure, the description of the nature of the results produced, and the interpretation of the synoptic groupings.

6.2.4 Methodology - Classification Procedure

The size and complexity of the data sets used for the establishment of a synoptic climatology necessitate the application of a variety of automated multivariate statistical methods. One technique recently employed in air mass-based synoptic climatological approaches, which involves a combination of principal components analysis and clustering, has been selected for use in the current study (Kalkstein and Corrigan, 1986; Key and Crane, 1986; Yarnal and White, 1987; Davis and Kalkstein, 1990a, 1990b; Puvaneswaran, 1990; Davis and Walker, 1992; Eder *et al.*, 1994). The PC software package STATGRAPHICS version 7.0 was used in the correlation analysis, principal components analysis and clustering undertaken for the current study.

6.2.4.1 Correlation Analysis

Since the units of the various weather elements are not commensurate (degrees, percentages, hectoPascals, etc.) correlation matrices were generated as input for principle components analysis (Srivastava and Carter, 1980; Davis and Kalkstein, 1990b).

6.2.4.2 Principal components analysis

The inter- and intra-variable correlation inherent in the meteorological data set necessitated the use of PCA prior to the classification of days into synoptic types. PCA facilitates the transformation of a set of collinear or correlated data into a number of components, each of which are linearly independent. Each component accounts for a portion of the total variance characterising the data set, and the components are ordered according to the amount of variance that they explain. The first component explains the highest proportion of the total variance in the data set, whereas the last component explains the least variance (Christensen and Bryson, 1966; Daultrey, 1976; Srivastava and Carter, 1980).

The number of components to retain for subsequent analysis was determined through the application of Cattell's scree test (Cattell, 1966). In this scree test the eigenvalue (or explained variance) is plotted against the component number. Since the eigenvalues of the first few components are much larger than those of the later ones, the scree test curve tends to be logarithmic; the components located on the flattened tail of the curve are omitted. Alternatively, the amount of variance in the original data set which needs to be accounted for could be determined, and the number of components accounting for the selected variance retained. A substantial amount of variance may be accounted for by relatively few components, enabling the exclusion of insignificant components (Karl *et al.*, 1982; Kalkstein and Corrigan, 1986; Davis and Walker, 1992).

Correlations, expressed as component loadings or eigenvectors, are calculated between the original variables and the components. An examination of the patterns of principal component loadings would reflect the nature of the components established. A high loading for temperature and relative humidity on a component would, for instance, indicate the importance of thermal and moisture variations in that component. High loadings for pressure or wind may characterise other components (Daultrey, 1976; Johnson, 1978; Srivastava and Carter, 1980). In the present application, the analysis of component scores are, however, more important than the interpretation of component loadings.

Component scores represent the projection of the original variables onto the principal component axes, so as to describe the relationship between the original daily data and the principle components generated. Each score is uncorrelated with all other scores (Davis and Kalkstein, 1990a, 1990b). Following the computation of components scores, a clustering procedure may be used to group days with similar component scores. Each group of days represents a particular synoptic type.

6.2.4.3 Cluster Analysis

The main aim of clustering is to maximise within-group similarity while minimising between-group similarity (Balling, 1984). Despite the common goal of all clustering techniques, different techniques yield highly diverse results. In the selection of an appropriate clustering procedure for the determination of homogeneous synoptic classes, the unique properties of meteorological data need be taken into account. Meteorological data are not strongly nucleated, and since agglomerative clustering procedures are considered most efficient when dealing with a large number of individuals, such procedures appear appropriate for the establishment of synoptic classes (Anderberg, 1973; Johnston, 1978; Everitt, 1980; Balling, 1984).

Kalkstein *et al.* (1987) evaluated the suitability of the three most commonly used hierarchical and agglomarative clustering procedures in the development of a synoptic methodology, viz. Ward's Algorithm, centroid and average linkage. In hierarchical agglomarative techniques, each individual object begins as a group of one. Close objects are then merged step by step, until they are united into one group containing all of the objects. Ward's technique was found to assign an observation to a cluster with few numbers, while centroid clustering frequently culminates in one very large cluster and many smaller clusters which contain only one or two observations. Average linkage, however, was able to minimise within-cluster variance and maximise between-cluster variance effectively. The study concluded that average linkage is more suitable for use in synoptic climatological categorisation than are Ward's technique and centroid clustering.

In the development of the three year synoptic climatology for South Africa, a two-stage clustering procedure combining average linkage and seeded cluster analysis was applied.

Seeded clustering is an agglomarative technique, in which user-specified individual data points are eventually built into groupings (Davis and Kalkstein, 1990b). Average linkage was used in the first stage of the clustering procedure to select the numbers of clusters. In the second stage, days representing the cluster means (average component scores) served as seeds for seeded clustering, to generate the final clusters. This two-stage clustering procedure was found to develop clusters with smaller within-group variances than would be achieved by using average linkage alone.

6.2.4.4 Problems Encountered during the Clustering Procedure

One of the greatest methodological problems encountered in an automated synoptic climatological approach is that of minimizing the number of synoptic categories while maximizing the percentage of days classified (Yarnal and White, 1987). Synoptic classification based on annual data sets produced too many categories to deal with effectively. Measures taken to reduce the number of synoptic categories could, however, have decreased the percentage of days classified and overlooked important synoptic types. The problem was addressed by making use of seasonal data sets. Summer months (December - February) from various years were, for instance, analysed. The use of seasonal data sets proved particularly beneficial in the development of a synoptic climatology for the coastal regions of South Africa where various synoptic circulation types tend to occur in rapid succession.

6.2.5 Interpretation of Results

The development of automated synoptic climatologies elsewhere indicates, as would be expected, that the synoptic categories identified tend to exhibit marked spatial and seasonal patterns that correspond to spatial and seasonal variations in the general circulation (Davis and Kalkstein, 1990b, Davis and Walker, 1992; Key and Crane, 1992). Synoptic classifications produced, need therefore be interpreted within the context of the spatial and temporal variations in atmospheric circulation. An extensive review and synthesis of all existing knowledge concerning synoptic circulations over southern Africa was undertaken prior to the establishment of the three year synoptic climatology for South Africa for the summer and winter seasons (see Chapter 2, Section 2.3).

Each cluster was found to represent either a particular synoptic type or the transformation phase between two specific synoptic types. The identity of each cluster was determined through an assessment of its meteorological characteristics. Mean values for each of the weather variables (surface pressure, temperature, humidity and where possible dew point temperature) were calculated, and deviations of such cluster means from longer-term averages noted. Due to the nature of zonal and meridional wind components the mean values attained were analysed, deviations of such means from seasonal averages not being significant.

Daily weather charts produced by the SAWB were used to aid the identification of clusters. Having identified the synoptic types, the implications of each type for regional air pollution dispersion were assessed through an analysis of four main factors, viz. the meteorological characteristics, frequency of occurrence and persistence of each air mass type, and the sequence in which synoptic types occurred.

The results of the three year air mass-based seasonal synoptic climatology are presented in Appendix C. These results were used to develop regional dispersion potential indices for inclusion in the dispersion climatology data base. The wintertime synoptic climatology developed for the Central Plateau is presented in the next section to provide an example of the nature of the results included in Appendix C.

6.2.6 Example: Winter Synoptic Types over the Central Plateau

Results of the three year air mass-based synoptic climatology established for the Irene station (Pretoria) for the wintertime (June, July, August) are presented in this section. The synoptic types influencing the region are identified, and the meteorological characteristics and atmospheric dispersion potential of each type discussed. The synoptic trends noted for the Irene station is perceived to be representative of the central plateau region.

Eight significant clusters were identified for Irene, based on the statistical procedure outlined in section 6.2.4. Surface pressure and vertical profiles of temperature, dew point temperature, and zonal and meridional wind components are illustrated for each cluster in Figures 6.1 to 6.5. Surface pressure, temperature and dew point temperature are given as deviations from winter mean values, whereas the zonal and meridional wind components are presented as averages for each cluster.

Based on the meteorological characteristics, persistence and sequence of occurrence of each cluster, the following synoptic types were identified as being represented by each of the clusters:

1. Continental High Pressure Dominant over Interior
2. Eve of Frontal Depression
3. Miscellaneous Cluster (Associated with Continental HP)
4. Anticyclonic Bridge over Subcontinent
5. Westerly Wave Trough in Upper Atmosphere over Interior
6. Cold Frontal Passage
7. Day Following Passage of Cold Front
8. Ridging Anticyclones off Southeast or East Coast

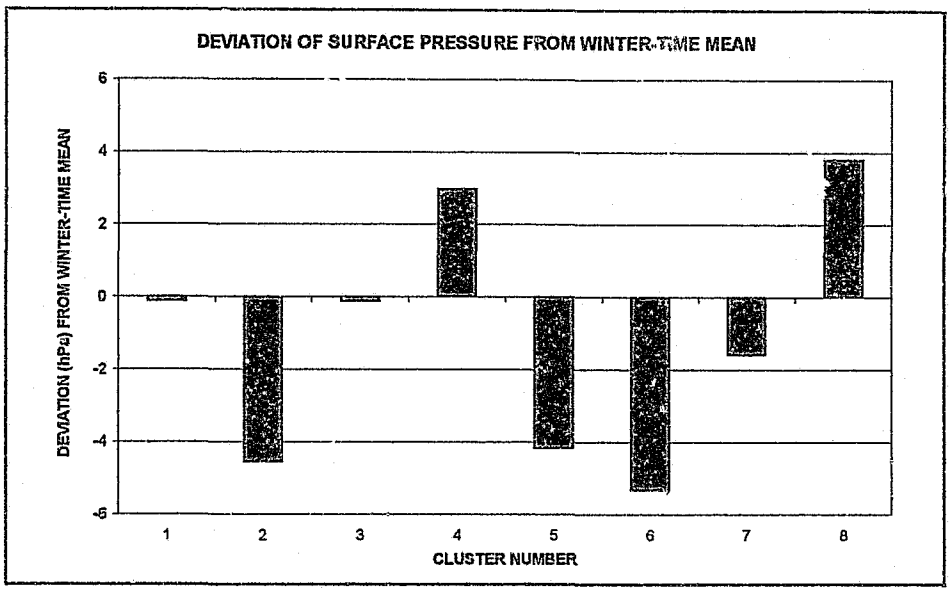


Figure 6.1 Deviation of average surface pressure for each cluster identified for Irene from the wintertime mean surface pressure for this station (1989-1992).

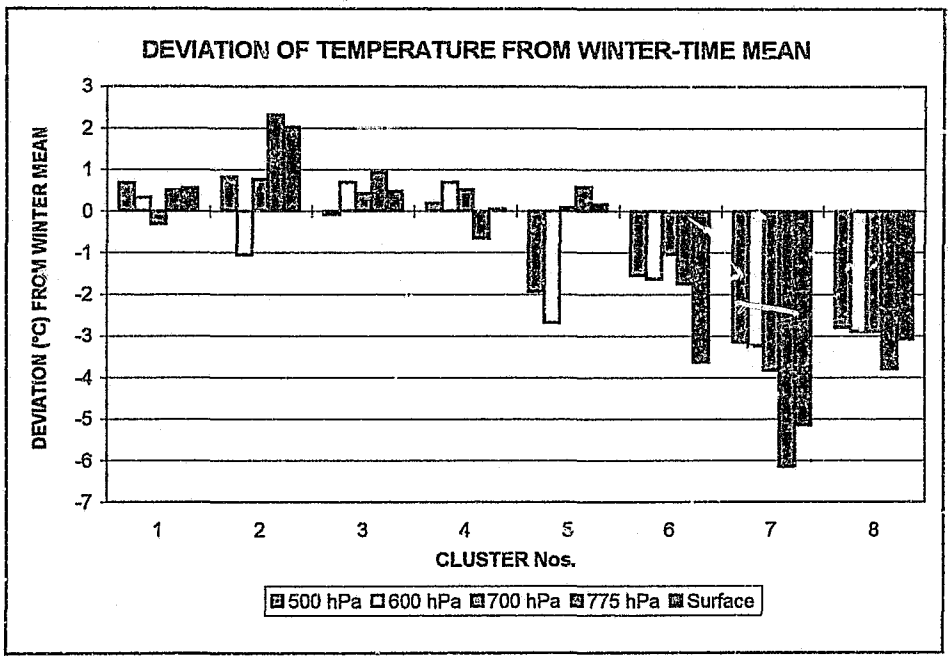


Figure 6.2 Deviation of average temperature (at various pressure levels) for each cluster identified for Irene from the wintertime mean temperature for this station (1989-1992).

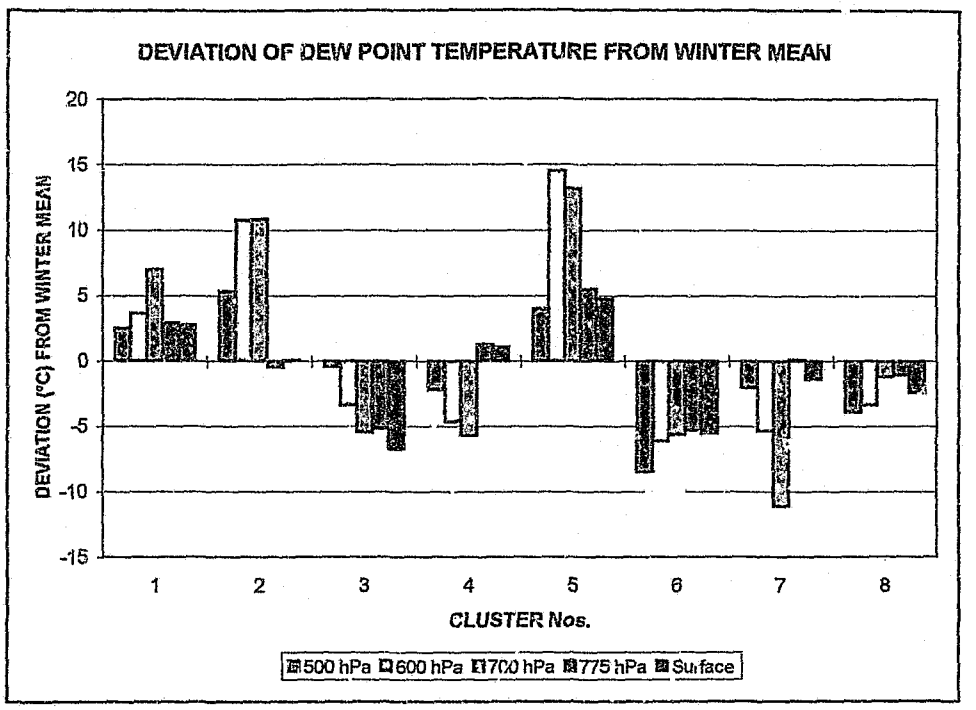


Figure 6.3 Deviation of average dew point temperature (at various pressure levels) for each cluster identified for Irene from the winter mean dew point temperature.

