PREDICTION, MANAGEMENT AND CONTROL OF ODOUR FROM LANDFILL SITES

By

Guy Laister
BScEng (Civil)

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ABSTRACT

Due to the spread of urbanisation and increased environmental awareness, odour has become a major problem in communities surrounding landfills. The aim of this research was to investigate odour emissions from landfills and develop a management tool that operators could use to assist in minimising the impacts of odour. The management tool would be in the form of real-time predictions of odour concentrations in the vicinity of a source. The Bisasar Road landfill in Springfield, Durban was a case study site for the research.

The methodologies used in this project can be divided into three broad categories. Firstly, flow visualisation experiments were conducted on the case study site to investigate the effects of complex terrain and the results compared to predictions from a dispersion model. Secondly, source characterisation was done on-site. Sources of odour were identified using a portable odour monitor (Electronic nose). Sources of odour were then sampled using sorbent tubes and analysis done using Gas Chromatography – Mass Spectrometry. Thirdly, numerical dispersion modelling was done. Five available dispersion models were assessed and compared against one another in order to select the most suitable model for this application. A software management tool or *'Odour Management System' (OMS)*, was designed and implemented on a computer at the Bisasar Road landfill.

Qualitative results of the flow visualisation experiments show that terrain does have an effect on a dispersing plume path for short-range predictions. Comparisons between the flow experiments and model predictions are qualitatively consistent. Quantitative results were not obtained for the emission flow rate and emission concentration of landfill gas. The chemical composition of the fresh waste gas was determined. *ADMS™ (Advanced Dispersion Modelling System)* was found to be the most suitable dispersion model for this application. The *OMS* has been installed on-site to produce odour concentration graphics every ten minutes. A fence line odour control misting system has been installed along approximately 600 metres of the landfill border based on work done as part of this project. Weather conditions and information provided by the *OMS*, assist in running the odour control system economically.

PREFACE

Unless specifically indicated to the contrary in the text, this whole dissertation is the work of Guy Laister and has not been submitted in part, or in whole to any other university.

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Date Signature

The research work for this dissertation was carried out at the University of Natal, Durban under the supervision of Prof. D. D. Stretch.

As the candidate's supervisor I have/have not approved this thesis/dissertation for submission

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Date Name Signature

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Last, but by no means least, to my supervisor, Prof. D. D. Stretch for firstly initialising the project and securing the funding. But most of all, thanks for the endless stream of ideas and support that never ceased throughout the research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF SYMBOLS

A	Area	
C	Concentration	
C_m	Mean concentration	(Eq. 2.3)
or	Concentration at receptor	
C_o	Concentration at source	
C_p	Peak concentration	(Eq. 2.3)
or	Specific heat capacity of air =	1010 J/kg/K
E_v	Exit velocity of emissions from source	
F_s	Vertical momentum flux	
g	Acceleration due to gravity	
h	Mixing depth / Boundary layer height	
H	Sensible heat flux	
K_s	Eddy diffusivity	
L_{MO}	Monin-Obukhov length	
L(z)	Eddy length scale at height z	
P	Atmospheric pressure	
Q	Volume flow rate	
Q_s	Source strength	
t	Time	
T	Temperature	
$\bar{u}$	Mean wind velocity	
U	Mean wind velocity	
u(z)	Mean wind velocity at height z	
u_*	Friction velocity	
V	Volume	
W	Hourly waste deposition rate	
x, y, z	Rectangular co-ordinates, x usually along the mean wind, y at 90° x in the horizontal plane, and z vertical	
z_0	Roughness length	
z_s	Height of source	
χ	Concentration	
ϕ	Latitude	
κ	von Karman's constant	
ρ	Air density	

σ^2	Variance	
σ	Standard Deviation	
σ_y	Transverse (Cross wind) dispersion parameter	
σ_z	Vertical dispersion parameter	
τ	Shear stress	
Ω	Earths rate of rotation	= 7.29×10^{-5} sec^{-1}

LIST OF ABBREVIATIONS

ABL	Atmospheric Boundary Layer
ADMS™	Advanced Dispersion Modelling System
AQS	Air Quality Standard
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
CBE	Communities for a Better Environment
CERC	Cambridge Environmental Research Centre
CTDMPLUS	Complex Terrain Dispersion Model PLUS algorithms for unstable conditions
DEAT	Department of Environmental Affairs and Tourism
DMWS	Durban Metro Water Services
DSW	Durban Solid Waste
DWAF	Department of Water Affairs and Forestry
FID	Flame Ionisation Detector
GC	Gas Chromatography
GPS	Global Positioning System
ISCST3 (ISC3)	Industrial Source Complex Short Term model Version 3
LFG	Landfill Gas
MRL	Maximum Recommended Limit
MS	Mass Spectrometry
MSW	Municipal Solid Waste
NMOC	Non Methane Organic Compound
OMS	Odour Management System
OMU	Odour Monitor Unit
OFR	Odorant Flow Rate
OT	Odour Threshold
P-G	Pasquill-Gifford (stability coefficients)
PID	Photo Ionisation Detector
POS	Place of Safety
SAC	Static Accumulation Chamber
UND	University of Natal, Durban
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WHO	World Health Organisation

CHAPTER 1

1. INTRODUCTION

This chapter introduces the research carried out for this dissertation as well as the motivation behind the research. The main objectives and key issues are discussed. Papers written and work presented at conferences by this author are highlighted. An outline of the dissertation concludes the chapter.

1.1. Motivation

The unpleasant odour associated with landfill gas is one of the contributing factors to the general public's negative perception of landfilling as a means for disposal of waste. Unpleasant odour from open dumpsites and landfills has in the past been considered a nuisance rather than a health hazard. Recently, greater attention has been paid to possible health effects. With these environmental issues gaining more attention, combined with the spread of urbanisation and increased public awareness, nuisances such as odour are now threatening the closure of waste disposal facilities. This is the case for one particular landfill in the Durban Metropolitan area that was used as a case study in this research.

The research for this project was motivated by the need to find a solution to combating odour from landfill sites. This is the case for one site in particular under the supervision of Durban Solid Waste (DSW), Bisasar Road landfill.

More than half the complaints received by environmental regulatory agencies worldwide concern odour (Kaye and Jiang, 1999). Many of these complaints are due to emissions from waste facilities such as wastewater treatment plants, sewage works, composting facilities and landfills. In the case of Bisasar Road landfill, the number of complaints has risen to the stage where the closure of the landfill is being threatened.

1.2. Objectives

The main objective of this research was to develop and implement an *'Odour Management System' (OMS)*. This *OMS* would consist of odour concentration predictions, a decision-making support system and technology relating to the control of odour. A key output of the *OMS* would be a graphic display of 'realtime' odour concentrations resulting from emission sources. The *OMS* would use a dispersion model integrated with weather data recorded by an on-site weather station to produce the predictions.

The information produced by such a system could then be used to minimise and manage odour emanating from the Bisasar Road landfill.

Various key issues, central the development of the *OMS*, were investigated.

1.2.1. Complex terrain effects

The first specific objective was to qualify and quantify the effects of complex terrain. Complex terrain affects the wind field and therefore affects the dispersive characteristics of the atmosphere. This in turn affects the concentration of airborne substances.

1.2.2. Investigating effects of concentration fluctuations

It may not be sufficient to use a traditional air quality analysis approach for odour and calculate long-term averages of concentration. The effect of short-term concentration fluctuations was investigated.

1.2.3. Selection of dispersion modelling technology

A dispersion model is required to formulate the odour concentration predictions. Five dispersion models were assessed in terms of capability, accuracy and user-friendliness. The aim was to select the best dispersion model for this application.

1.2.4. Source emission characteristics

In order to predict accurate downwind concentrations, the source needs to be characterised accurately. In the case of multiple sources on one particular site, either all the sources can be modelled or the primary sources determined and modelled. Once the sources have been selected, the concentration and the flow rate of the sources need to be determined. The aim was to sample sources on-site to determine site-specific emission rates and concentrations.

The *OMS* will form part of the total odour minimisation strategy. Odour minimisation consists of many components that need to be implemented in combination in order gain effective results. Odour can be minimised indirectly through good operational practice on-site and also directly by odour control systems such as fence-line chemical spraying systems. Various methods of odour control were investigated, with the aim of finding and implementing good operational procedures and an effective control system.

1.3. Publications

Work contained in this dissertation has been presented at two international conferences, one local conference and one local training seminar. Work was first presented at the biennial "Wastecon" conference, in September 2000 (Laister et al, 2000).