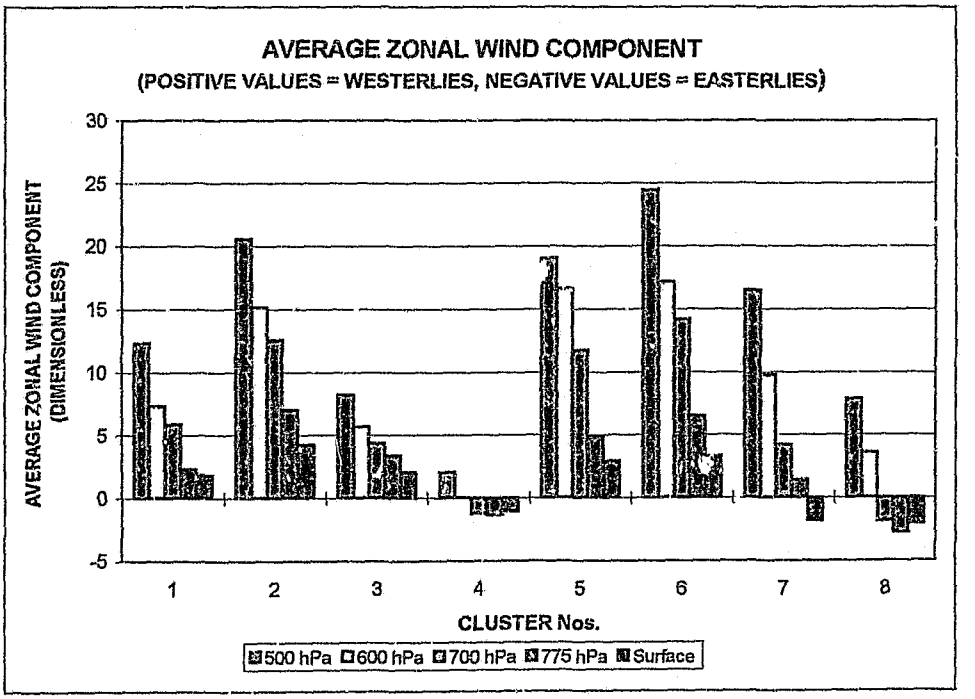


Figure 6.4 Average zonal wind component (at various pressure levels) for each of the clusters identified at Irene (1989-1992).

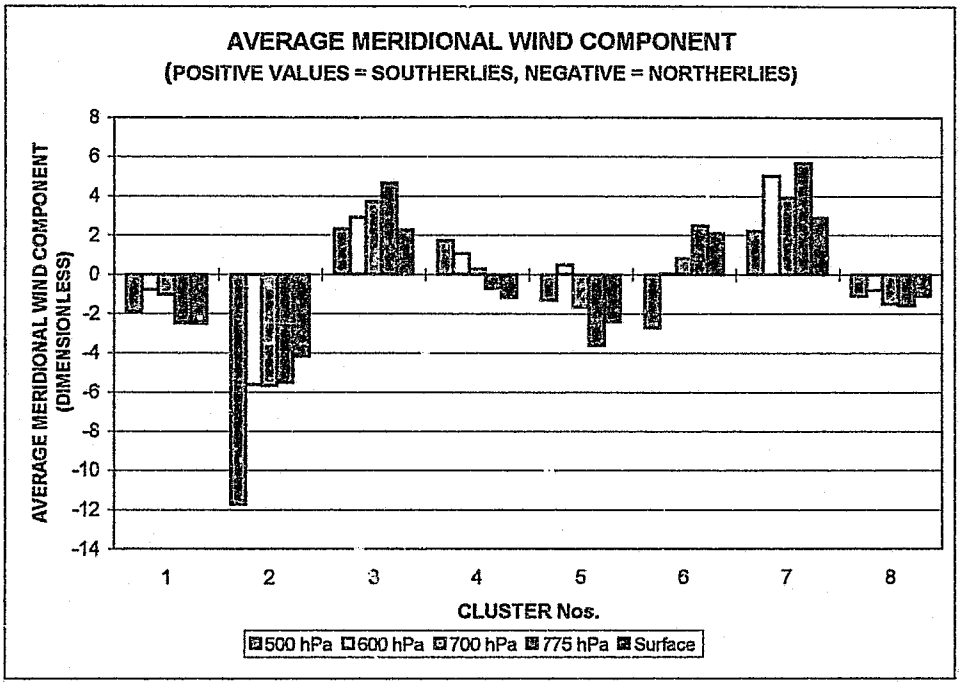


Figure 6.5 Average meridional wind component (at various pressure levels) for each of the clusters identified at Irene (1989-1992).

A more detailed description of each of the meteorological characteristics is given in the next subsection, with the atmospheric dispersion potential and persistence of each type considered in subsections 6.2.6.1 and 6.2.6.2, respectively.

6.2.6.1 Meteorological Characteristics of Synoptic Types Affecting the Central Plateau

Cluster 1: Dominant High Pressure over the Interior

Anticyclones situated over the subcontinent are associated with convergence in the upper levels of the troposphere, strong subsidence throughout the troposphere, and divergence in the near-surface wind field. Subsidence inversions, fine conditions with little or no rainfall, and light variable winds occur as a result of such widespread anticyclonic subsidence. This cluster is characterised by average to above average surface pressures, warm dry conditions and weak, variable (but predominantly northwesterly) winds.

Cluster 2: Eve of Frontal Depression

The onset of a frontal depression is heralded by a warm moisture surge with distinct increases in temperature (~2°C above winter mean) and often rather small increases in humidity. Surface pressure decreases generally falling to 4.0 to 4.5 hPa below the seasonal average, and exceptionally strong northwesterly winds are experienced.

Cluster 3: Miscellaneous Cluster Associated with Continental High Pressure

This cluster, identified for both the central and northern plateau regions, is characterised by increases in surface pressure, low relative humidity, above average temperatures, and weak winds with a northerly wind component.

Cluster 4: Anticyclonic Bridge over Subcontinent

A high pressure ridge may develop between the continental HP and an anticylone with its core to the east or southeast of the subcontinent. The establishment of a HP ridge over the subcontinent results in widespread subsidence, very high surface pressures (~3 hPa above the winter mean, generally warm and dry conditions and weak variable winds. The influence of the HP off the east coast may result in an easterly component in the wind field.

Cluster 5: Westerly Wave Trough in Upper Atmosphere over Interior

The location of a fairly strong upper trough over the interior favours the occurrence of rain over the eastern half of the country. Low surface pressures (~4 hPa below the wintertime mean), high relative humidities and very strong northwesterly winds particularly in the upper air, characterised days within this synoptic type. Average to slightly above average temperatures in the lower atmosphere and cold conditions in the upper atmosphere were also observed for such days.

Cluster 6: Cold Frontal Passage

During winter months, the high pressure belt intensifies and moves northward and the upper level circumpolar westerlies expand and displace the upper tropical easterlies equatorward. The winter weather of South Africa is, therefore, largely dominated by pertubations in the westerly circulation. Such pertubations take the form of a succession of cyclones and ridging anticyclones moving eastwards around the coast or across the country. The uplift resulting from the passage of frontal depressions provides a distinct shift from the widespread subsidence which dominates the winter months. The passage of a cold front results in low surface pressures (5.4 hPa below the winter average), a sharp decrease in temperatures (3.7°C below the seasonal mean), and very strong southwesterly winds below the 700 hPa level.

From the analysis of the vertical profiles of meteorological parameters it is apparent that cold fronts seldom result in the dissipation of the lowest subsidence inversion located at about the 700 hPa level. The atmosphere above this level is therefore frequently decoupled from conditions in the lower atmosphere. For days within this synoptic typing, strong northwesterly winds predominated in the upper atmosphere (upper level winds being enhanced by the westerly jet), while a strong southwest to westsouthwest wind component was observed below the 700 hPa level. Whereas very cold and humid conditions are observed in the lower atmosphere, average temperatures and predominantly dry conditions prevail above the 700 hPa level. In certain instances southwesterly winds prevail throughout the atmosphere, the winds become more westerly in the upper atmosphere with the southerly wind component weakening with altitude. The sharp discontinuities in the temperature and dew point temperature profiles attest, however, to the persistence of the low level subsidence inversion despite the occurrence of west-south-westerly winds in the upper air.

Cluster 7: Day Following Passage of Cold Front

Days within this cluster generally refer to days following the passage of a strong frontal depression, and occasionally the occurrence of a westerly trough over the interior. It should be noted that the coldest air temperatures and rising pressure occur in the wake of the cold front and not at the time of minimum surface pressure.

Surface pressure for days within this synoptic typing remain below the seasonal average (-1.5 hPa) despite having increased by on average 4 hPa from previous days on which frontal systems occurred. For the central plateau, this cluster is characterised by the lowest temperatures, particularly within the lower atmosphere at and below the 700 hPa level (4°C to 6°C below the winter mean). Dry conditions prevail in the upper atmosphere, with average to slightly above average relative humidities occurring near the surface. Very strong southwesterly winds prevail throughout the atmosphere except at the surface where localised winds may be apparent.

The effects of the passage of a frontal depression are not always proceeded by the impact of a ridging anticylone on the weather of Upington. In certain instances a RA may not follow the progression of the cold front, or the RA may be so weak that its effects are not felt that far inland. This cluster may also precede days on which the impact of RAs are evident (i.e. days within clusters 7 and 8).

Cluster 8: Ridging Anticyclones off the Southeast and East Coasts

Ridging anticyclones follow the passage of the cold front, resulting in the influx of very cold moist air. During winter months strong RAs may impact fairly frequently on the weather of the plateau, particularly the western and southeastern regions. The RA to the southeast and

east of the country results in very high surface pressures (approximately 3.8 hPa above the seasonal mean) over the central Plateau, with the location of the highest surface pressures depending on the proximity of the core of the RA to the region.

The influx of cold marine air results low temperatures, particularly in the lower atmosphere (4 degrees Celsius below the winter mean). The location of the RA determines the direction of the wind in the lower atmosphere. Ridging anticyclones located to the southeast of the country result in a distinct easterly wind component As the RA moves to the east of the country northeasterly winds predominate in the lower atmosphere. Northwesterly winds may prevail in the atmosphere above the 700 hPa level despite the location of the RA. Alternatively southwesterly winds generated by the earlier passage of the cold front may continue to persist in the upper air.

It should be noted that days on which RAs occurred to the southeast and east were clustered together for the central and eastern plateau. For the northern plateau, the distinction was made during clustering, between RAs located to the southeast and east of the subcontinent, based on their characteristics wind field, i.e. southeasterly and northeasterly respectively.

6.2.6.2 Implications of Synoptic Types for Dispersion Potential over the Central Plateau

The impact of each synoptic type on the air pollution dispersion potential of the central plateau was assessed based on the classification of synoptic types into three classes, viz. ventilating systems, stagnating systems and neutral systems. The classification of synoptic types was based on the mixing depth, the vertically averaged wind speed (VAWS) characteristic of the synoptic type and on the potential for precipitation to occur as a result of the synoptic type. All synoptic types associated with precipitation events were classified as ventilating systems. The remainder of the synoptic types were categorised according to their characteristic mixing depth and vertically averaged wind speed class, as outlined in Table 6.1.

Table 6.1 Criteria for classification of non-precipitation synoptic types into stagnating (S), ventilating (V) and neutral (N) systems, based on vertically averaged wind speed (VAWS) and mixing depth.

VAWS (m/s)	MIXING DEPTH (m)					
	≤ 600	≤ 800	≤ 1 000	≤ 1 500	≤ 2 000	> 2 000
≤ 2	S	S	S	S	S	N
≤ 4	S	S	S	S	N	V
≤ 6	S	S	S	N	V	V
≤ 8	S	S	S	V	V	V
≤ 10	S	S	V	V	V	
> 10	S	V	V	V	V	

The vertically averaged wind speed, mixing depth and precipitation potential of certain synoptic types varies between plateau stations. A particular synoptic type may therefore represent a ventilating system in one region, despite being labelled a stagnating or neutral system in another. The atmospheric dispersion potential classification given to each of the synoptic types impacting on the central plateau is presented in Table 6.2.

Table 6.2 Classification of Winter Synoptic Types for Central Plateau into stagnating (S), ventilating (V) and neutral (N) systems.

SYNOPTIC TYPE	VAWS (m/s)	MIXING DEPTH (m)	PRECIPITATION POTENTIAL	CLASS
1 – Continental HP over Interior	≤ 4.0	≤ 1 500	Low \ No	S
2 - Eve of Frontal Depression	8.3 - 14.3	≤ 1 500	High	V
3 – Miscellaneous HP Cluster	4.9 - 5.0	≤ 1 500	Low \ No	N (S)
4 - HP Bridge over Subcontinent	≤ 2.0	≤ 1 500	Low \ No	S
5 - Westerly Wave Trough in Upper Air	7.5 - 9.8	> 1 500	Low \ No	V
6 - Cold Frontal Passage	4.8 - 13.2	≤ 1 500, > 1 500	High	V
7 - Day Following Cold Front	4.4 - 8.1	≤ 1 500, > 1 500	Low \ No	V
8 – Ridging HP off SE or E Coast	2.4 - 2.7(b)	≤ 1 500	Low \ No	S

HP = high pressure; VAWS = vertically averaged wind speed

The mixing depth varies between days within this synoptic type, although mixing depths of less than 1 500 m predominate, the mixing depth is extended intermittently when the passage of a frontal depression is able to displace or dissipate the low level subsidence inversion.

6.2.6.3 Frequency and Persistence of Winter Synoptic Types over Central Plateau

The frequency of occurrence and persistence (including the average and maximum number of days over which synoptic patterns exits) of each of the clusters are given in Table 6.3.

Table 6.3 Frequency of Occurrence and Persistence of Winter Synoptic Types over the Central Plateau.

CLUSTER NUMBER	FREQUENCY OF OCCURRENCE (%)	PERSISTANCE - NO. OF DAYS	
		MEAN	MAXIMUM
1 - Continental HP over Interior	28.5	1-2	3
2 - Eve of Frontal Depression	8.3	1	1
3 - Miscellaneous HP Cluster	15.5	1	1
4 - HP Bridge over Subcontinent	33.4	3-4	5
5 - Westerly Wave Trough in Upper Air	5	1	2
6 - Cold Frontal Passage	2.1	1	1
7 - Day Following Cold Front	3.8	1	1
8 – Ridging HP off SE or E Coast	3.4	1	2

It should be noted that HP systems (viz. clusters 1, 3 and 4) occurred 77.4% of the time over the central plateau, whereas the remaining clusters comprising low pressure systems only occurred on 22.6% of the days within the study period. These results appear therefore to support earlier studies which found that anticylones occurred with a maximum frequency of occurrence of approximately 79 percent in June and July (Preston-Whyte and Tyson, 1988).

6.3 Dispersion Climatology Data Base

Information gathered from the literature, and data generated through the development of the three year air mass-based synoptic climatology were integrated to provide a single index of the macro-scale ventilation potential of each region for winter and summer. The macro-ventilation potentials generated are presented and a brief description of the nature of the summer-time and winter-time dispersion potential given in Section 6.3.1. The quantitative theories applied in the generic meso-scale ventilation model for uneven terrain are discussed in Section 6.3.2 of the data base.

6.3.1 Macro-scale Ventilation Potentials

Each synoptic system identified by the synoptic climatology was classified as either stagnating, ventilating or neutral systems (Appendix C). The classification was based on the consideration of the vertical averaged wind speeds, mixing depths and precipitation potentials characterising each system at each station for summer and winter (see Table 6.1).

The macro-scale ventilation potential was defined as the ratio of number of stagnating days within an episode to total number of ventilating days, an episode being defined as a period in which stagnating systems persisted for four or more days. The smaller the macro-scale ventilation potential index the greater the ventilation potential of the region. Based on the estimated ventilation potential, regions were classified according to three classes: (1) regions prone to poor dispersion (i.e. ventilation potential of $\geq$ 2.0), (2) regions characterised by median dispersion potentials (i.e. ventilation potential between 1.0 and 2.0), and (3) regions with good dispersion potentials (i.e. ventilation potential of $\leq$ 1.0). Regional macro-ventilation potential indices for winter and summer are given in Figures 6.6 and 6.7, respectively. A brief description of the nature of ventilation characterising regions during summer and winter months is subsequently provided.

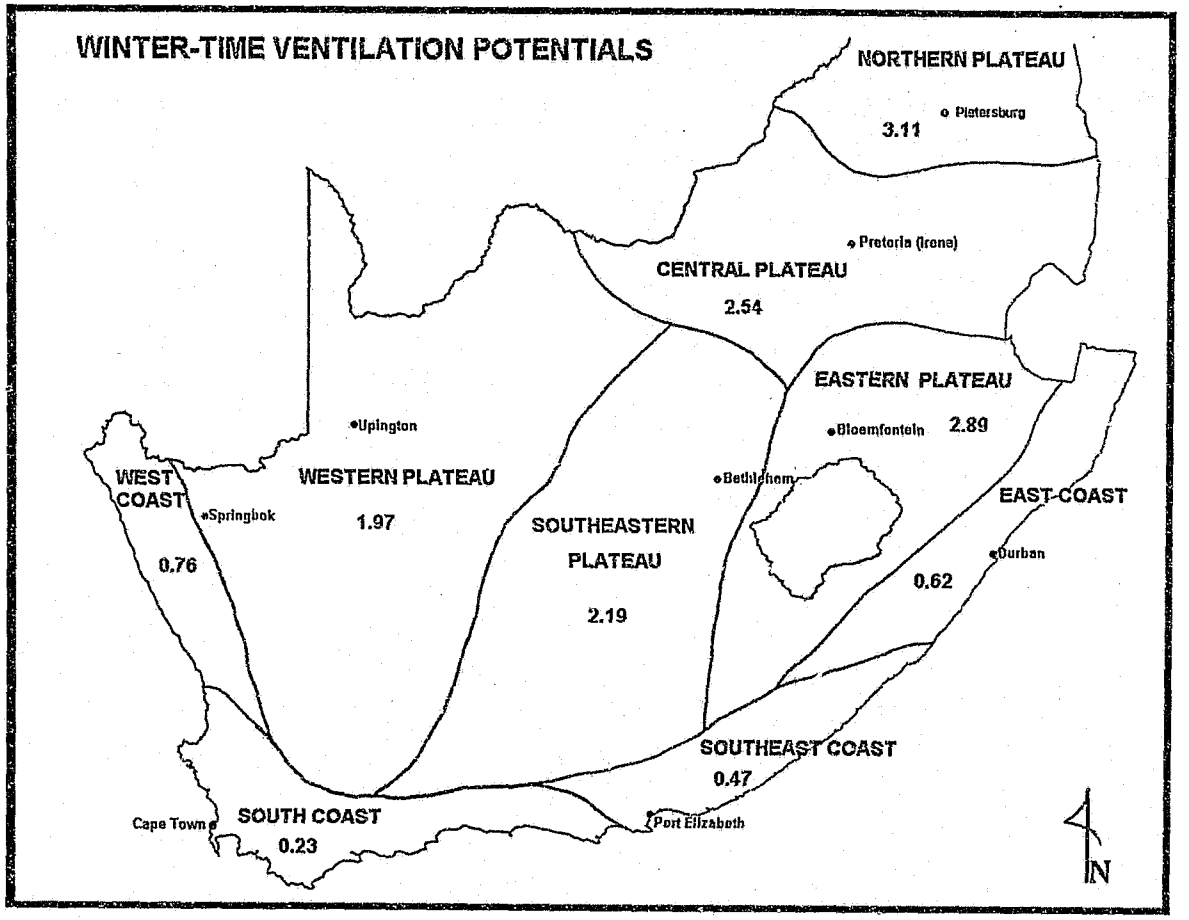


Figure 6.6 Winter-time ventilation potentials (VPs), expressed as a ratio of the percentage of episode days to the percentage of days on which ventilating systems predominated. An episode is given as a period in which stagnating systems persisted for four or more days. Where VPs $\geq$ 2.0 represent poor dispersion conditions; VPs between 1.0 and 2.0 median dispersion potentials; and VPs $\leq$ 1.0 are indicative of good dispersion.

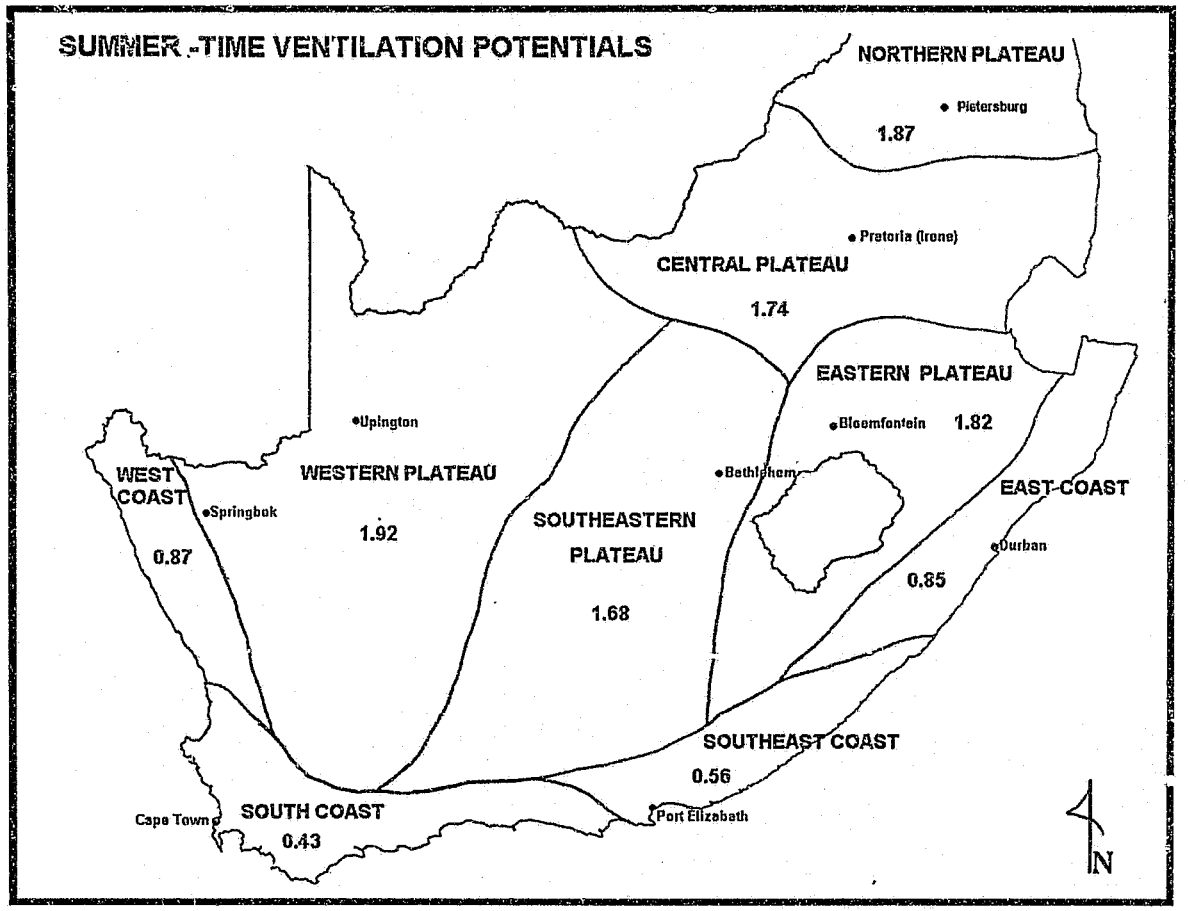


Figure 6.7 Summer-time ventilation potentials (VPs), expressed as a ratio of the percentage of episode days to the percentage of days on which ventilating systems predominated. An episode is defined as a period in which stagnating systems persisted for four or more days. Where VPs ≥ 2.0 represent poor dispersion conditions; VPs between 1.0 and 2.0 median dispersion potentials; and VPs ≤ 1.0 are indicative of good dispersion.

6.3.1.1 Wintertime Synoptic Climatology of Plateau Regions

The continental anticyclone dominates the circulation of the entire plateau, particularly during the winter months with high pressure systems occurring between 73% and 77% of the time for all regions. Such systems are characterised by strong subsidence and elevated inversions, fine conditions, and light variable winds. With vertically averaged wind speeds (VAWS) being generally less than 4 m/s, and the mixing depth confined to below 1 500 m for such systems, and with little to no potential for precipitation, HP systems give rise to poor dispersion potentials. The persistence of such systems for up to eight days in certain regions may result in the accumulation of high pollutant concentrations.

The central plateau is characterised by a higher frequency of occurrence (77.4%) and greater persistence (maximum of 8 days) of continental high pressure systems than are the western, southern and northern plateau regions. Despite the lower frequency of occurrence of days on which continental high pressures dominate for the northern and eastern plateau regions, the increasing influence of ridging anticyclones on these regions serves to enhance their stagnation potential. Ridging anticyclones which influence the central, eastern and northern plateau regions during winter have been found to be characterised by low VAWS and little to no potential for producing rainfall. Based on the three year synoptic climatology undertaken, stagnating systems (including systems associated with the continental anticyclone and ridging high pressures) were found to have frequencies of occurrence of 80.8%, 84.2% and 88.5% for the central, eastern and northern plateaus, respectively. Relatively higher wind speeds are associated with the influence of ridging anticyclones over the western and southern plateau, when compared to the influence of such systems over the central, eastern and northern plateau. Due to the higher wind speeds, RAs are not classified as representing stagnating systems for these regions. Periods of atmospheric stagnation over the western and southern plateau are therefore mainly due to the occurrence of continental HP systems which dominate the synoptics of these regions for 73.6% and 76.9% of the time, respectively.

The passage of frontal systems over the plateau is associated with high VAWS and precipitation potentials. Strong systems may even result in the dissipation or displacement of the lowest elevated inversion, thus enhancing the mixing depth. The passage of frontal systems thus enhance the ventilation potential of the region, facilitating the dispersion of accumulated pollutants. Even the eve of frontal depressions, during which time the mixing height may be reduced due to intense subsistence, may be seen to improve the ventilation potential. The high velocity winds characteristic of such pre-frontal periods make up for the possible reduction in the mixing depth.

The occurrence of westerly waves in the upper atmosphere over the interior serves to enhance the ventilation potential of the northern, central and eastern plateau. Such systems are characterised by high VAWS and enhanced mixing depths. The ventilation of the

southern and western parts of the plateau is similarly improved due to the occurrence of surface troughs over the west coast and western interior. These surface troughs are responsible for high VAWS and the occurrence of precipitation. Based on the three year synoptic climatology undertaken, the total frequency of occurrence of all ventilating systems (including systems associated with surface troughs, upper air low pressures and frontal depressions) for each region are as follows: central plateau (19.3%), eastern plateau (15.8%), northern plateau (11.5%), southern plateau (21%), and western plateau (26.4%). (3.1% of the days at Bloemfontein were classified as being characterised by neutral systems.)

6.3.1.2 Wintertime Synoptic Climatology of Coastal Regions

During winter, the core of the continental anticyclone is usually located over the northeastern parts of the country resulting in northwesterly (off-shore) airflow over the east and southeast coasts. Below the 900 hPa level the occurrence of slightly moister air and northeasterly winds reflect the influence of sea breezes. Westerly airflow occurs over the south coast above the 900 hPa level, with the lower atmosphere similarly characterised by moister, cooler air with an easterly flow component. Based on the three year synoptic climatology undertaken, the continental high pressure was found to influence the circulation of the east coast, southeast coast, south coast and west coast on 52.1%, 43.3%, 30.6% and 59% of summer days. The smaller impact of the continental HP on the south coast is clearly evident, with the influence of the HP frequently classified as resulting in bergwind conditions (23.3%). The influence of the continental high pressure system persisted for a maximum of 3 days over the south coast to a maximum of 6 days over the west coast. As at plateau stations, the continental anticyclone is responsible for poor dispersion potentials at coastal stations. The frequent passage of cyclonic disturbances at coastal regions, however, prevents the establishment of anticyclonic circulations for any length of time, and enhances the ventilation potential of coastal regions.