Further work was presented at the 1st international conference on Odour and VOC's, in Sydney, Australia in March 2001 (Laister et al, 2001a).

A paper was delivered at a second international conference in October 2001. Prof. Stretch presented a paper at the Eighth International Waste management and landfill symposium in Sardinia, Italy (Stretch et al, 2001). This paper won the Kriton Curi Best Paper Award.

1.4. Outline of dissertation

Chapter two of this dissertation contains a review of literature covering topics of waste management and landfills in particular, the process of olfaction and qualification and quantification of odour as well as dispersion in the atmosphere and a review of dispersion models.

Bisasar Road landfill site in Springfield Park, Durban was used as a case study site for this research. Chapter three describes the landfill, visualisation experiments carried out on-site and the identification of sources of odour.

This author, as well as consultants have carried out sampling on-site. Chapter four reviews the results obtained.

Chapter five reviews work done using atmospheric dispersion models. Five available atmospheric dispersion models were obtained. These five models were reviewed and compared against each other for scenarios applicable to modelling emissions in the vicinity of Bisasar Road landfill. The most applicable model was chosen and simulations run for conditions when complaints were logged. A dispersion model was also used to determine the effect of varying the type of source modelled.

The main objective of this research was to develop and implement a software tool as the basis of an 'Odour Management System' for the Bisasar Road landfill. The details of this software system are described in chapter six.

Odour mitigation and control methods were also important foci of this research. Various methods of odour control were tested on-site. The experiments and research done to determine the best form of odour control for Bisasar Road are discussed in chapter seven. Methods of odour minimisation involving the application of the Odour Management System are also described in chapter seven.

Conclusions of the research and recommendations are summarised in chapter eight.

CHAPTER 2

2. LITERATURE REVIEW

Chapter two introduces waste management strategies and the concept of landfilling and the associated nuisances. A review of odour is given, including how humans perceive odour. Methods of quantifying, regulating and controlling odour are discussed. Dispersion in the atmospheric boundary layer is discussed. A review of currently available dispersion models is also included. The climate and weather patterns applicable to the area of the case study site are summarised.

2.1. Waste management

Waste disposal is a necessary service that can be expensive and possibly detrimental to the environment. Waste management options include landfilling, composting, incineration and recycling.

South Africa's total waste stream for 1991 was estimated to be 460 million tonnes of which urban waste or Municipal Solid Waste (MSW) accounts for 37 million tonnes (8%) (DWAF, 1998). MSW includes sewage sludge, domestic refuse, non-hazardous industrial waste and commercial waste. Mining waste constitutes 81% of the total waste stream.

In South Africa, approximately 95% of all urban waste is disposed of in open trenches or sanitary landfills (DWAF, 1998).

2.2. Landfills

2.2.1. From dumping sites to Sanitary Landfills

In the past, organic waste and other refuse have been deposited in open dumps and allowed to decompose in the open air. With the spread of urbanisation and the nuisances associated with decomposing waste (odour, flies, litter, and generation of gas and leachate), greater control of the deposition of waste was needed. The controlled deposition of waste was termed, 'Sanitary landfilling'

Landfilling is one of the most economical disposal techniques (Gendebien et al, 1992).

Sanitary landfilling implies four conditions of operation (e.g. Gendebien et al, 1992):

a) Compaction and consolidation of waste,
b) Minimum daily cover of the filled waste,
c) No open burning of the filled waste, and
d) No pollution of the surface or ground waters below and around the landfill site.

Landfilling does have many disadvantages including the decreasing availability of land to landfill, the nuisances created by noise, flies, dust, litter, and odour as well as the generation of gas and leachate. With current technology, it is possible to minimise the nuisances and control the leachate and landfill gas. At the same time, however, laws are getting more and more stringent regarding the placement of new landfills.

The advantages of waste disposal by sanitary landfill include the relatively low capital cost involved in implementation of a facility, low labour and operating costs and gas emissions can have economic value.

2.2.2. Landfill gas

Gas forms as a by-product of the biological, chemical and physical transformation of waste. These transformations interact simultaneously and constantly to form an ongoing relationship between the solid, liquid and gaseous phases. Gas formed by these processes in a landfill is known as Landfill Gas (LFG).

More specifically, gas is generated under aerobic (In the presence of oxygen) as well as anaerobic (In the absence of oxygen) conditions. For specific reference, gas produced under aerobic conditions will be referred to as “Fresh waste gas”, and gas produced under anaerobic conditions is commonly referred to as “Biogas”.

The dominant anaerobic process is the microbial conversion of organic carbon (present in all organic waste) to methane (CH_4) and Carbon Dioxide (CO_2). This biological process is the major mechanism by which waste decomposes in a landfill. Biogas consists mainly of Methane (CH_4) and Carbon Dioxide (CO_2) in roughly equal proportions (e.g. Gendebien et al, 1992). The composition of fresh waste gas (formed by aerobic processes) is less certain.

CO_2 is heavier than air with a dry relative density (compared to air) of 1.53. CH_4, on the other hand, is less dense than air with a dry relative density of 0.55. Therefore, a 50/50 mixture of CO_2 and CH_4 has a density nearly equal to that of dry air.

The time scale for the establishment of anaerobic decomposition is dependant on local climatic conditions but is typically less than one month (Robinson, 1989). Due to relatively high temperature, humidity and rainfall (See section 2.5.3) this could be even shorter in Durban.

Although methane and carbon dioxide typically constitute over 99% of LFG, they are not the only constituents as trace components are also emitted. Carbon based compounds are categorised as either Volatile Organic Compounds (VOC's) or Non-Methane Organic Compounds (NMOC's). Other common trace compounds are based on Sulphur and Nitrogen.

Gas generating processes are influenced by three main factors: The composition and diversity of the waste landfilled, local environmental factors and landfill operating procedures. This will be discussed in chapter 3 with direct reference to Bisasar Road landfill.

2.3. Odour

2.3.1. Human olfactory sensory system

Odour can be defined as a sensation resulting from the reception of a stimulus by the olfactory sensory system (Prokop, 1992). Odour is a subjective phenomenon based on perception of stimulus (odorant).

The reception and perception of odour is based upon a two step process (Christensen et al, 1996 and Figure 1):

ODORANT ——→ reception (physiological) ——→ interpretation
(psychological) ——→ ODOUR PERCEPTION

Figure 1: Reception and perception of odour (Christensen et al, 1996).

The physiological and psychological processes that comprise the sense of smell are not yet fully understood. However, for the purposes of this investigation it is necessary to understand the basics of how humans receive odorants and then perceive the odour.

The process by which organisms respond to chemical stimuli is known as chemoreception. The process begins when chemical stimuli come into contact with chemoreceptors which are specialised cells in the body that convert the immediate effects of such substances into nerve impulses (Encyclopaedia Britannica).

The olfactory region (Olfactory Epithelium) in humans is located in the roof of the two nasal passages (Leffingwell, 2000). The olfactory (primary) receptor or neuron is a long thin cell, which lies in the olfactory epithelium. Each olfactory neuron in the epithelium is topped by at least 10 hair-like cilia that protrude into a thin bath of mucus on the surface (Pines, 1995). The olfactory cilia are the sites where molecular reception of the odorant occurs and sensory transmission starts (Leffingwell, 2000; Pines, 1995). The end of each receptor narrows to a fine nerve fibre, called an axon, which, along with many others, enters the olfactory bulb of the brain through a fine channel in the bony roof of the nasal cavity (Leffingwell, 2000). Figure 2 illustrates the olfactory sensory system.

Whilst the psychological events following the physiological reception of odorants are not yet fully understood, many theories exist. The details of these working theories are not important to this research. What is important is that following reception, a signal is sent to the brain, which then translates the information forming a subjective perception.