Ventilating systems occurring over the south coast, noted during the establishment of the three year synoptic climatology, included coastal lows, cold fronts, ridging anticyclones located to the southwest and south of the subcontinent, and the occurrence of strong moist west-northwesterly airflow. The passage of coastal lows, cold fronts and ridging anticyclones with cores to the south, southeast or east of the subcontinent similarly enhance the ventilation potential of the southeastern and eastern coastal regions. Ventilating systems affecting the west coast included bergwind conditions associated with pre-frontal divergence and ridging anticylones and the passage of cold fronts. The establishment of a cold high pressure over the west coast also resulted in conditions conducive to dispersion over the west coast. Based on the three year synoptic climatology, the frequency of occurrence of ventilating systems for the various coastal regions are given as follows: west coast (30.0%), south coast (56.9%), southeast coast (35.3%) and the south coast (29.2%).

Bergwind conditions are associated with the occurrence of high pressure systems over the interior and depressions along the coast, and frequently occur as a result of large-scale prefrontal divergence and adiabatic warming of subsiding off-shore airflow. Bergwinds have been linked to the pre-frontal divergence generated ahead of coastal lows, westerly waves, and cold fronts. In the three year synoptic climatology undertaken, almost all rapid rises in temperature from day to day for all coastal stations was found to be as result of bergwind warming. Bergwinds occurred on 13.6%, 25.9%, 10.4% and 23% of winter days for the eastern, southern, southeastern and western coasts, respectively. Based on the meteorological characteristics associated with bergwinds, namely low VAWS and precipitation potentials, these systems were largely classified as resulting in poor dispersion potentials. A notable exception was the occurrence of bergwinds over the west coast, which resulted in high wind speeds and the dissipation or upward displacement of the subsidence inversion. Such bergwinds are linked to the occurrence of extensive dust plumes extending out over the South Atlantic Ocean (Diab, 1978a).

Pre-frontal warming associated with the subsidence and divergence of air ahead of the passage of frontal depressions was estimated to occur on 3% to 5% of winter days. Such pre-frontal divergence was associated with a significant reduction in the mixing depth, and consequently classified as a stagnating system. It should, however, be noted that the impact of such systems occurs over a short period. Immediately following the passage of the front a dramatic rise in mixing depth occurs at coastal stations.

6.3.1.3 Summertime Synoptic Climatology of Plateau Regions

During the summer months, the frequency of occurrence of days on which the continental anticyclone dominates the synoptics of plateau regions is reduced to below 10%. The reduced impact of such systems during summer months is due to the weakening and southward shift of the anticyclonic belt, allowing the tropical easterly flow to resume its influence over the subcontinent. The summertime circulation is dominated by a weak surface heat low, strong upper air low pressures (associated with the tropical easterlies), and the frequent occurrence of ridging anticyclones. Ridging anticyclones are able to influence the circulation over the plateau due to the increased height of the capping elevated inversion as a result of the weaker continental anticyclonic activity.

Based on the three year synoptic climatology, ridging anticyclones influence plateau regions on 40 to 50% of summer days. The implications of such systems on the ventilation potential of a region is generally dependent on the location of such systems in relation to the region. The passage of ridging anticyclones is generally characterised by increased VAWS, and may be responsible for both precipitation and enhanced mixing depths, and are consequently classified as ventilating systems. The influence of ridging anticyclones located off the southwest coast on the western plateau is a notable exception.

These systems have been found to be associated with relatively low VAWS and little to no precipitation potential, and have therefore been classified as neutral systems.

Surface convergence, unstable conditions and the potential for precipitation characteristic of easterly waves and lows are largely responsible for the summer rainfall pattern and the northerly wind component which occurs over the interior. Such convective activity is associated with strong winds and upward vertical air motion which may serve to destroy, weaken, or increase the altitude of elevated inversions. The surface troughs associated with easterly wave disturbances therefore facilitate the dispersion and dilution of accumulated atmospheric pollution. Based on the three year synoptic climatology, the frequency of occurrence of ventilating systems for each region was estimated to be as follows: eastern plateau (74.6%), northern plateau (73.6%), southern plateau (82.9%), central plateau (83.8%), and the western plateau (52.7%). The low frequency of occurrence of such systems for the western plateau is largely due to the frequent influence of ridging anticyclones located off the west and southwest coasts on this region (20%), and the classifications of such systems as neutral in terms of ventilation potential.

Summer months are characterised by greater ventilation potentials than are winter months due to the high frequency of occurrence of ventilating systems, and the infrequent occurrence and short duration of stagnating systems and hence the small number of episode days.

6.3.1.4 Summertime Synoptic Climatology of Coastal Regions

The frequency of occurrence of ventilating systems over coastal areas during summer months is lower than for winter months, as may be expected. The three year synoptic climatology concluded that ventilating systems occurred on 24.8%, 28.1%, 29.6% and 23.4% of summer days for the eastern, southeastern, southern and western coasts respectively. The southward shift of the high pressure belt during the summer is clearly evident in the frequency within which the continental anticyclone influences the circulation over the southern and western coasts.

Due to the less frequent passage of cyclonic systems over the southern and southeastern Cape coast, and the reduction in the height of the subsidence inversion due to the southward shift in the HP belt, ventilation potentials are generally lower over these regions during summer months. The migration of HP cells around the south of the subcontinent tends to increase to frequency of occurrence of low level subsidence inversions at Cape Town and Port Elizabeth, despite failing to influence the atmospheric stability of the east coast. The impact of the generally low mixing depths characteristic of coastal regions on the dispersion potentials tends to be offset by the frequent occurrence of high velocity winds. During the summer, the mixing depth over the west coast was also reduced due to the increase in the frequency, depth and temperature intensity of the low level subsidence

inversion as a result of the eastward migration of the Atlantic Anticyclone High Pressure system. As for other coastal regions, however, the high summer wind speeds which occur over the west coast tend to offset the effects of the low mixing depths.

Due to the generally high VAWS observed for various systems (e.g. bergwind conditions), such systems were classified in the three year synoptic climatology as being neutral systems, rather than stagnating systems. Therefore, despite the low frequency of occurrence of ventilating systems, and the high percentage of days on which the continental anticyclone appeared to dominate the circulation, the ventilation potentials of coastal regions remained relatively good.

6.3.2 Meso-Scale Ventilation Potentials

The construction of generic meso-scale models requires a clear understanding of the factors within each type of environment (e.g. urban areas, land-sea interfaces, valleys) which govern airflow near the ground and thermal structure of the boundary layer. Due to the complexity of establishing such models, meso-scale systems related to uneven terrain were selected for inclusion in the data base. Such systems include the impact of *hills* and *valleys* on the low-level wind field and atmospheric stability regime. No generalisations have been formulated for surface temperature inversions, urban boundary layer modifications and circulations due to land-sea interfaces.

The following factors need to be taken into account in the analysis and characterisation of meso-scale circulation systems due to uneven terrain:

- meteorological properties (such as vertical wind speed and temperature profiles, and horizontal temperature and pressure gradients);
- characteristics (including the depth, strength, frequency of occurrence and duration of the system);
- spatial and temporal variations in the nature of circulation systems; and
- implications of the occurrence of the circulation system on the dispersion potential of the atmosphere.

Several observational, numerical and theoretical investigations have been conducted on the dynamic and dispersive behaviour of valley atmospheres (Davidson and Rao, 1963, Atkinson, 1981; Egan and Schiermeier, 1986; Allwine, 1993; Whiteman and Doran, 1993). Numerous studies have similarly been conducted of boundary-layer flow over hills (Mason and Sykes, 1979; Sacre, 1979; Bradley, 1980; Arya and Shipman, 1981;Taylor *et al.*, 1987; Zeman and Jensen, 1987; Gong and Ibbetson, 1989; Finnigan *et al.*, 1990). Such studies have resulted in a more complete understanding of the processes governing dispersion within complex terrain. Little work has, however, been done on assessing the applicability

of case-specific findings to other environments and on formulating generalisations with regard to the nature of wind field and boundary-layer modification across similar environments. For the purpose of the scoping study, the ventilation potential within the vicinity of hills and within valleys will be assessed based on *generalisations* with regard to the nature of airflow and atmospheric stability regime within such environments.

The airflow over non-uniform terrain is not easy to generalise. Each hill, valley, depression, tree, rock (etc.) creates a perturbation in the pattern of flow so that the specific wind climate of every landscape is unique (Oke, 1990). It is, however, possible to isolate some typical flow patterns around specific features and to develop generalisations with regard to such environments. Detailed wind field data would require modelling. Quantitative theories selected for application in the characterisation of boundary-layer modification due to hills and valleys by the meso-scale model are presented in the current section.

6.3.2.1 Isolated Hills

Due to the comparable results of various studies which take diverse hill dimensions into account it appears that the upstream, cavity and wake parameters not far from the hill are, in principle, predictable. The model base parameterizes the boundary layer modifications and dispersion potentials associated with isolated hills based on four main factors:

- Angle of hill slope (determines depth of inner layer);
- Horizontal extent of boundary layer modifications;
- Location of source in relation to the hill; and
- Height of source in relation to the 'inner layer' depth.

The algorithms and assumptions which support such parameterisation are described below.

(a) Classification of Hills According to Slope Angle

Slopes of varying elevation with low gradients (usually less than 17°) allow the boundary layer to adjust without separation. The airflow normally accelerates as it nears the hill, due to the flow being constricted vertically, and decelerates after the hill due to the increase in depth. If the slope of the hill exceeds about 17° flow separation occurs. As the flow approaches the steep ridge a pressure build-up occurs, and the pressure maximum is in the middle to upper part of the face. The major portion of the flow moves upwards and squeezes over the ridge with a maximum wind speed at the top. Some of the flow is deflected and drawn downwards into the area of lower pressure and forms a bolster eddy (or roll vortex) along the base. At the base of the face, winds are therefore weak, unsteady

and turbulent. The flow which streams over the ridge separates and a lee eddy forms. The winds on the leeward slope are thus counter to mean flow, weak and unsteady, and although the area is usually sheltered it may be subject to short-term gustiness. The turbulent wake of the hill, shaped like a horseshoe in plan, extends downstream for a considerable distance.

Flow separation on less steep hills (i.e. less than 17°) will occur if the surface is rough (Finnigan *et al.*, 1990). Intermittent flow separation has been found to occur on rugged hills with maximum slope angles as low as 12.5° and for a number of gentle vegetated hills.(Britter *et al.*, 1981).

Boundary-layer flow over hills are frequently divided into inner and outer layers based on the theory of Jackson and Hunt (1975). The inner layer is perceived as being in equilibrium with the underlying surface and Reynolds stresses are dynamically important, whereas the mean flow in the outer region is predominately inviscid.

The depth of the inner layer (l) at the hill top is given by Jackson and Hunt (1975) as follows:

$$\frac{l}{L}\ln(\frac{l}{z_o}) = 2k^2 \qquad (6.1)$$

where,

l = depth of the inner layer at the hill top(m)
L = horizontal length of terrain (m)
z_o = surface roughness length (m)
k = von Karman constant (dimensionless) (0.4)

L is defined as the distance from the hill top to the point where the elevation is half its maximum.

It should be noted that the theory of Jackson and Hunt (1975) has been developed for flow over low hills with no significant mean flow separation (i.e. h/L ≤ 0.05, where H is the height of the hill top and L the horizontal length calculated as the half-length at half-height.) Further tests and applications have proved that this theory gives reasonably good results on the upstream side and on the top of hills with h/L ≤ 0.3 - 0.4 (16.7 to 21.8 degrees) (Taylor *et al.*, 1987) and for h/L ≤ 0.58 (30 degrees) (Finardi *et al., 1993).*

For steep hillslopes, where greater potential exists for flow separation and enhanced turbulence, the work of Arya and Shipman (1981) needs to be used to characterise the depth of the inner layer, particularly on the downstream side of the hill. Arya and Shipman

(1981) propose that this layer extends to a depth 2.5 times the height of the hill (i.e. 2.5h) on the windward and leeward side of the hill, and to a depth of 1.5h at the top of the hill.

Based on the work reviewed above, it was decided to divide hills for which generalisations are to be made into 3 classes based on the angle of the hillslope (HS), viz.:

- HS ≥ 30° (HILL CLASS 1).
- 17° < HS < 30° (HILL CLASS 2).
- HS < 17 °(HILL CLASS 3).

For the purpose of the generic model all slopes which are lower than 17° are regarded as "flat terrain" and meso-scale ventilation potentials not estimated. The theory of Jackson and Hunt (1975) is applied in estimating the depth of the inner layer for hills with slopes of between 17° and 30°, whereas the work of Arya and Shipman is applied by the model for the steeper hillslopes.

The classification of hills according to slope is also important when considering the horizontal extent of the wake region. For steep slopes (i.e. HS > 30°) the mean wind velocity is decreased and the boundary layer disturbed up until 30h, whereas for hillslopes of between 20° and 30° the impact of the hill on the boundary-layer is only evident up to about 60h.

(b) Characterisation of Location of the Source in Relation to the Hill

The horizontal dimension of the flow perturbation resulting from a hill is frequently related to the size of the forcing obstacle or hill (Atkinson, 1981). Various studies have made generalisations with regard to the horizontal extent of the bolster eddy, the cavity zone and the wake region. The bolster eddy, located on the windward side of the hill, is estimated to have a horizontal extent of about 6 x the height of the hill (i.e. 6h). Significant modification of the boundary layer is, however, evident at upstream distances of up to about 20h.

The horizontal extent of the boundary layer modification downstream of the hill is much greater than that upstream. The cavity zone, located on the lee of the hill, extends to approximately 13 x the height of the hill (i.e. 13h) for more gentle slopes (HILL CLASS 2) and about 17h for steeper slopes (HILL CLASS 1). A region of strong downward motion exits at approximately 13h or 17h (depending on the slope angle) with pollution emitted close to the separation streamline being advected down to ground level. Turbulent airflow within the cavity zone significantly influences the extent and location of ground-level pollutant concentrations. A worst case, noted by Arya *et al.* (1981), with regard to the

extent of ground-level concentrations was found to be due to a low-level source (approximately 0.5h in height) located at a distance of about 5h downwind of the ridge.

Emissions from sources located further downstream from the ridge, within the wake zone, are less influenced by airflow modifications due to the ridge. Despite this there is a real risk of poor dispersion in this region due to increased turbulence and reduced mean wind velocity compared to cases with no ridges. For steep hills (i.e. HILL CLASS 1) the wake region extends from 13h to 80h, whereas for ridges with more gradual slopes (HILL CLASS 2) the wake region is smaller being between 13h and 60h. In order to estimate the degree of change in mean wind velocity at various distances from the ridge relative to an undisturbed boundary layer, the following equation may be applied:

$$\Delta(U)_{max} \approx [m\,(x/h)^{-1}][100] \qquad (6.2)$$

where $\Delta(U)_{max}$ = the difference, expressed as a percentage, between the magnitude of the maximum perturbation in mean wind velocity with and without the ridge. Parameter x is the distance of the source from the hill point (h/2) in metres, and h is the height of the hill in metres. The dimensionless coefficient (m) varies with the slope angle being 4.2 and 5.6 for HILL CLASSES 2 and 3 respectively.

Variations in turbulence may be determined by using the following equation which characterises the relationship between the Reynold's stress and the location of the source:

$$\Delta(-u'w')_{max} \approx [(p)(x/h)^{-1}(32)(10^3)]\text{-}100 \qquad (6.3)$$

Where $\Delta(-u'w')_{max}$ is the difference (in percent) between the magnitude of the maximum perturbation in the Reynold's stress within and without the ridge, x is the distance of the source from the hill point (h/2) in metres, h is the height of the hill in metres, and p is a dimensionless parameter which varies with the angle of the hillslope. For HILL CLASS 2 and HILL CLASS 3, p is 0.25 and 0.178 respectively.

The horizontal extent of boundary layer modification both upstream and downstream of the hill is frequently expressed as a function of the hill height as is evident from the above description of the bolster eddy and cavity and wake zones. The location of a source as a function of the height of the hill is calculated by the meso-scale model as follows, in order to determine whether the source is located within the bolster eddy, cavity zone or the wake zone:

$$L_s = (SL - L)/h \qquad (6.4)$$

where,

L_s	=	source location expressed in metres as a function of hill height (h)
SL	=	source location given as distance (metres) from the hill top
L	=	length of the hill (metres), defined as the length from the hill crest to a point which is half the hill crest height (h/2).
h	=	height of the hill (metres)

Following the characterisation of the source location as a function of hill height, the likelihood of such sources being located within the bolster eddy region (i.e. $L_s \leq 6h$), the cavity zone (i.e. $L_s \leq 17h$ for HILL CLASS 1; $L_s \leq 13h$ for HILL CLASS 2), or the wake zone (i.e. $17h \leq L_s \leq 80h$ for HILL CLASS 1; $13h \leq L_s \leq 60h$ for HILL CLASS 2) is assessed by the meso-scale model. For $L_s < L$, the source is classified as a hill top source.

(c) Parameterisation of Source Height in Relation to Inner Layer Depth

The depth of the inner layer is important in evaluating the dispersion of pollutants from a source. The height of a source located on a hill top is compared by the meso-scale ventilation model to the depth of the inner layer in order to determine whether the source is within the turbulent layer, and consequently whether the potential exists for entrainment of its emissions into the cavity region on the lee of the hill. Emissions from sources emitted above the separation streamline are assumed not to be entrained into the cavity region resulting in lower ground level concentrations.

For reasons given previously (section 6.3.2.1.1) the theory of Jackson and Hunt (1975) is used by the model to estimate the depth of the inner layer for hills with slopes of between 17° and 30° (i.e. HILL CLASS 2). The calculation of the depth of the inner layer (l) at the top of the hill is made possible through the application of Equation 6.1. The depth of the inner layer at a specific source upstream or downstream location (l_*) in metres is estimated as follows:

$$l_* = l + x \tag{6.5}$$

where l is the depth of the inner layer at hill top (metres) and x is the difference between the altitude of the hill top and the altitude of the source site in metres. For hilltop sources x is zero and l_* made equivalent to l as would be expected.

The work of Arya and Shipman (1981) is applied to characterise the depth of the inner layer for the steeper hillslopes (HS ≥ 30°). The depth of the inner layer is given as 1.5 x the height of the hill (1.5h). Although the depth of the inner layer for upstream and downstream sites is generally given by Arya and Shipman (1981) as 2.5h, use is made of a

similar equation to that of (6.5) in estimating inner layer depth at a specific site (l_*) in metres:

$$l_* = 1.5h + x \tag{6.6}$$

where h is the height of the hill and x is the difference between the altitude of the hill top and the altitude of the source site in metres.

All sources where the height of the source (H) is greater than the depth of the inner layer (i.e. $H > l_*$ for upstream and downstream sources for all slope angles; $H > 1.5h$ for hilltop sources on slopes greater than 30°; and $H > l$ for hilltop sources on gentle slopes with angles less than 30°) are classified as being above the separation streamline. Emissions from such sources are unlikely to be entrained into the cavity and bolster eddies causing high ground level concentrations. Poor dispersion potentials occur for emissions emanating from sources located below the separation streamline.

It should be noted that the source height (H) includes possible plume rise due to the temperature of the emissions being greater than that of the ambient environment, i.e. for stacks H is thus equal to the effective stack height.

6.3.2.2 Valley Atmospheres

The dynamic and dispersive behaviour of valley atmospheres has been the focus of many observational, numerical and theoretical investigations. Such studies have produced a more complete understanding of dispersion and the processes governing dispersion within valleys. Although the findings of several studies are used in the development of meso-scale scenarios for the current study, it needs to be recognised that further work must be undertaken in this field to ascertain the applicability of findings generated by case-specific investigations to other valleys.

(a) Characterisation of the Structure of the Valley Circulation

The circulation within valleys is assumed by the meso-scale model to comprise three layers, viz. the near-surface up- or down-valley flow, the "anti-wind" which represents the compensating return current above the valley wind, and the gradient wind in the upper atmosphere (as discussed in Chapter 2, section 2.4.1.1). The dispersion of pollutants within a valley is furthermore assumed to be dependent on the layer within which the pollutants are released. It is, therefore, necessary to characterise the source height according to the valley wind profile, following the estimation of the vertical extents of the valley wind system and the "anti-wind" zone.

The depth of the valley wind system is not only closely related to the relative relief of the valley, i.e. the valley depth, but may also be a function of the wind speed in the free atmosphere (gradient wind). The relationship between depth of down-valley wind and the free atmosphere wind speed at 1 000 metres above ridge height is expressed by the model based on the following equation (Davidson and Rao, 1963):

$$H_v = H_0 (1\text{-}0.05*U) \qquad (6.7)$$

where,

H_v = depth of the down-valley wind in metres.
H_0 = the height of the ridge line (i.e. depth of the valley) in metres.
U = wind speed in m/s at about ridge height (but in the free atmosphere).

From the above equation it is clear that strong gradient winds will be assumed to restrict the depth of the valley-wind. Gradient winds above 10 m/s may even suppress the development of such local winds. Although anti-valley winds are more prone to obliteration by gradient winds than are valley winds due to their being located above the level of the ridges bordering the valley, it is frequently assumed in empirical studies, that the zone of anti-valley winds is of a similar depth to that of the valley wind. This assumption is similarly made by the meso-ventilation model.

(e) Location of Within-Valley Wind Maxima

The dispersion potential of a within-valley source may be greatly enhanced should the source be emitting at the height at which the maximum valley wind velocities occur. The relationship between the depth of the up- or down-valley wind and the height at which maximum velocities occur, expressed in terms of the Prandtl formula, provides useful information for the design of new sources. The height of stacks may, for example, be altered so as to emit within the zone of maximum valley winds so as to promote the horizontal dispersion of pollutants. According to the Prandtl formula, the vertical profile the ratio h^*/H_v should equal about 0.25, where h^* is the height of maximum wind speed, and H_v is the depth of the valley wind.

6.4 User Interface – Estimation of Site-Specific Dispersion Potential

The estimation of dispersion potential of the proposed site is based on the macro-ventilation potential of the region within which the site is located, and meso-ventilation characteristics of the local environment. Local environments which may be taken into account are: the location of a proposed site near an isolated hill, or the situation of the site within a valley. Scenarios of generalised wind field and boundary layer modification

within valleys and due to isolated hills are included in the dispersion climatology data base, and ventilation potentials within such environments may be estimated by the model base. The manner in which macro- and meso-ventilation characteristics are reconciled will be determined on the basis of the site location, the height of emission and the nature of the topography.

The identification of the regional and local environments within which the proposed source is located forms the basis of Sections 6.4.1 and 6.4.2 respectively. The nature of the local environment selected in Section B will determine the nature of subsequent questions. The response of the user will take various forms (toggle, menu, range or open-ended responses) depending on the nature of the question. The nature of the response required for each question is indicated by the following symbols: <T> for toggle options, <M> for menu options, <R> for range options, and <O> for open-ended response options.

6.4.1 Selection of Macro-Scale Environment

From the list below indicate the region within which the proposed site is located. **<T>**

- East Coast
- SouthEast Coast
- South Coast
- West Coast
- Northern Plateau
- Central Plateau
- Eastern Plateau
- Western Plateau
- SouthEastern Plateau

[Reference may be made to Figures 6.6 and 6.7.]

6.4.2 Selection of Meso-Scale Environment

Select the environment within which the proposed site is located. **<T>**

- Isolated hill
- Within-valley site

6.4.3 Parameterisation of Boundary-Layer Flow over Isolated Hills

6.4.3.1 Classification of Hills According to Slope Angle

Give the slope angle (degrees) of the isolated hill within the environment under consideration. **<R>**

6.4.3.2 Characterisation of the Location of the Proposed Source

Provide information for each of the following:

- Height of the hill (h) in metres. **<O>**
- The length of the hill (L) in metres, defined as the length from the hill crest to a point which is half the hill crest height (h/2). **<O>**
- The source location (SL) in metres from the hill crest. **<O>**

For sources for which SL < L, specify whether the proposed site is to be classified as being upstream or downstream of the hill. **<T>**

- Upstream source.
- Downstream source.

Should the general location not be specified and the SL be greater than L, the proposed source will be classified as being a downstream source. Sources for which SL > L are classified as hill-top sources.

6.4.3.3 Parameterisation of Source Height in Relation to Inner Layer Depth

Provide information for each of the following:

- The surface roughness length (metres). **<O>**
- Difference between altitude of hill top and altitude of source site (metres). **<O>**
- Height of the proposed source (H) in metres, including if appropriate possible plume rise. **<O>**

6.4.4 Parameterisation of Dispersion Behaviours of Valley Atmospheres

Provide information for each of the following:

- Height of the ridge line (i.e. depth of the valley) (metres). **<O>**
- Wind speed in m/s at about the ridge height, but in the free atmosphere. (The average speed of the regional gradient wind may be specified should this information not be available.) **<O>**
- Gradient of the valley floor (degrees). **<O>**
- Height of the proposed source (H) in metres, including if appropriate possible plume rise. **<O>**

6.5 Model Base – Estimation of Dispersion Potential

6.5.1 Determination of Macro-Scale Ventilation Potential

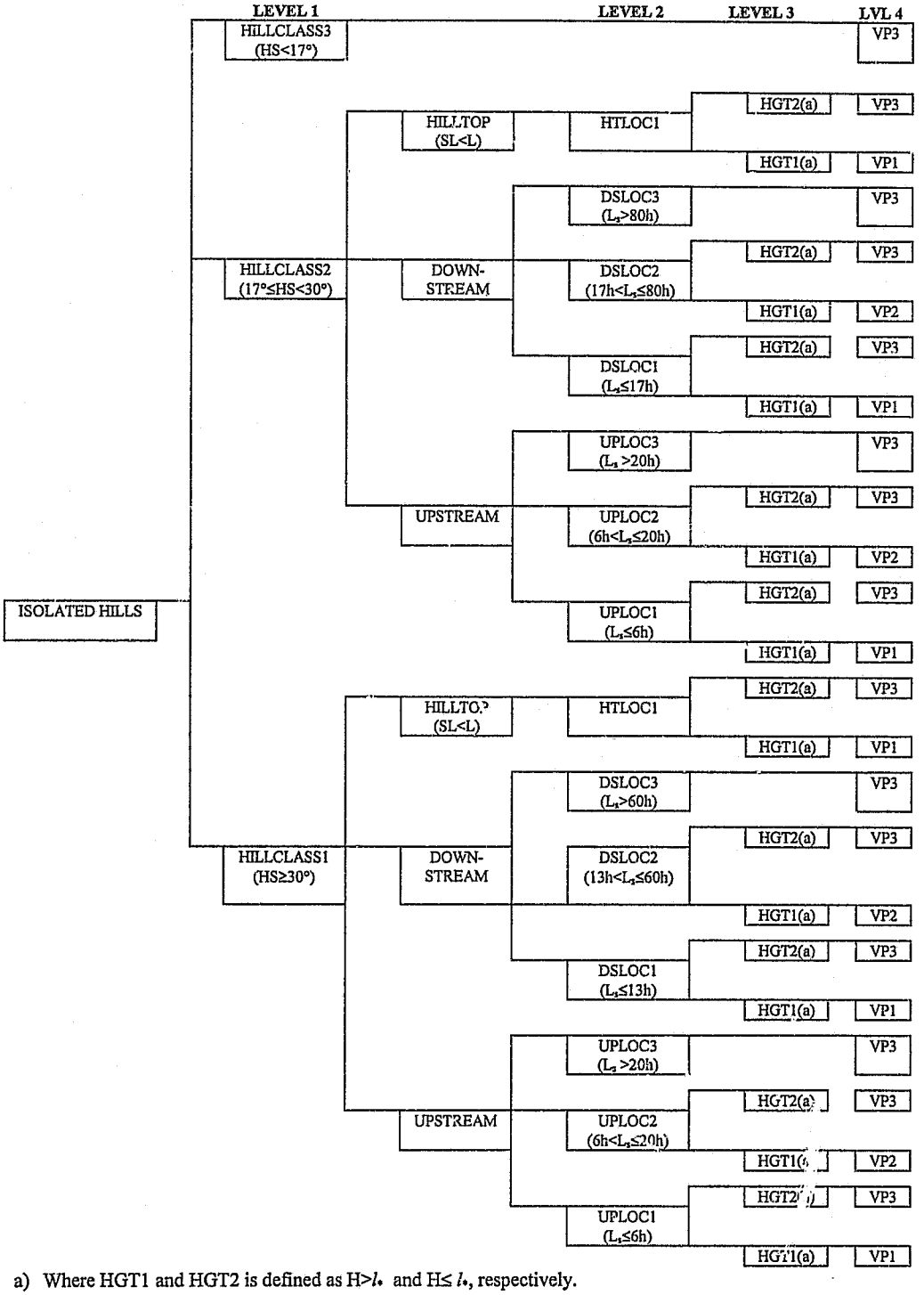
Summer and winter macro-ventilation potentials are identified from the dispersion data base (Figures 6.6 and 6.7) depending on the region within which the proposed site is located.