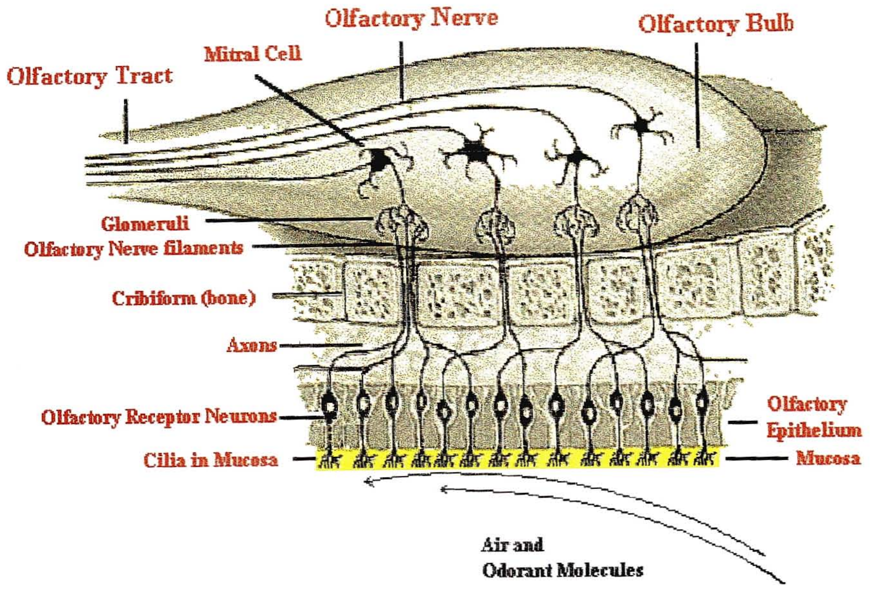


Figure 2: Olfactory sensory system (Leffingwell, 2000).

2.3.2. Factors affecting human perception of odour

Perception of odour varies between persons and in time. Individual perception is due to a number of different factors. Differing perception between individuals living near the landfill may have an influence on the complaints.

It is widely accepted that increasing age is correlated with decreasing olfactory sensitivity (e.g. Jiang, 1999; Finger and Silver, 1987; Amoore, 1982). There are differing views however, on relative sensitivity between gender types. Smoking affects sensitivity to odour (Jiang, 1999) but perhaps only in terms of temporary loss in sensitivity following smoking (Amoore, 1982).

General anosmia is a total loss or absence of the sense of smell (Amoore, 1982). Specific anosmia is lack of sensitivity to some groups of odours (Jiang, 1999).

Adaption or olfactory fatigue is a phenomenon that occurs when a person with normal sense of smell experiences a decrease in perceived intensity of an odour due to continuous exposure to odour (Prokop, 1992). Adaption is an important issue when conducting olfactometry (see section 2.3.4). Recovery from olfactory fatigue may range from seconds to minutes.

Prolonged exposure to an odour causes a progressive decrease in the perceived odour intensity (Finger and Silver, 1987). Based on this, it could be argued that certain individuals living near a landfill may become immune to the odour and therefore may no longer regard the odour as a nuisance.

2.3.3. Principal odour characteristics

No unique chemical or physical property that can be said to elicit the experience of odour has yet been identified. However, Leffingwell (2000) identifies certain properties that odorants must possess in order to provide sensory properties. An odorant must have some water solubility, a sufficiently high vapour pressure i.e. be volatile, low polarity and have some ability to dissolve in fat (lipophility). Amoore (1982) explains why odorants must have a high vapour pressure. Humans can only detect chemicals that have an appreciable volatility (expressed as vapour pressure) at ordinary temperature. To be odorous, a substance must be sufficiently volatile for its molecules to be given off and carried into the nostrils by air currents.

Five properties are used to qualify and quantify odour.

The detectability of an odour is measured by its concentration. Concentration will be dealt with in more detail in section 2.3.4.

Odour intensity is best described as a physiological response to the concentration of a particular odorant. Odour intensity represents the increase in sensation intensity experienced by an individual as the chemical concentration increases. The intensity has to be assessed by test persons. It has been shown that odour intensity conforms to a power law function of chemical concentration by Steven's law

$$I(perceived) = k(C)^n \tag{2.1}$$

where:

$I\ (perceived)$ = Perceived intensity
k = constant
C = concentration
n = exponent

This law has been confirmed using n-butanol as a reference (Amoore, 1982). Published values for the exponent, n, vary between 0.2 and 0.7 (Amoore, 1982; Prokop, 1992; Dravnieks, 1972; Finger and Silver, 1987).

Using n = 0.5 (as an example), Steven's law indicates that a reduction by 75% (concentration lowered by 4 times) will reduce the intensity by only a factor of 2.

It has generally been noted (Jiang, 1999; Finger and Silver, 1987; Amoore, 1982) that the perceived intensity of a physical mixture of odorants is less than the algebraic sum of the perceived intensities of the unmixed components, but more than the average perceived intensity of the unmixed components.

The character of an odour enables the odorant to be recognised. Character evaluation is either carried out using descriptive words or by comparison with other odours.

The hedonic tone of an odour is the scale of pleasantness or unpleasantness. In the case of landfill odour, the hedonic tone is usually unpleasant.

Probably the most important dimension of an odour is acceptability e.g. what percentage of the population is annoyed by a particular odour? There are no physical methods of determining acceptability and one must resort to sociological inquiry methods. This will be discussed further in section 2.3.11.

2.3.4. Quantification of odour

The most common method of predicting the impacts of odour on communities, is to quantify the strength of the odour at the source and then use a dispersion model to calculate off-site predictions (e.g. Schmidt, Wilsey and Hasek, 1998). In order to determine the strength of an odour or calculate the concentration, a sample needs to taken and then analysed. Both sampling and analysis need to be carried out carefully using the best available technology in order to obtain meaningful results.

Rapid advancements have been made in the fields of sample collection and analysis as well as dispersion modelling. Methods for measuring the concentration of specific compounds in airbourne samples as a mass concentration (e.g. $\mu g/m^3$) or volume concentration (e.g. ppb) are now widely documented and accepted (e.g. Rathunathan et al, 1999). However, due to the varying perception of odour, the interpretation of results is a lot more complicated with odour as opposed to common pollutants such as SO_2 and NO_2. Added to this, odorous compounds are often present at low concentrations near to the limit of detection and are therefore difficult to sample and analyse accurately (Christensen et al, 1996). An additional factor is that sampling and analysis techniques are generally formulated to measure the concentration of compounds in the gaseous state only. This does not cover the measurement of odours potentially released by particles of odorous solids or droplets of odorous fluids suspended in emissions i.e. dusts and condensates.

2.3.5. Emission sampling

Generally, pollutant material is emitted into the atmosphere via area, line, point or volume sources. Line and volume sources are rare and can be sampled using methods developed more specifically for point and area sources.

Sampling area sources is more difficult than sampling point sources. Variability is introduced due to uncertainty in the spatial variability of emission strength and flow rate. Generally, area sources are too large to cover entirely and only points within a given area source can be sampled. Individual points sampled are then assumed to yield information representative of the entire area source. Because of the spatial variability of emissions from area sources, no single perfect sampling technique exists. There are however, various options for sampling area sources. The options can be divided into methods capable of determining the emission rate as well as emission concentration, and those that are only capable of determining the emission concentration. The focus of this investigation was to determine both the emission rate as well as concentration, so those methods are described first.

The flux box is the most commonly used apparatus for sampling area sources. This approach uses an enclosure device (or flux chamber) to sample gaseous emissions from a defined surface area.

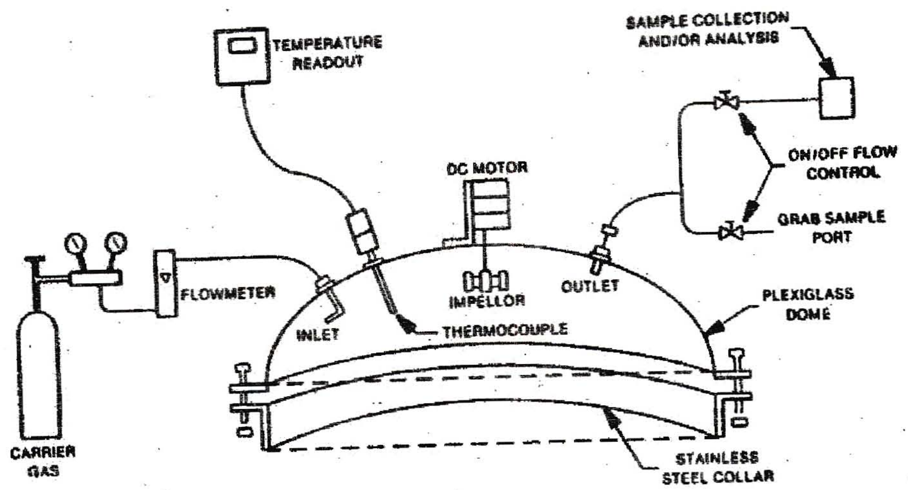


Figure 3: Typical flux box used for sampling area sources (Eklund et al, 1985).

Uncontaminated air is passed through the chamber at a fixed controlled rate significantly exceeding the gaseous release rate from the surface (Reinhart and Cooper, 1992). The sweep air mixes with the landfill emissions and transports them to the exit port. The flow rate of the sweep air is recorded and the concentration of the gas is measured (either directly using portable equipment or sampled and analysed in a laboratory) at the exit of the chamber.

As an alternative to the flux box, the Environmental Odour Laboratory at the University of New South Wales in Australia designed a portable wind tunnel. The principal behind the wind tunnel is too simulate the natural wind conditions at the surface. Emissions from the surface are mixed with clean air input at a constant flow rate, and the mixture vented out of the tunnel into a sampling vessel.

The flux box and wind tunnel are known as 'Dynamic Chambers', due to the fact that air is continually passing through the system. Both the flux box and wind tunnel were costly in terms of the funds available for this project. They can also be complex to operate. A simple, cost effective yet accurate design in the form of a Static Accumulation Chamber (SAC) was investigated. Advantages of Static Accumulation Chambers include low cost and low construction technology, operation and maintenance, rapid data turn-around and easy deployment in the field (Morris, 1999). The disadvantages of SAC's include their spatial limitation as well as their potential to influence the gas-flow field, temperature and gas concentrations at the enclosed surface/atmosphere interface.

Sampling with a SAC involves the enclosing of a known volume of atmosphere above a known surface area of soil so that emissions from the surface area can be measured as a concentration change of a given gas against time. The assumption is that, for each series of measurements, the increase in concentration of a given gas in the chamber's atmosphere is linearly proportional to the gas emission flux across the surface. The methodology used to calculate the flow rate is to identify specific compounds common in each sample and determine an emission rate for each compound. Depending on the number of individual compounds identified and the scatter of their relative emission rates, individual compounds could either be input into the dispersion model or the emission rates averaged. Details of a SAC that was built and tested for this study will be discussed further in chapter 4.

Multiple methods exist for determining only the emission concentration and not the emission rate.

Bag sampling using vacuum chambers consists of a rigid, enclosed sampling box or suitcase, which allows the direct filling of a gas sample into a flexible bag using negative pressure. A sampling bag (usually made of Tedlar™, Teflon™ or Nalophane™) is placed in the box and attached to an inlet valve that opens to the atmosphere (See Figure 4).

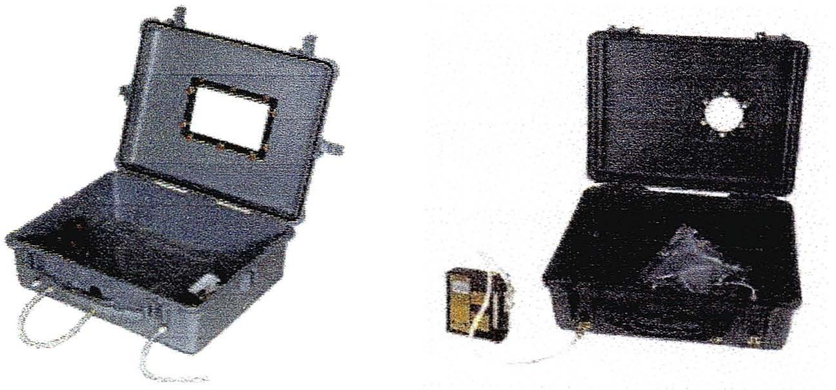


Figure 4: Examples of commercially available vacuum chambers (AC'SCENT, 1999; SKC, 1998).

When the box is closed air is sucked out of the box using an external pump, creating negative pressure in the box. When the inlet valve is opened, the air sample enters the bag directly without passing through the pump. This prevents contamination of the sample.

Based on the vacuum chamber design, an environmental organisation known as the Communities for a Better Environment (CBE) created the 'Bucket' air-sampling device. This community based sampling program was called the 'Bucket Brigade'.

The principle behind the device is the same as for the vacuum chamber described above, with the enclosed box being a 5-Gallon (approximately 25 L) plastic paint bucket.

Unfortunately, CBE was not willing to sell the buckets for purely sampling purposes, but required that a community involvement program be set-up and that the public perform the sampling. No such program was developed for the area surrounding the Bisasar Road landfill.

In order to lengthen sample storage times as well as improve inertness to sulphur compounds, stainless steel canisters are now widely used. The stainless steel cans are lined on the inside with fused silica. The canisters are filled at a constant rate using a flow controller. The flow can be regulated so that the canister can be filled over 1, 3, 8, 24 hours or 7 days.

Instead of collecting a sample volume of air in a bag or canister, gas can also be trapped on an adsorbent material. Various adsorbent materials are used, the most common include activated charcoal and Tenax™. Figure 5 shows a typical glass tube containing adsorbent material. The sampling apparatus is also shown in Figure 5. The procedure for sampling ambient air using adsorbent material is to take the tube, break off the ends, place the tube in a holder, with the one end open to the atmosphere and the other attached to the pipe connected to the pump. The pump can then be turned on and air is drawn through the tube, trapping pollutants on the adsorbent material.

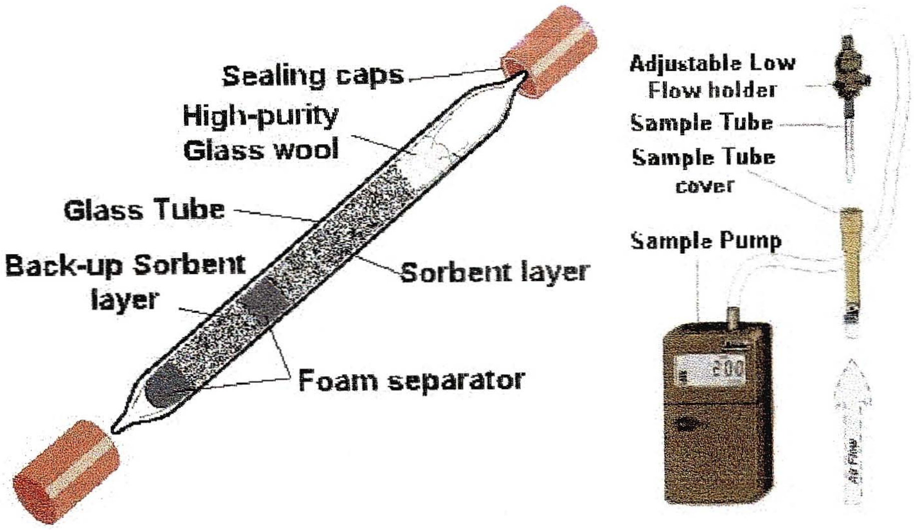


Figure 5: Sorbent tubes (SKC, 1998).

2.3.6. Analysis

The relevant problem in the case of odour may not be the presence or absence of specific air compounds, but to obtain knowledge about the effects of the air compounds (Christensen et al, 1996). Analytical methods for identifying and quantifying substances contained in a sample collected give substance related values. Analytical methods have the advantage of objectivity, repeatability and accuracy (Gostelow and Parsons, 1999). They do not allow any calculation of the odour sensation of a human being (Frechen, 1995). Therefore measurements should be based on the judgement of human persons. Sensory methods are particularly useful in the case of gaseous mixtures, as interactions between different odorants may lead to synergistic or antagonistic effects (Gostelow and Parsons, 1999).

Figure 6 gives an overview of various options and capabilities of both analytic and sensory methods.

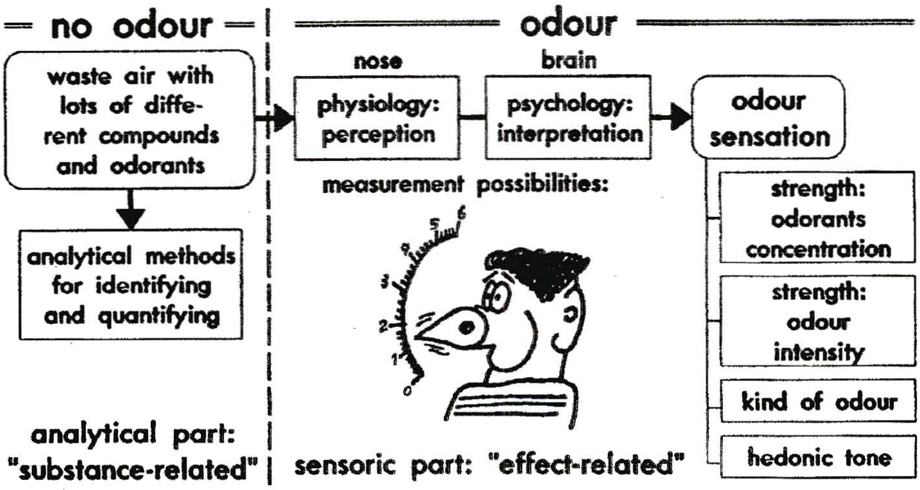


Figure 6: Analytical and sensoric measurement possibilities (Frechen, 1995).