6.5.2 Identification of Meso-Scale Environment

The manner in which meso-scale ventilation potentials are computed is dependent on the nature of the local environment, as specified by the user. The manner in which boundary layer modifications due to valley environments and isolated hills are parameterised is presented in Sections 6.5.3 and 6.5.4, respectively.

6.5.3 Parameterisation of Boundary-Layer Flow over Isolated Hills

An overview of the estimation of ventilation potentials based on the characteristics of the hill in the local environment, and on the relationship between the location and height of the source and the hill is presented in Figure 6.8.



a) Where HGT1 and HGT2 is defined as H>l_s and H≤ l_s, respectively.

Figure 6.8 **Designation of meso-ventilation potentials (VPs) based on: hill slope angle (HS) (level 1), source location with regard to horizontal recirculation zones (level 2), and source height with regard to inner layer depth (level 3).**

6.5.3.1 Classification of Hills According to Slope Angle (Level 1)

From the angle of the hillslope (HS) specified by the user, the environment is classified into the following classes:

- HILL CLASS 1 : HS ≥ 30°.
- HILL CLASS 2 : 17° ≤ HS < 30°.
- HILL CLASS 3 : HS < 17°.

6.5.3.2 Characterisation of the Location of the Proposed Source (Level 2)

The location of the source as a function of the height of the hill (L_s) is calculated using Equation 6.4 according to the information provided by the user in section 6.5.3.2. Following the calculation of L_s the likelihood of user-defined upstream sources being located within the bolster eddy region, and the likelihood of downstream sources being within the cavity or wake zones is assessed and the source location classified accordingly:

Classification of user-defined upstream sources (UP):

- UP LOCATION 1 : $L_s \leq 6h$
- UP LOCATION 2 : $6h < L_s \leq 20h$
- UP LOCATION 3 : $20h < L_s$

UP LOCATION 1 sources are located within the bolster eddy region on the windward side of the hill. Although not within the bolster eddy region, UP LOCATION 2 is also subject to significant modification of the boundary layer due to the presence of the hill. The wind field and stability regime at UD LOCATION 3 is not affected by the presence of the hill.

Classification of downstream (DS) sources for HILL CLASS 1:

- DS LOCATION 1 : $L_s \leq 17h$
- DS LOCATION 2 : $17h < L_s \leq 80h$
- DS LOCATION 3 : $L_s > 80h$

Classification of downstream sources for HILL CLASS 2:

- DS LOCATION 1 : $L_s \leq 13h$
- DS LOCATION 2 : $13h < L_s \leq 60h$
- DS LOCATION 3 : $L_s > 60h$

LOCATION 1 is situated within the cavity zone located on the lee of the hill, whereas DS LOCATION 2 is located in the wake zone. DS LOCATION 3 falls beyond the horizontal extent of the boundary layer modification zones downstream of the hill.

All "hill-top" sources are classified as HT LOCATION 1.

6.5.3.3 Parameterisation of Source Height in Relation to Inner Layer Depth (Level 3)

From the information provided by the user, the depth of the inner layer at the hill crest is calculated based on Equation 6.1 for HILL CLASS 2. For HILL CLASS 1 the depth of the inner layer at the hill top is made equivalent to 1.5h. The depth of the inner layer at the proposed site is then estimated using Equations 6.5 and 6.6 for HILL CLASS 1 and HILL CLASS 2, respectively. The depth of the inner layer at the proposed site (l_*) will then be compared to the user-specified height of the proposed source (H), and the source classified accordingly:

- HEIGHT 1 : $H \leq l_*$
- HEIGHT 2 : $H > l_*$

Sources classified as HEIGHT 2 emit above the separation streamline of the bolster, cavity or wake zones. Emissions from such sources are unlikely to be entrained into the cavity and bolster eddies causing high ground level concentrations. Emissions emanating from sources located below the separation streamline will be subject to the increase turbulence and decreased wind speeds within the bolster, cavity and/or wake zones.

6.5.3.4 Designation of Meso-ventilation Potential Indices (Level 4)

Meso-scale ventilation potentials (VPs) are assigned on the basis of: (1) the potential for airflow separation taking into account the gradient of the hillslopes; (2) the source location, taking into account the horizontal extent of the bolster and wake eddies; and (3) the height of the source, with regard to the depth of the inner layer. The three meso-ventilation potential classes are defined as follows:

VP1 - Poor dispersion potential. High probability of fumigation conditions.

VP2 - Potential risk for poor dispersion. Macro-ventilation potential need be considered.

VP3 - No risk foreseen due to meso-scale circulations. Macro-ventilation potentials need be taken into account.

6.5.4 Parameterisation of Dispersion Behaviours of Valley Atmospheres

6.5.4.1 Estimation of Depth of the Valley Wind

The depth of valley wind (H_v) is calculated based on Equation 6.7 and the user input given in Section 6.4.4.

6.5.4.2 Characterisation of Dispersion Potential of within-Valley Sources

Sources are characterised according to the relationship between the height of emission (H), the structure of the valley circulation and the velocity of the gradient wind. Elevated sources are classified according to the criteria given in Table 6.4. Factors affecting the dispersion of pollutants within each class are described in the table. Based on the nature of the anticipated dispersion potential, each class is categorised as one of three possible ventilation potential categories (i.e. VP1, VP2 and VP3, as defined in Section 6.5.3.4). Ground level sources are classified as emitting within the valley wind system (i.e. Class 1).

Table 6.4 Classification of the dispersion potential of within-valley sources

Criteria(a)	Source Class	Factors Affecting Dispersion	Ventilation Potential
$H \leq H_v$	Class 1	Dispersion of pollutants dependent on behaviour of valley atmosphere and its interaction with the underlying topography. The dispersion of pollutants from such sources thus dependent on the valley wind and on the development and dissipation of the valley inversion.	VP1
$0.2H_0 < H > 0.3H_0$	Class 1*	Emissions from sources within this class are also dependent on within-valley circulations and valley inversions, and therefore form a subgroup of Class 1. The height of emission of sources within the group, however, occurs at approximately the height at which the maximum velocities of the valley wind occur. Such sources may therefore be characterised by increased potentials for the horizontal transport of pollutants.	VP1
$H_v < H < 2H_v$ $G < 10$ m/s	Class 2	Dispersion of pollution plumes emitted at altitudes higher than the valley sidewalls are governed by the anti-valley wind which occurs above the ridge of the valley. Under stable conditions the plume does not interact with the valley topography except that the plume trajectory may be channelled along the valley axis.	VP2
$H_v < H < 2H_v$ $G > 10$ m/s	Class 3	Despite the location of the height of emissions within the anti-valley wind zone, the occurrence of strong gradient winds are expected to obliterate the anti-valley winds and dominate the flow regime.	VP3
$H > 2 H_v$	Class 4	Dispersion of emissions from sources within this category will be dependent on the nature of the gradient wind which is a function of the synoptic climate of the region.	VP3

a) Where H = height of source, H_v = depth of valley wind, H_o = height of the ridgeline (depth or valley), and G = wind speed in the free atmosphere above the ridgeline.

6.5.5 Reconciliation of Macro- and Meso-Ventilation Potentials

For the purpose of the scoping procedure, macro-ventilation potentials given in Figures 6.7 and 6.8 are categorised into three classes: MVP1 refers to all ventilation potentials ≥ 2.00; all ventilation potentials ranging between 1.00 and 2.00 are classified as MVP2, and MVP3 refers to all ventilation ≤ 1.00. The dispersion potential indicated by each of the three classes, viz. MVP1, MVP2 and MVP3, are described simply as requiring caution, fair and good, respectively.

It is unlikely that all potential sources will be excluded from an entire region which is identified as being prone to poor dispersion. It was therefore decided that macro-ventilation potentials would only serve to provide a cautionary note rather than a decisive recommendation as to whether or not the planned development be allowed to go ahead at the proposed site. Meso-scale ventilation potentials are thus given a greater weighting than are macro-ventilation potentials in the final classification of the dispersion potential of the site into one of four classes, viz. (1) poor dispersion potential; (2) potential risk of poor dispersion, caution recommended; (3) fairly good dispersion potential; and (4) good dispersion potential. The manner in which such macro- and meso-ventilation potentials are reconciled for a particular source location is given in Table 6.5.

Table 6.5 Dispersion classes based on meso- and macro-scale ventilation potentials

Macro-ventilation Potential	Meso-ventilation Potential		
	VP1 (Poor)	VP2 (Potential Risk)	VP3 (No Risk)
MVP1(Caution)	Poor	Poor	Caution
MVP2(Fair)	Poor	Caution	Fair
MVP3(Good)	Poor	Caution	Good

6.6 Conclusion

The dispersion potential of the proposed site having been characterised into one of four categories; viz. poor, posing a potential risk, fair and good; the recommended dispersion potential class will be taken into account in the final decision making phase (Chapter 8). The air pollution scoping procedure will not be continued for proposed sites which are classified as being characterised by poor dispersion potentials, as is evident in the decision making framework. In such instances it will be recommended that an alternative site be chosen, or that the proposed development be subject to a comprehensive air pollution impact assessment.

CHAPTER 7 - ENVIRONMENTAL RISK IDENTIFICATION

7.1 Introduction

The failure to include an appraisal of environmental risk in the assessment of environmental impacts represents one of the most adverse omissions in the methodology of current EIAs. Air pollution impact assessment studies should involve the identification of sensitive receptors in the vicinity of the proposed site and the characterisation of the risk to such receptors posed by the proposed industry's emissions. The four stages of analysis needed for the assessment of risk, viz. risk identification, dose-response analysis, exposure assessment and finally risk characterisation, have been discussed in Chapter 2.

The characterization of risk requires the estimation of doses, based on quantified ambient pollutant concentrations. Although the scoping framework facilitates source strength estimations (Chapter 4), ambient concentration levels are beyond the scope of the framework, requiring atmospheric dispersion modelling. The air pollution scoping phase is therefore restricted to the identification of environmental risk. Based on the potential risks associated with the predicted emissions from the proposed development, and the proximity of sensitive receptors to the proposed site, the sensitivity of the receiving environment may be ascertained.

7.2 Aims and Objectives of the Current Section

The aim of the current section is the development and outline of a data base, model base and user interface which would facilitate the identification of potential environmental risks arising from proposed industrial developments, and the characterisation of the sensitivity of the receiving environment.

The risk identification data base, model base and user interface will be designed so as to fulfill the following objectives:

- Establish whether the receiving environment is included in the "list of environments" defined in the Integrated Environmental Management Guidelines as necessitating a full-scale environmental impact assessment (Department of Environmental Affairs, 1992a).
- Facilitate the identification of potentially sensitive receptors in the vicinity of the site by the data base user.
- Ascertain the distance between the proposed site and the nearest potentially sensitive receptor.

- Classify the receiving environment into one of three classes, viz. (1) sensitive, (2) potentially sensitive, and (3) non-sensitive. The classification will be based on four criteria: the inclusion of the receiving environment in the Department of Environmental Affairs and Tourism's "list of environments", proximity of potentially sensitive receptors to the proposed site, the atmospheric dispersion potential of the receiving environment, and the extent of emissions estimated to emanate from the proposed development.

7.3 Structure of Risk Identification Data Base, Model Base and User Interface

The risk identification data base will incorporate:

- The "list of environments" defined in the Integrated Environmental Management Guidelines as necessitating full-scale environmental impact assessments (Department of Environment Affairs, 1992a).
- General list of environmental components, e.g. human health and welfare, fauna, flora and the built environment, which may potentially be sensitive to each pollutant type.
- Information of the impacts which may be anticipated following the exposure of sensitive receptors to different concentrations of pollutants over various averaging periods.

For the purpose of the current study only environmental components which are potentially sensitive to atmospheric concentration of criteria pollutants will be indicated. Criteria pollutants include sulphur dioxide, nitrogen oxides, lead, ozone, and particulate matter. Dose-response information provided in the data base will similarly be restricted to the potential impacts of criteria pollutants on human health.

The user interface is structured so as to ascertain:

- The type of pollutant(s) to be taken into account in the assessment of environmental risk impact (should such information not be supplied by the industrial model output).
- Whether or not the receiving environment is represented in the Department of Environment Affair's "list of environments".
- The proximity of potentially sensitive receptors to the proposed site.

The type of pollutant(s) which need be taken into account for the proposed development will be indicated by the industrial model output (Chapter 4). The user will be expected to identify potentially sensitive receptors for the given pollutant(s), based on information contained within the data base on the impact of such pollutants on various environmental components.

The model base will draw on data input by the user, and on the outputs of the industrial and atmospheric dispersion potential model bases so as to classify the sensitivity of the receiving environment.