Non-sensory analysis of odorous samples used to determine compound concentration is important and useful especially for odour control. It is possible to determine the exact chemical composition of a gaseous mixture by 'Gas Chromatography' (GC). GC separates individual components according to their vapour pressures and solubility (Jiang, 1999). GC analysis can be combined with a 'Mass Spectrometer' (MS), which identifies the separated components, by their ionised molecular fragmentation patterns (e.g. Jiang, 1999). The relative abundance of each compound is determined by GC-MS. By calibrating the MS using pure compounds of known concentration, the concentration of identified compounds can be determined.

If the problem is suspected of being due to Hydrogen Sulphide, a portable Jerome Hydrogen Sulphide meter can be used to quantify the concentration of H_2S.

In order to calculate the odour concentration of a sample, whether it is a pure compound or complex mixture of different substances, the odour detection threshold has to be determined. The determination of odour detection thresholds has always been a debatable issue and argument still exists over the best method to use, the optimum testing parameters, etc. The following is a brief review of the process of determining odour detection threshold and odour concentration.

The standard method of determining an odour threshold is to use a panel of human subjects. Panels consist of approximately 8 individuals, trained in odour assessment. The process involves diluting an odorous sample with clean, odourless air until half the test panel can no longer detect the odour. This concentration is defined as the odour detection threshold and is by definition 1 ou/m^3 (Comitte Europeen de Normalisation, 2001). The number of dilutions necessary to reach the detection threshold is the number of odour units (ou/m^3) in the original sample. Other terms used for odour concentration are Threshold Odour Numbers or Dilution to Threshold (D/T) ratios.

Guidelines most commonly referenced for calculating the odour concentration using olfactometry include a German standard (VDI-guideline 3881, 1986), a Dutch standard (NVN 2820, 1996), and an American standard (ASTM E 679-91, 1997). These standards have since been replaced by two global standards, a draft standard (Comitte Europeen de Normalisation, 2001) formed by the European Committee for Standardisation (CEN), as well as a set of guidelines (A&WMA, 1995) *prepared* by the Air and Waste Management Association of America.

In the case of pure compounds, comprehensive lists of odour thresholds have been compiled. Appendix A contains a list of threshold concentration values for common odorous compounds (Ruth, 1986). The easiest method of calculating the odour concentration of a pure compound is to take the compound concentration (measured by analytical means) and divide by the odour threshold concentration, the resulting ratio being the odour concentration (ou/m^3). Unfortunately pure compounds are rarely responsible for odour annoyance, but rather a mixture of compounds is usually the cause of community annoyance. The interaction between individual compounds in a mixture is not fully understood, therefore the best method of determining the odour concentration of a mixture is using an odour panel as described above.

The method of using continuous dilution to determine odour thresholds is known as 'Dynamic Olfactometry' and the instrument used to dilute samples is referred to as an 'Olfactometer'.

In an attempt to reduce the variability and increase the repeatability of measuring odour concentration, instruments have been developed to simulate the human olfactory sensory system. These instruments are known as electronic noses or E-noses.

E-noses use an array of chemical sensors that respond to the presence of odorous compounds in air (Jiang, 1999). The E-nose is a recent advancement and still has many limitations, especially for use in environmental applications. Jiang (1999) suggests that work needs to be carried out in using both GC – MS and sensory methods to confirm the repeatability and reproducibility of E-nose techniques. Stuetz, Engin & Fenner (1998) have carried out such work and these results suggest that an electronic nose is capable of measuring odour concentrations derived from sewage odours of a similar biochemical composition.

2.3.7. Landfill odour

Landfill gas can contain over 100 trace components that are malodorous (e.g. Knox, 1990).

Fresh waste odour is generated over relatively short periods of time. Municipal waste is usually a few days old when it arrives at the landfill and the degradation process has already begun.

Gendebien et al (1992) suggests that the major contribution to landfill odour come from two groups of compounds. The first group is dominated by esters and organosulphur compounds. This first group includes 'foul' odours such as methanethiol (methyl mercaptan), hydrogen sulphide and esters such as ethylbutanoate.

The second group includes alkylbenzenes and limonene together with other hydrocarbons. This second group is more responsible for the less unpleasant typical background smell.

Termonia & Termonia (1999) have published results of testing using GC – MS analysis of landfill emissions. Both landfill gas (biogas) and fresh waste emissions were analysed by GC – MS. A tracer compound was identified for both biogas (p-cymene) and fresh waste emissions (limonene) and a gas chromatograph installed on-site. This analytical system was used to determine and quantify trace gases in the air on site.

At the same time and place where the sampling was performed, the odours were perceived by human assessors who reported the intensity of the smell.

The observations performed indicated a strong positive correlation between specific odorous tracers and the intensity of odours perceived in the environment of the landfill.

Knox (1990) reports results of sampling trace components of landfill gas from eight landfill sites. Between fifty and eighty individual compounds were quantifiable at >0.1 mg/m^3. For the eight sites, fresh waste produced high total concentrations of trace organics, with concentration falling with an increase in the age of waste. Fresh waste also produced a high percentage of alcohols and halogenated hydrocarbons. Hydrocarbons (Alkenes, Alkanes and Aromatics) are by far the most common compounds, representing between 53 and 98 percent of the total trace compounds. Sulphur compounds were only detected at one of the eight sites, and only constituted 0.4 percent of the total trace compounds.

An example of using a combination of sensory and instrumentation methods is an assessment carried out for a landfill in Helsinki, Finland (Tolvanen et al, 1998) The project found that approximately 110 different compounds, most of which were low molecular weight carboxylic acids, were causing the odour problem.

Young and Parker (1983) determined the concentration of trace compounds emitting from an uncovered pile of three-week-old wet, pulverised domestic refuse. The highest three trace components (rated by abundance) totalled over 1 gm^{-3}. Methyl mercaptan was not detected in large concentrations but due to methyl mercaptan's low odour threshold, it was detected at 2 200 400 times it's odour threshold. The next two highest compounds rated by threshold exceedance were Limonene and propyl benzene detected in concentrations of 1800 and 3000 times their respective thresholds. Clearly methyl mercaptan was the main source of odour. No Hydrogen sulphide was detected.

2.3.8. Emission rates and concentrations

Due to the inherent difficulties of sampling an area source as well as the lack of standardised sampling equipmant and analysis techniques, there is little published information on emission rates and concentrations from landfill surfaces.

Schmidt, Wilsey and Hasek (1998) report results from an investigation using a United States Environmental Protection Agency (*USEPA)* recommended flux box to determine emission concentrations from a large municipal landfill in America. Sampling was done on an active section of the landfill with daily cover (six inches). Fifty-seven individual compounds were found, with the total mass emission rate found to be 15.131 $mg/m^2/min$. Assuming this emission rate is applicable to Bisasar Road and assuming a filling area of $1000m^2$, the emission rate per tons of waste deposited per day, would be $1 \times 10^{-3}\ gs^{-1}(tpd)^{-1}$.

Eklund et al (1985) performed measurements using a flux chamber at two active hazardous waste landfills. Results from one landfill showed an average emission rate of $3.3 \times 10^{-5}\ gs^{-1}(tpd)^{-1}$ from one and from the other, an average emission rate of $2.9 \times 10^{-4}\ gs^{-1}(tpd)^{-1}$.

Frechen (1989) conducted sampling at two landfills using a cone (500mm base diameter) and sucking sample air into bags. Analysis was done using olfactometry. At landfill A, the average emission concentration from freshly tipped waste was $666ou/m^3$. At landfill B, the average emission concentration was $950ou/m^3$. The emission concentration from compost was determined to be $5000ou/m^3$. Frechen (1989) also suggests an equation to calculate the Odorant Flow Rate (OFR) in ou/h. For an active depositing area, the OFR can be calculated from:

$$OFR = k * OC * W \tag{2.2}$$

where:

k = constant
OC = Odour Concentration (ou/m^3)
W = Hourly waste deposition rate (m^3/h)

Values for k range between unity and two depending on the waste stream and local weather conditions. Based on the results reported in Frechen (1989), the recommended OC is 1000 ou/m^3. Based on a waste deposition rate for Bisasar Road of 3000 (tpd), and assuming a waste density of 0.8 m^3/t (Frechen, 1989), the OFR for Bisasar Road becomes:

$$\begin{aligned} OFR &= k*1000*3000*0.8*(1/24) \\ &= k*100\ 000 \end{aligned}$$

Therefore, depending on the value of k, the Odorant Flow Rate from Bisasar Road's working face ranges between 100 000 and 200 000 ou/m^3/h.

2.3.9. Odour control

Unconfined odours, as in the case of landfill emissions, are difficult to eliminate or even minimise. However, there are two main methods of odour control in the case of large, stationary area sources such as landfill sites. Either the waste input into the landfill must be controlled or the output of gas must be controlled.

The most obvious method of controlling waste input is to minimise the amount of waste. A more feasible method of controlling waste input is to exclude organic waste, such as household wastes, garden refuse, wastewater sludge and organic industrial waste (Christensen et al, 1996).

Effective management of facilities that emit odour can reduce the effect of the odour on neighbouring communities.

The control of gaseous discharge can be achieved by restricting various migration paths. South African law requires (Minimum requirements for waste disposal by landfill, 1994).

> *"that there be always an acceptable physical separation between the proposed waste body and the wet season high elevation of the ground water"*

This is usually achieved by lining the base of the landfill with layers of clays, gravel and geomembranes. These lining systems create a barrier against the migration of gas underground. Therefore, it is reasonable to assume that odour detected off-site originated from surface emissions and not from sub-surface migration.

The odour associated with fresh waste can only be controlled by rapid compaction and covering of the waste.

Sections of the landfill that are complete and will not be covered further are typically capped with a thick layer of soil or with geomembranes similar to those used for lining the base. If the base and the top of the landfill are effective barriers against gaseous flow, it is necessary to extract gas from the landfill body to avoid build up of gas. One method of extracting gas is to insert wells in the landfill. This facilitates an easy migration path for the biogas. The wells can either be left open or a transport system for the gas can be connected up to the wells and the biogas collected at a central point. Gas collected can either be flared off or treated and used to generate energy.

Despite high levels of housekeeping, it seems impossible to eliminate odours from landfill facilities completely. It may be necessary to use chemicals to control odours. An unpleasant odour can either be masked with a more pleasant odour or the chemical make-up of an odour can be altered. In order to modify an odour, the origin and chemical properties of the odour must be known. Once these properties are known then it is possible to choose the best counteractant.

Masking agents change the character of an odour, but also increase its resultant intensity since they operate on the principle of overpowering an unpleasant odour with a more intense, more pleasant odour (Federici, 1998). Masking agents are the most common and least expensive method to control odours from solid waste operations (O'Connell, 1999).

Caution should be exercised when masking odours to be sure that no poisonous substance is masked, and that the chemical masking itself does not become offensive and create an odour problem.

Counteractants are chemicals that change the character of an odour but most importantly, they also reduce the intensity of an odour. Odour counteractants were developed in the early 1990's (Federici, 1998). Odour counteraction involves releasing a compound into the air or onto an emission surface that reacts or combines chemically with the odorous compounds forming non-odorous compounds.

Product developers and suppliers offer various theories as the basis of their counteractants. The most popular theories include (Federici, 1998) 'absorption' and 'reaction'. Absorption works on the basis of absorbing the odorants into the liquid solution of the counteractant, which then neutralises the odour. 'Reaction' works in a similar manner but the counteractant reacts chemically with the odorants by chemical bonding, oxidation or reaction to form non-odorous compounds.

Federici (1998) concludes that, based on pilot studies, certain counteractant products can reduce certain types of odour effectively. However, only product screening and specific product testing can determine a suitable product for specific applications.

2.3.10. Odour fluctuations

Air Quality Standards (AQS) are in general quoted in terms of mean concentrations and exceedance probabilities. Depending on the regulatory authority and the pollutant, mean concentration levels of pollutants may be specified over time intervals from half an hour to a year. While time averaged concentration levels are useful for regulating emissions, what may be even more important in the case of odour is the effect of fluctuations or deviations from the mean. Concentration fluctuations occur on very short time scales due to turbulent fluctuations in the atmosphere. Even though the mean odour concentration may be below a threshold detection level, there could be several intervals within any given time period, where the instantaneous concentration is above the threshold value (Figure 7).

To regulate compliance with standards, airbourne pollutant concentrations in the vicinity of emissions are usually tested in one of two ways. Either continuous monitoring is done to analyse atmospheric concentrations directly or sampling is done at the source and a dispersion model used to predict receptor concentrations. Continuous monitoring is costly and difficult to implement.

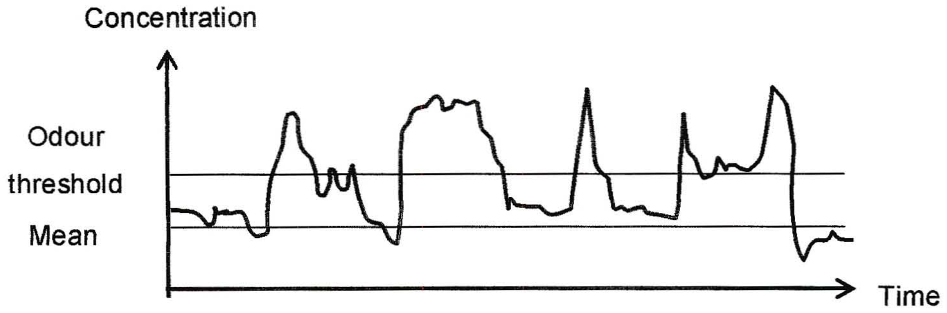


Figure 7: Schematic showing how concentration can exceed the threshold several times during a time period while the mean is below the threshold.

At present most dispersion modelling techniques do not take into account the effects of short-term fluctuations. Concentration predictions downwind of a source are generally in terms of mean concentrations averaged over one hour. This may be sufficient for general atmospheric pollution studies, since the time series analysis of air pollution levels involves the identification of long term variation in the mean and of cyclical or periodic components (Salcedo et al, 1998). The sensation of odour, on the other hand, depends on the momentary odour concentration and not on a long-term average value (Piringer and Schauberger, 1998).

It is necessary to understand how long a 'short' time span is in this context. The relevant time scale is the time taken from when an odour molecule enters the nasal passage, to the time when the brain has registered and perceived the odour. This delay is known as the 'Onset latency period'. Amoore (1982) and Finger & Silver (1987) summarise the work done to determine this delay period.

These studies have revealed considerable information on topics such as the latency time of the olfactory system. It has been found (Amoore, 1982;Finger & Silver, 1987) that the time taken for the entire physiological and psychological processes of odour perception is of the order of one second. It may therefore not be sufficient to formulate predictions on downwind concentrations and generate control measures on the basis of mean concentration levels averaged over one hour.

In Germany, the regulations stipulate that if the limit value is exceeded during 10% of 1 hour i.e. during 6 minutes, then it is assumed that the specified limit has been exceeded (Christensen et al, 1996). In practice, it is therefore assumed to be sufficient to multiply the hourly mean by a factor of 10.

Piringer and Schauberger (1999) provide a relationship between peak and mean concentrations for Pasquill-Gifford stability categories B – D as:

$$\frac{C_p}{C_m} = \left(\frac{t_m}{t_p}\right)^u \tag{2.3}$$

where:

C_p = peak concentration calculated for time t_p

C_m = mean concentration calculated for time t_m

u = exponent dependent on the stability of the atmosphere

They suggest, based on wind spectrum analysis, that short-term concentration fluctuations peak at time scales of 100 seconds.

Using equation (2.3) with t_p = 100 s, the peak to mean factors range from 2.8 (P-G stability category D) to 6.5 (P-G stability category B).

Simms et al (1999) argue, based on analysis done using the *ADMS*™ dispersion model, that peak-to-mean ratios may be as high as 7500, close to a point source and as low as 4 at a distance of 500m, both in stable conditions.

Cha et al. (1992) offer a conversion scheme for modelling odour, using the Industrial Source Complex model (*ISC3*). This scaling method is based on the fluctuating plume model. Examples of the use of the scaling method show factors ranging between two and forty-five.