7.4 Risk Identification Data Base

7.4.1 List of DEAT Specified Sensitive Environments

The following designated areas and features, which have been declared in terms of an Act of Parliament or by agreement between land-owners and the State President or the Minister of Environmental Affairs and Tourism, are included in the DEAT's "list of environments":

- Limited development areas as declared under section 23 of the Environmental Conservation Act (73/1989).
- Protected natural environments as declared under section 16 of the Environmental Conservation Act (73/1989).
- National, provincial and municipal nature reserves as declared by national, provincial or local authorities.
- Private nature reserves as declared under the respective Nature and Environmental Conservation Ordinances of the Provinces.
- Mountain catchment areas as declared under section 2 of the Mountain Catchment Areas Act (63/1970).
- Wilderness areas as declared under section 15 of the Forest Act (122/1984).
- National monuments as declared under section 10 of the National Monuments Act (28/1969).
- Archaeological and palaeontological sites as declared under section 12 of the National Monuments Act (28/1969).
- National gardens of remembrance as declared under section 9c of the National Monuments Act (28/1969).
- Conservation areas as declared under section 5 of the National Monuments Act (28/1969).
- Intertidal zone (sea-shore) as defined in section 1 of the Sea Shore Act (21/1935).
- Lake areas falling under section 2 of the Lake Areas Development Act (39/1975).
- National heritage sites, declared as such by the State President.
- Sites of conservation significance, declared as such by the Minister of Environmental Affairs and Tourism.

- Streams and river channels, and their banks (as declared in the relevant demarcation notice).
- Floodplains (as declared in the relevant demarcation notice).
- Wetlands (as declared in the relevant demarcation notice).
- Lakes (as declared in the relevant demarcation notice).
- Dunes (as declared in the relevant demarcation notice).
- Beaches (as declared in the relevant demarcation notice).
- Reefs (as declared in the relevant demarcation notice).
- Indigenous forests (as declared in the relevant demarcation notice).
- High-potential agricultural land (as declared in the relevant demarcation notice).
- Green belts or public open space in municipal areas (as declared in the relevant demarcation notice).
- Buildings (as declared in the relevant demarcation notice).
- Landscapes and areas or sites of outstanding natural beauty (as declared in the relevant demarcation notice).
- Scenic drives and panoramic views (as declared in the relevant demarcation notice).
- Habitat of Red Data Book species (as declared in the relevant demarcation notice).
- Bird migration sites (as declared in the relevant demarcation notice).

(Department of Environment Affairs, 1992a)

7.4.2 Environmental Components which may be affected by Criteria Pollutants

Environmental components which may be sensitive to specific criteria pollutants are given in Table 7.1. Criteria pollutants included in the current data base include carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), ozone (O_3), particulate matter with an aerodynamic diameter of 10 μm (PM10), and lead (Pb). The pollutant nitrogen oxides of concern are nitric oxide (NO), and nitrogen dioxide (NO_2). The effects of combinations of pollutants are often greater than what would be predicted from the occurrence of individual pollutants. Table 7.2 indicates the potential impact of various mixtures of pollutants.

Table 7.1 Environmental components sensitive to presence of criteria pollutants

Pollutant	Potentially Sensitive Receptors
CO	• Human health (animals). The adverse effect of CO on human health is due to its reaction with haemoglobin to form carboxyhaemoglobin which is relatively stable, causing a reduction in the oxygen-carrying capacity of the blood. Elevated CO produces adverse effects on the cardiovascular system and reduces physical endurance. • (CO is not known to have any effects on vegetation, visibility or materials.)
NO_x	• Human health (animals). Human respiratory tract irritation represents a direct effects of exposure to NO_x. • Plants. Direct exposure to NO_x causes damage to plants. NO_x may also impact indirectly on plants since the oxidation of NO_2 to nitric acid contributes to acid rain problems. Acid rain serves to increase the leaching of base cations from most soils in affected areas, resulting in the change in the acidity of the soils. • Visibility. Indirect effects arise from the role of NO_2 in photochemical smog reactions • Economic costs. Nitrogen oxides cause dyes to fade and fabrics to deteriorate.
Pb	• Human health (animals). Pb can result in the degradation of the renal function, the impairment of hemoglobin synthesis, and may alter the nervous system. Although lead accumulation over a long period occurs in the bones, the occurrence of lead in the soft tissue (liver and kidney) represents a potentially greater toxicological hazard.
PM10	• Human health (animals). PM10 represent particles of a size that would be deposited in, and damaging to, the upper and lower airways and the gas-exchanging portions of the lung. Exposures to PM10 are related to increases in the prevalence of chronic respiratory disease and increased risk of acute respiratory disease. • Visibility. Particulates diminish visibility by scattering or absorbing light. The scattering efficiency of such particles is dependent upon the mass concentration and size distribution of the particulates. Air pollutants change the spectral transmission. Various costs are associated with the loss of visibility, including: the need for artificial illumination and heating; delays, disruption and accidents involving traffic; vegetation growth reduction associated with reduced photosynthesis; and commercial losses associated with aesthetics. • Built environment. Particulates may result in the soiling of buildings and materials and may chemically attack materials through their own corrosivity or through the corrosivity of substances absorbed or adsorbed by it. Ambient concentrations of particulates may also impact negatively on sensitive industries, e.g. bakeries.

Pollutant	Potentially Sensitive Receptors
O_3	• Human health (animals). O_3 is less soluble than SO_2 and may penetrate to the pulmonary region. Exposure to O_3 has been associated with decrements in the pulmonary function, coughing and chest discomfort, and increased asthma attacks. Evidence of adverse health effects arising from human exposure to ozone have been noted for concentrations exceeding 120 ppb as an hourly average. • Crops. Ozone readily damages plants, resulting in a characteristic brown or white flecking appearing on the foliage of affected plants. Damage to crop plants may occur at levels below 120 ppb for an hour of exposure, with some varieties of crops showing adverse effects at concentrations as low as 50 ppb. At lower concentrations O_3 tends to reduce the growth rate or physiological activity of plants. Economic losses to crops in the US due to ozone damage are considerable. • Visibility. Photochemical smog. • Economic costs. Ozone attacks a wide variety of organic chemicals, including synthetic fibres (e.g. nylon and rayon), and results in the deterioration of rubber.
SO_2	• Human health (animals). SO_2 is damaging to the human respiratory function, increasing both the prevalence of chronic respiratory disease, and the risk of acute respiratory disease. (Being highly soluble, SO_2 is more likely to be absorbed in the upper airways rather than penetrate to pulmonary region.) • Plants. SO_2 is damaging to plants at modestly elevated concentrations. Injury to plants includes both visible markings (yellowing of leaves) and damage to foliage, and invisible injury such as reductions of growth and productivity or reduced potential of plants to survive under periods of environmental stress, e.g. enhanced sensitivity to frost. Despite clear evidence that SO_2 does damage plants, no critical concentrations which can usefully be regarded as a threshold for injury has been identified. Different amounts of SO_2 can be tolerated under different climatic conditions. • Built environment and economic costs. SO_2, and the sulphuric acid it forms, may corrode iron and steel and damage building stones containing carbonates (limestones and marble). The higher the humidity and/or the moister the surface of the material, the greater the conversion rate of SO_2 to sulphuric acid, and the greater the impact. Sulphur oxides can also affect leather, paper and textiles.

Table 7.2 Environmental sensitivity to synergistic impacts of criteria pollutants

Pollutant	Potentially Sensitive Receptors
SO_2 and NO_2	• Crops and trees. Short-duration fumigations with SO_2 and NO_2 lead to severe plant injury, far greater than that found with the pollutants separately. (In one study in which four-hour exposures were considered, injuries were found to occur at concentrations of 10% of those required for injury by the individual gases.)
SO_2 and O_3	• Plants. SO_2 may result in enhanced opening of the stomata of plants assisting the access of O_3 into the leaf's interior and consequently increasing the risk of damage due to O_3 concentrations.
Particulates and SO_2	• Human health (animals). Particulates and sulphur dioxide act synergistically in adversely affecting human health. Particles act as a carrier taking SO_2 to lower parts of the respiratory system which it would not reach alone due to absorption on the walls of the upper respiratory tract. Ambient air quality standards for SO_2 in certain countries, e.g. the UK, are therefore dependent upon the level of smoke.

7.4.3 Impact of Criteria Pollutants on Human Health

The tables in the previous section merely provide a general indication of the sensitivity of various environmental components to pollutants. It should be noted that the susceptibility of environmental components varies greatly depending on the particular species (of plant or animal), the length of the exposure, and the general health of the receptor. Information contained within this section serves to reflect the specific symptoms with regard to human health which may be anticipated for various concentrations or dosages of pollutants.

The effects attributed to air pollutants range from mild eye irritation to mortality. Air pollution mainly affects the respiratory, circulatory, and olfactory systems. The respiratory system is the principal route of entry for air pollutants, some of which may alter the functioning of the lungs. The respiratory system may be divided into three regions: the nasal, the tracheobronchial, and pulmonary. The nasal region is composed of the nose and mouth cavities and the throat. The tracheobronchial region begins with the trachea and extends through the bronchial tubes to the alveolar sacs. The pulmonary regions is composed of the terminal bronchi and the alveolar sacs, where gas exchange with the circulatory system occurs. The effects of particulates and gases in the respiratory system is in part dependent on the region of the lung which the pollutants reach. In most cases, the effect is to aggravate preexisting diseases or to degrade the health status, making persons more susceptible to infection or development of a chronic respiratory disease. Broncho-constriction caused by SO_2 can aggrevate predisposition to asthma (Ferris *et al.*, 1978; Dassen *et al.*, 1986; Harrison, 1990; Scanlan *et al.*, 1990; Dockery *et al.*, 1993; Vandenberg *et al.*, 1993).

7.4.3.1 Particle Behaviour in the Respiratory System

Particle behaviour in the lung is dependent on the aerodynamic characteristics of particles in flow streams. The aerodynamic properties of particles are related to their size, shape and density. The deposition of particles in different regions of the respiratory system depends on their size. The nasal openings permit very large dust particles to enter the nasal region, along with much finer airborne particulates. Larger particles are deposited in the nasal region by impaction on the hairs of the nose or at the bends of the nasal passages. Smaller particles pass through the nasal region and are deposited in the tracheobronchial and pulmonary regions. Particles are removed by impacting with the walls of the bronchi when they are unable to follow the gaseous streamline flow through successive bifurcations of the bronchial tree. As the airflow decreases near the terminal bronchi, the smallest particles are removed by Brownian diffusion, which pushes them to the alveolar membrane (Opperman *et al.*, 1993; Dockery and Pope, 1994; Pope *et al.*, 1995; Reichhardt, 1995).

The respiratory system has several mechanisms for removing deposited particles. The walls of the nasal and tracheobronchial regions are coated with a mucous lining. Nose blowing, sneezing, coughing, and swallowing help remove particles from the upper airways. The tracheobronchial walls have fibrous cilia which sweep the mucous fluid upward, transporting particles to the top of the trachea where they are swallowed. This mechanism is referred to as the mucociliary escalator. In the pulmonary region of the respiratory system, foreign particles can move across the epithelial lining of the alveolar sac to the lymph or blood systems, or they may be engulfed by scavenger cells called alveolar macrophages. The macrophages can move to the mucociliary escalator for removal (Dockery and Pope, 1994). The macrophages with embedded particles are removed by the lymph nodes causing the nodes to become heavily mineralised, in the case of chronic exposures.

7.4.3.2 Gas Behaviour in the Respiratory System

The main factor affecting the behaviour of gases in the lung is the solubility of the gaseous molecules in the linings of the different regions of the respiratory system. Highly soluble gases such as SO_2 are absorbed in the upper airways, whereas less soluble gases such as NO_2 and O_3 may penetrate to the pulmonary region. Irritant gases are thought to stimulate neuroreceptors in the respiratory walls and cause a variety of responses, including sneezing, coughing, bronchoconstriction, and rapid shallow breathing. The dissolved gas may be eliminated by biochemical processes, or may diffuse into the circulatory system (Dassen *et al.*, 1986; Harrison, 1990; Scanlan *et al.*, 1990).

7.4.3.3 Symptoms Related to Specific Dosages

Symptoms related to human exposures to various dosages are given in Tables 7.3 to 7.9 for CO, NO_2, SO_2, PM10, total suspended particulates (TSP), O_3 and lead, respectively. In the compilation of these tables an attempt was made to integrate existing knowledge from various disciplines, including environmental epidemiology and toxicology, and ecotoxicology.