Depending on the method used to quantify short time scale effects, scaling factors can vary by a factor of a thousand. A different approach may be necessary in order to incorporate the effects and set appropriate standards and regulations.

2.3.11. Laws, regulations and guidelines

In South Africa, laws and regulations pertaining to waste management are addressed in the Environmental Conservation Act (Act No 73 of 1989 Section 20, 24 and 29). Other relevant laws include the Atmospheric Pollution Prevention Act (Act No 45 of 1965) and the Health Act (Act No 63 of 1977).

Waste disposal in South Africa is further regulated by a set of documents prepared by the Department of Water Affairs and Forestry, known as the 'Waste Management Series'. Minimum requirements relating specifically to landfill gas, odour and associated impacts are referenced in volume 1 of the series, entitled: "Minimum requirements for Waste Disposal by Landfill" (1994).

Landfilling has the potential to have an adverse impact on the environment. Among possible impacts, the minimum requirements refer to odour, as well as flies, unsightliness and windblown litter, as giving rise to short-term impacts or nuisances.

Whether in the form of active or passive methods, measures must be put in place for the control of landfill gas. At present it is mandatory in many countries (Including the USA and Europe), for landfill sites to have active LFG extraction and utilisation processes.

With regard to gas extraction, the South African minimum requirements state the following (Minimum requirements for Waste Disposal by Landfill, 1994).:

> *"Gas management and gas monitoring systems are required if, in the site investigation and Environmental Impact Assessment, landfill gas migration and accumulation are found to represent a potential safety hazard or odour problem, or if an operating or closed site is situated within 250 metres of residential or other structures."*

Bisasar road landfill site does have a gas extraction system in place to collect the gas, which is subsequently flared.

For the purpose of eliminating odour, waste must be compacted, and covered at the end of each day's operations problems (Minimum requirements for Waste Disposal by Landfill, 1994).

The minimum requirements also require "*prompt covering of malodorous waste*" to reduce odour problems (Minimum requirements for Waste Disposal by Landfill, 1994). No specification is given to the type or depth of cover material required.

In the United States federal law (Municipal Solid Waste LandFill criteria, 1991) requires:

> "*cover disposed waste with six inches of earthen material at the end of each operating day, or at more frequent intervals if necessary, to control disease vectors, fires, odors, blowing litter, and scavenging.*"

Very few odorous compounds are deemed to be harmful to human health. For this reason, odour is considered a nuisance as opposed to a health threat. As with determining odour concentration, quantifying the nuisance or annoyance level of an odour is subjective. This inherent subjectiveness makes it difficult to establish standards to regulate by.

The most simple and common criterion used for odour regulation is that no odour be detectable at the boundary of an odour emitting facility. Due to variations in emissions and meteorological conditions, this criterion is in excess of that required to prevent a nuisance occurring (Simms et al, 1999).

Another regulatory approach is to consider directly the frequency of exceedance of levels of impact of, for example, 5 ou/m^3.

Piringer and Schauberger (1999) state that the level of 'unmistakable perception' occurs at 5 ou/m^3, which is also, the level at which complaints will start occurring. Murphy (2000) states that an odour is repulsive when the odour concentration reaches 5 – 7 ou/m^3.

Kaye and Jiang (1999) found that complaints should cease when the odour concentration is below 23 ou/m^3.

For a waste water treatment plant case study, reported by Witherspoon et al (1999), the nuisance-causing odour criterion was assumed to be 50 times the odour threshold, based on 3-minute average concentrations.

Yang and Hobson (1999) state that odour strengths as low as 5 ou/m^3 may lead to a nuisance if they result from an unpleasant odour despite the fact that the odour could be faint. Yang and Hobson (1999) also report that intense odours '*will frequently have odour strengths in excess of 1 million.*'

It may not however, be sufficient to quote only a threshold value as the limit, as this limit may be exceeded a certain percentage of time without causing annoyance. An odour with relatively low concentration but that is detectable for long periods of time, may cause similar nuisance to an odour with relatively higher concentration but which is only detectable for short periods of time. Therefore a criterion of a limit on the number of odour units as a percentile of time can be specified. I.e. a number of odour units cannot be exceeded for more than a cetain percentage of the time.

The specified limit of odour concentration and exceedance percentage can vary widely. In Germany the regulations demand that (Christensen, 1996):

> *"No unacceptable annoyance is present if only during less than 3% of the hours in one year odours are present that are above the perception threshold, and that unacceptable annoyance is present if during more than 5% of the hours of one year odours are clearly perceivable."*

Clarkson (2000) argues that, based on experience in the Netherlands, a standard of 5 ou/m^3 as the 98th percentile of the hourly average is a stringent enough standard. Table 1 shows the criteria considered in the Netherlands. Note that both the odour concentration and the percentage of time can be altered for various circumstances.

As another example, a compliance standard of 1 ou/m^3 for the 99.5th percentile has been accepted in the UK for a wastewater treatment plant (Clarkson, 2000).

Simms et al (1999) argue that standards set as percentiles are not sufficient as, for example, 2 % of the year equates to 175 hours which is enough to cause nuisance.

Table 1: Compilation of odour criteria considered in the Netherlands (Adapted from McIntyre, 1999; Yang and Hobson, 1999)

Concentration limit, ou/m^3	Percentile value, %	Application
10	98	Upper limit value. Above this value, serious annoyance can be expected
1-5	98	'Normal' value for most odours and sources. Large area sources tend to be at the upper end of the range.
<1	98	No serious annoyance to be expected in the majority of cases
1	99.5	Safe target values for new sources
10	99.99	Value applicable to sources that operate only a short period of the year (intermittant)

Settings standards is complicated by the fact that background odours can range from 15-200 ou/m^3 (McIntyre, 1999). McIntyre (1999) reports that odours are not detectable until a level of five times the odour threshold is reached. It is generally accepted that annoyance or nuisance leading to complaints associated with recognition of an odour, does not occur until a level of between 10 and 20 times the detection threshold is reached.

2.4. Dispersion modelling

2.4.1. Atmospheric motion

Atmospheric motion serves both to advect and to diffuse (dilute) air pollutants. Motion in the atmosphere or flow can be viewed as consisting of two components: a steady component (mean) combined with a superimposed fluctuating component (turbulence) (e.g. Pasquill and Smith, 1983; Panofsky and Dutton, 1984).

The mean component in the ABL generally has a logarithmic dependence of height above the surface (Pasquill and Smith, 1983). Turbulence consists of eddy structures, which occur randomly in space and time in a spectrum of sizes and intensities. These eddy motions create fluxes of momentum, heat and moisture, which characterise the structure of the atmospheric boundary layer. If a cloud of pollutant is released into the ABL, these eddies lead to the 'advection' (or dispersion) and 'mixing' of the pollutant. That is, if the size of these eddies are smaller than the pollutant cloud or plume they will diffuse it; if they are larger they will advect it (Csanady, 1973).

2.4.2. Characteristics of the atmospheric boundary layer

Effective dispersion of gaseous material released into the atmosphere near the ground depends on natural mixing processes. Mixing is a consequence of turbulence generated in the atmospheric boundary layer (ABL).

The atmospheric boundary layer is the region, which extends upwards from the surface to a height where turbulence resulting from surface friction has fallen to zero (Pasquill and Smith, 1983).

The boundary layer is also known as the mixing layer or Ekman layer. By day, the mixing layer over land typically extends to between five hundred metres and two kilometres above the ground (Pasquill and Smith, 1983). No clear top may mark the boundary layer under these conditions and the turbulent fluxes decrease gradually with increasing height. At night however, especially when the sky is clear and the wind light, the mixing layer is often confined to a shallower layer than in the daytime and may be capped by a very stable layer, called an inversion, where the potential temperature increases rapidly with height. The absolute temperature also increases with height in an inversion (e.g. Turner, 1973). Typically, inversion layers are shallow layers separating an unstable, well-mixed region below from a stable upper region. In the event of an inversion, the boundary layer may be only a few tens of metres deep.

The flow properties in the ABL are determined partly by the aerodynamic friction of the underlying surface and also by the density stratification of the atmosphere (Pasquill and Smith, 1983).

The changing state of the weather introduces variability into the ability of the atmosphere to advect, dilute, transform and remove pollutants. In general the atmosphere has a tremendous capacity for dispersion, but at certain times and locations this may be substantially curtailed. This depends on the stability of the atmosphere.