Table 7.3 Symptoms related to various concentrations of carbon monoxide

Symptoms	Concentrations (% of carboxyhemoglobin in blood (CoHb)
Death	80
Loss of consciousness, death if exposure is continued	60
Collapse on exercise, confusion	40
Headache, fatigue, judgement disturbed	30
Cardiovascular damage; electrocardiographic abnormalities	20
Decline (linear with increasing CoHb level) in maximal oxygen uptake; decrements in visual perception, manual dexterity and performance of complex sensori-motor tasks	5
Decrements in vigilance (i.e. ability to detect small changes in one's environment that occur at unpredictable times); decreased exercise performance in both healthy and those with chronic obstructive pulmonary disease	4
Aggravation of cardiovascular disease	2.5

Table 7.4 Symptoms related to various dosages of NO_2

Symptoms	Concentration (ppm)	Duration of Exposure
Rapid death	300	-
Death after 2 or 3 weeks by bronchiolitis fibrosa obliterans	150	-
Reversible, nonfatal bronchiolitis	50	-
Impairment of ability to detect odour of NO_2	10	-
Impairment of normal transport of gases between the blood and lungs in healthy adults	5	15 min
Increased airway resistance in healthy adults	2.5	2 hr
Increased airway resistance in bronchitics	1.0	15 min
Odour perception threshold of nitrogen dioxide	0.12	-

Table 7.5 Symptoms related to various concentrations of PM10

Symptoms	Concentration ($\mu g/m^3$) over 24-hour Averaging period
Aggravation of bronchitis	350
Increased respiratory disease symptoms	90
Increased respiratory disease risk	55

Table 7.6 Symptoms related to various dosages of SO_2

Symptoms	Concentration (ppm)	Duration of Exposure
Lung edema; bronchial inflammation	400	-
Eye irritation; coughing in healthy adults	20	-
Decreased mucociliary activity	14	1 hr
Bronchospasm	10	10 min
Throat irritation in healthy adults	8	-
Increased airway resistance in healthy adults at rest	5	10 min
Increased airway resistance in asthmatics at rest and in healthy adults at exercise	1	10 min
Increased airway resistance in asthmatics at exercise	0.5	10 min
Odour threshold	0.5	-
United States National Secondary Ambient Air Quality Standard promulgated in 1973	0.5	3 hr
Aggravation of chronic respiratory disease in adults	0.19	24 hr
United States National Primary Ambient Air Quality Standard promulgated in 1971	0.14	24 hr
Aggravation of chronic respiratory disease in children	0.07	Annual
United States National Primary Ambient Air Quality Standard promulgated in 1971	0.03	Annual

Table 7.7 Symptoms resulting from exposure to concentrations of ozone

Symptoms	Concentrations (ppm)
Severe pulmonary edema; possible acute bronchiolitis; decreased blood pressure; rapid weak pulse	10.0
Coughing; extreme fatigue; lack of coordination; increased airway resistance; decreased forced expiratory volume	1.0
Chest constriction; impaired carbon monoxide diffusion capacity; decrease in lung function without exercise	0.5
Headache; chest discomfort sufficient to prevent completion of exercise; decrease in lung function in exercising subjects	0.3
Increase in incidence and severity of asthma attacks; moderate eye irritation	0.25
For sensitive individuals, reduction in pulmonary lung function; chest discomfort; irritation of the respiratory tract; coughing and wheezing	0.15

Table 7.8 Symptoms related to human blood lead levels

Symptoms	Blood Lead Levels (µg/dl)
Coma, convulsions, death	300
Acute lead intoxication; deleterious irreversible effects; gastrointestinal and encephalopathic symptoms	100
Permanent severe neurological damage in children	80
Peripheral neuropathies; anemia in adults; central nervous system defects in children	50
Anemia in children; coproporphrin elevation; increased urinary aminolevulinic acid excretion	40
Maximum safe level for an individual child	30
Geometric mean maximum safe level for entire population of children; erythrocyte protoporphorin elevation	15

Table 7.9 Symptoms related to dosages of total suspended particulates (TSP)

Symptoms	Concentration ($\mu g/m^3$)	Duration of Exposure
Personal discomfort	2000	2 hr
Direct respiratory mechanical changes	1000	10 min
Increased respiratory disease symptoms	180	-
Increased respiratory disease risk	110	24 hr

7.5 User Interface – Risk Identification

Case-specific information is required to provide an indication of the sensitivity of the receiving environment. The nature of the response required for each of the questions given below is indicated by the following symbols: <T> for toggle options, <M> for menu options, <R> for range options, and <O> for open-ended response options.

- Specify whether or not the receiving environment for the proposed development is represented on the list of environments identified as being sensitive by the Department of Environmental Affairs and Tourism. The list of environments is given in section 7.4.1 of the data base.<T>

In instances where the receiving environment is not represented on the DEAT's list of environments, the following information needs to be provided:

- Indicate the relevant class reflecting the distance between the proposed site and the closest sensitive receptor (D):
  a) $D \leq 1$ km
  b) $1 \text{ km} < D \leq 10$ km
  c) $D > 10$ km

In identifying potentially sensitive receptors in the vicinity of the proposed site use should be made of maps and other readily available information on the receiving environment, and data contained in the risk identification data base.

7.6 Model Base – Classification of Environmental Sensitivity

The model base will facilitate the classification of the receiving environment into one of three classes, viz. "sensitive", "potentially sensitive" and "non-sensitive". For proposed developments where the receiving environment is represented on the DEAT's list of sensitive environments, and for proposed projects where sensitive receptors are located within 1 km of the proposed site, the receiving environment is classified as "sensitive".

In instances where potentially sensitive receptors are located beyond 10 km from the border of the proposed site, the receiving environment will be classified as being "non-sensitive". Maximum ground-level concentrations resulting from most source configurations (with the exception of very tall stacks), under all meteorological conditions, are unlikely to occur beyond 10 km from the source.

For cases where potentially sensitive receptors are located between 1 km and 10 km from the proposed site, the receiving environment will be classified based on the atmospheric dispersion potential of the region (as estimated in Section 6.5.5), and the extent of emissions predicted (as established in Section 4.7), according to the following criteria:

Emissions as % of Emission Limits	Atmospheric Dispersion Potential		
	Poor	Potential Risk	Fair/Good
> 100 %	"Sensitive"	"Sensitive"	"Sensitive"
80 % - 100%	"Sensitive"	"Sensitive"	"Potentially sensitive"
< 80 %	"Sensitive"	"Potentially sensitive"	"Potentially sensitive"

7.7 Conclusion

Following the classification of the receiving environment of proposed developments into "sensitive", "potentially sensitive" and "non-sensitive" classes, the next stage of modelling may be initiated. The air pollution scoping procedure will not, however, be continued for developments which are to be located within environments classified as being "sensitive", as is evident from the decision making framework contained in Chapter 8. It will be recommended that such proposed development be subject to comprehensive air pollution impact assessments.

CHAPTER 8 - DECISION MAKING FRAMEWORK FOR AIR POLLUTION IMPACT SCOPING

8.1 Introduction

The environmental consequences of a proposed industry will depend on the nature of the pollutants emitted, the magnitude of the release, existing ambient pollution concentrations, the dispersion potential of the atmosphere, and the nature of the receiving environment. The integrated assessment of these factors is complex. To ensure that the decision making process is carried out in a transparent and consistent manner, an assessment framework has been developed to enable relevant factors to be taken into account. The procedure recommended for the integration of the findings of the industrial, ambient air quality, atmospheric dispersion potential and environmental risk identification model phases (documented in Chapters 4, 5, 6 and 7) into the final decision making process is described in the current chapter.

Due to the anticipated shift toward effects-based air quality management, an attempt has been made to take both source-based controls and effects based controls into account in the development of the current air pollution scoping procedure. The acceptability of the proposed industry's emissions is determined on the basis of source based controls; emission inventory results regarding the magnitude of releases from various operations being compared with emission limits promulgated by the Chief Air Pollution Control Officer. It should be noted, however, that such emission limits are not available for all possible sources of emission. No emission limits are presently set for fugitive emissions arising from materials handling, dust entrainment from paved and unpaved roadways, and emissions from the aeolian or mechanical disturbance of open areas and stockpiles. The inclusion of an assessment of existing ambient air quality with regard to local and international air quality standards and guidelines in the scoping procedure reflects the integration of an effects-based approach. The analysis of atmospheric dispersion potentials and the sensitivity of receiving environments also forms an integral part of the effects-based approach.

Despite the need for a consistent decision making framework, the scoping procedure must provide opportunities for the review of initial proposals and the integration of alternatives to such proposals in instances where the impact of proposals is found to be unacceptable. Should the emissions from a proposed development be predicted to exceed the emission limits, for instance, the project proposer may be prompted to review various design, process and/or control options so as to reduce the proposed development's potential emissions. The scoping procedure may also be used during the site selection process, in

order to avoid the selection of sites characterised by poor dispersion potentials, should the location of the proposed development at alternative sites be possible.

8.2 Decision Making Framework Model Base

The information generated by the industrial, ambient air quality, atmospheric dispersion potential and environmental risk identification model bases will be integrated into the decision making framework. Based on the information, with regard to the potential emission, existing air quality, atmospheric ventilation potential, and environmental sensitivity estimated for a particular project, the proposal will be grouped into one of three classes for each stage within the decision making framework, viz.:

- **Proceed.** The scoping procedure will be allowed to proceed for proposals classified as acceptable for this stage.

- **Proceed with caution.** Despite a potential risk associated with the proposal, the scoping procedure is allowed to continue to the next decision making stage.

- **Procedure terminated.** The project proposal is found unacceptable in terms of the current stage and the scoping procedure is terminated.

Although the evaluation of a proposed project will be permitted to continue despite an initial "proceed with caution" note, the scoping procedure will be terminated for any subsequent "proceed with caution" notes. No further data input will be required by the user during the decision making phase. The user will, however, be given the option of returning to a previous model base should a "PROCEDURE TERMINATED" decision or a "PROCEED WITH CAUTION" note be returned. An outline of the various phases within the proposed decision making framework is given in Figure 8.1.

8.2.1 Proposed Development

During the initial phase of the air pollution impact scoping decision making framework, results from the industrial model base will be recalled. According to this model base, proposed developments were classified into three categories, based on the relationship between the magnitude of estimated emissions and the emission limits promulgated by the Chief Air Pollution Control Officer. The three categories are defined as follows:

(a) Proposed developments which demonstrated little to no risk of non-compliance with DEAT emission limits, i.e. emissions from all proposed scheduled processes were below 80% of the emission limits.

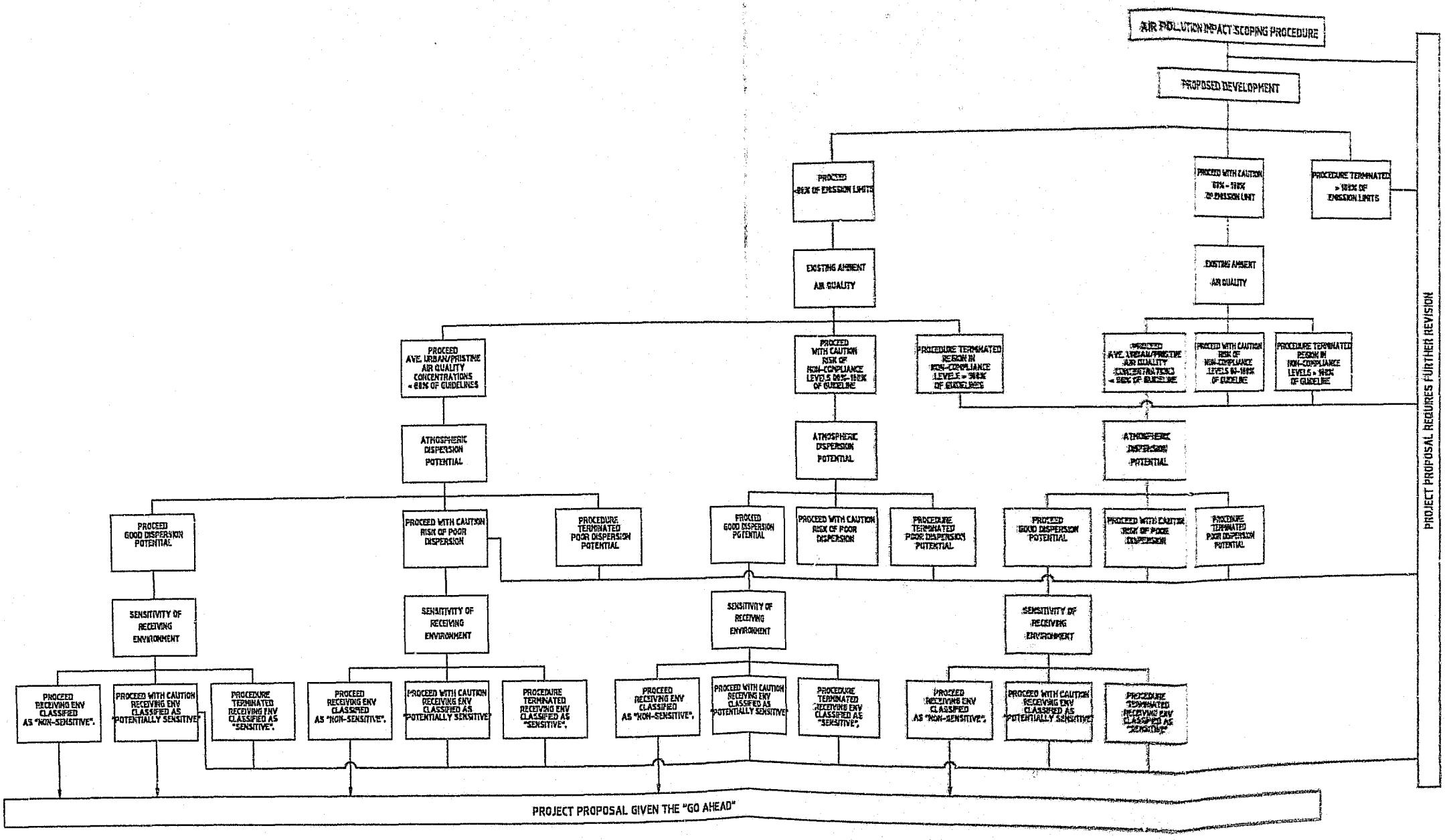


Figure 8.1 Outline of proposed decision making framework for air pollution scoping studies.

(b) Proposed developments for which a potential risk of non-compliance with DEAT emission limits exists, i.e. the extent of emissions from one or more of the proposed scheduled processes were predicted to be between 80% and 100% of the emission limits, with all other emissions being below 80%.

(c) Proposed sources in non-compliance with the DEAT's emission limits, i.e. extent of emissions from one or more of the proposed scheduled processes predicted to exceed the emission limit.

Proposed developments within the first category are entitled to "PROCEED" to the next level. Proposed developments within the second category are allowed to proceed, but are issued a note of caution, "PROCEED WITH CAUTION". All proposed projects within the third category are not allowed to proceed to the next level and the scoping procedure is terminated. For sources within the third category, the user should be referred to information contained within the industrial data base on various design, process and/or control options which may be implemented to reduce a development's emissions. Alternatively, it may be recommended that CAPCO be approached to review the achievability of the emission limits set.

8.2.2 Existing Ambient Air Quality

The second phase of the decision making framework comprises the integration of information on the extent of pollutant concentrations in the vicinity of the proposed site so as to assess the potential incremental impact of the proposed development on the air quality of the region. This phase is based on the ambient air quality indices generated for the region within which the proposed site is located. The air quality index to be used in the decision making procedure will have been selected previously by either the user or the model (Section 5.4.2). Five classes of air quality are defined for each index, based on the percentage that monitored levels of pollutant represented of the selected guideline and/or standard. The definition of each class is as follows:

(a) Areas in non-compliance, i.e. ambient concentrations $\geq$ 100% of relevant air quality standard and/or guideline.

(b) Areas at risk of non-compliance, i.e. ambient concentrations of 80% to 100% of the relevant standard and/or guideline.

(c) Areas characterised by average (urban) air quality, i.e. ambient concentrations of 50% to 80% of the relevant standard and/or guideline.

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