The stability of the atmosphere can be categorized by the vertical potential temperature gradients, where potential temperature is defined as (e.g. Turner, 1973) the temperature of a dry parcel air if compressed or dilated adiabatically from its ambient temperature and pressure to a standard pressure.

Near-zero potential temperature gradient - neutral stability
Negative potential temperature gradient (decreases with height) - unstable
Positive potential temperature gradient (increases with height) – stable

These stability classes characterise the role of buoyancy forces in the flow. Neutral stability is characterised by the absence of significant buoyancy forces. Buoyancy forces in unstable conditions are destabilising such that if a fluid particle is displaced vertically, buoyancy forces act to increase the displacement. The opposite is true in the stable atmosphere. Buoyancy forces in the stable atmosphere are restoring such that if a particle is displaced vertically, buoyancy forces act to restore the particle to its original position.

The atmospheric boundary layer is constantly in evolution between these three states. The best conditions for pollutant dispersion usually occur in unstable conditions with a deep mixed layer. Unstable conditions are characteristic of sunny, daytime conditions, especially in summer.

Conversely, the worst conditions for dispersion occur when there is a low-level temperature inversion and the atmospheric boundary layer is stable. Stable conditions are the usual nocturnal situation, and are not conducive to vertical mixing because the buoyancy forces act to suppress vertical turbulent motion. Nocturnal boundary layers result from the cooling of the land surface. An inversion usually results at a height where turbulence is completely suppressed. The wind velocity below the inversion decreases and turbulence decays, resulting in non-diffusive conditions.

One method of quantifying the stability of the ABL is to use Pasquill-Gifford stability categories as summarised in Table 2. ISC3 is an example of a dispersion model that utilises Pasquill-Gifford stability categories to characterise the stability of the ABL.

Table 2: Pasquill-Gifford stability categories in terms of wind speed, insolation and state of sky (Pasquill and Smith, 1983).

Surface wind speed (m/s)	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast (>4/8 cloud)	<= 3/8 cloud
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Within the atmospheric boundary layer there is a layer adjacent to the surface, where the shear stress may be regarded as approximately constant. This layer is known as the 'surface stress layer' or 'constant stress layer' (Pasquill and Smith, 1983). The vertical fluxes of momentum, heat and moisture are nearly constant in this layer (Panofsky and Dutton, 1984).

The most widely accepted approach for characterising the properties in the surface stress layer originates in the similarity arguments of Monin and Obukhov (e.g. Pasquill and Smith, 1983; Panofsky and Dutton, 1984). The basis of the approach is that for any transferable property, the distribution of which is homogeneous in space and stationary in time, the vertical flux/profile relation is determined uniquely by the parameters z, ρ, g/T, u_*, and $H/c_p\rho$

where:

z = vertical height

ρ = density of air

g = acceleration due to gravity

T = temperature

u_* = friction velocity = $(\tau/\rho)^{1/2}$

τ = shear stress at the surface

H = vertical heat flux

C_p = specific heat capacity

Applying Monin-Obukhov theory to momentum transport (Panofsky and Dutton, 1984), the mean flow velocity, $\bar{u}$ can be expressed as a function of height:

$$\frac{d\bar{u}}{dz} = \frac{u_*}{kz}\phi_M\left(\frac{z}{L_{MO}}\right) \tag{2.4}$$

where:

L_{MO} = Monin-Obukhov length scale defined by: $L_{MO} = -\dfrac{\rho c_p T u_*^3}{kgH}$

The eddy diffusivity for momentum then follows as

$$K_M = \frac{ku_*z}{\phi_M} \tag{2.5}$$

Integrating equation 2.4 with the mean velocity equal to zero at z = z$_0$ yields

$$\bar{u}(z) = \frac{u_*}{k}\left[f_M\left(\frac{z}{L}\right) - f_M\left(\frac{z_0}{L}\right)\right] \tag{2.6}$$

The forms of the functions ϕ_M and f_M have to be determined empirically. Pasquill and Smith (1983) provide a review.

Similar profiles can be written for heat and water vapour. For example, the appropriate gradient for heat is the potential temperature, which reflects the gradient of air density, positive or negative values representing stable or unstable conditions respectively.

The wind field in the boundary layer is largely controlled by the frictional drag imposed on the flow by the underlying rigid surface. The drag retards motion close to the ground and gives rise to a sharp decrease in mean horizontal wind speed as the surface is approached due to frictional drag.

The actual form of the wind variation with height under neutral conditions (neither stable nor unstable conditions) has been found to be described by a logarithmic form (See Figure 8) (Panofsky and Dutton, 1984;Pasquill and Smith, 1983):

$$\bar{u}(z) = \left(\frac{u_*}{\kappa}\right)\ln\left(\frac{z}{z_0}\right) \qquad (2.15)$$

where:

$\bar{u}(z)$ = mean wind speed at height z

z_0 = roughness length

The log law has been extensively verified in the boundary layer, and typically applies up to a height of approximately 100 metres (Csanady, 1973; Pasquill and Smith, 1983).

The logarithmic velocity distribution is consistent with an eddy length scale distribution, $L_t(z)$, which increases linearly with height (Panofsky and Dutton, 1984; Pasquill and Smith, 1983). Figure 8 shows a typical log profile (Csanady, 1973). Therefore as a diffusing cloud released from ground level grows it comes under the influence of larger and larger eddies. This process leads to 'accelerated' diffusion in the sense that the effective diffusivity increases in time.

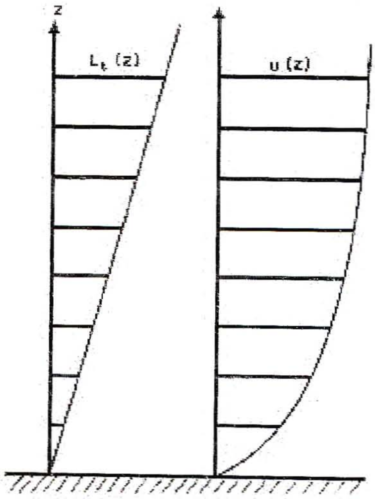


Figure 8: Schematic illustration of the idealised velocity and eddy length scale variations with height (Csanady, 1973).

2.4.3. Effects of topography on mean flow and turbulence

Terrain has an important effect on dispersion. Both by directly influencing the dispersion characteristics of individual plumes and their path of migration.

Obstacles such as uneven ground level affect the path of a plume in two ways. Firstly, a plumes average trajectory is deflected as an obstacle is approached. Secondly, there is also the effect of the flow disturbance on the intensity of turbulence, which affects the rate of spread of the plume and the distance at which contact with ground level occurs.

The characteristics of airflow over non-uniform terrain are not easily generalised. Different shapes and obstructions create unique perturbations to the flow pattern. It is, however, possible to describe some typical flow patterns around specific features.

Flow over a flat surface is usually smoothed adjacent to the surface. However, it is possible for the flow to become separated from the surface if it passes over a sudden discontinuity thereby generating additional local turbulence.

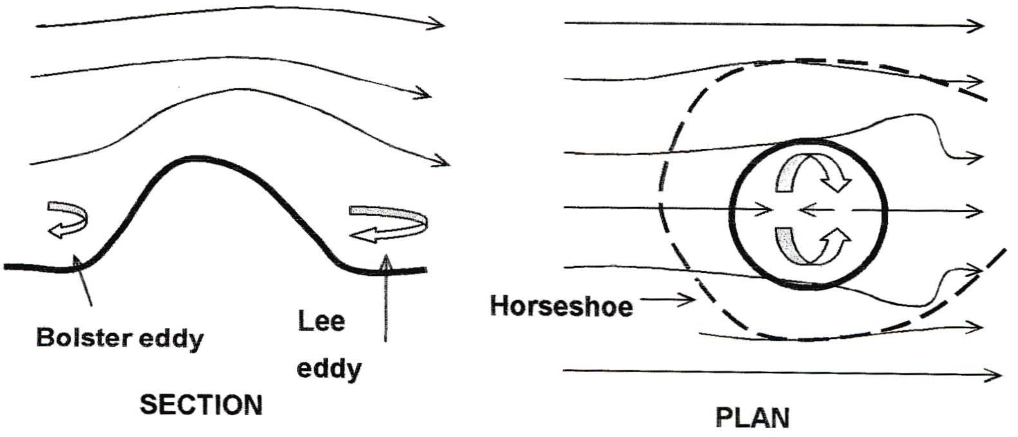


Figure 9: Typical flow pattern around an object with slopes greater than 17° (adapted from Oke, 1987).

Moderate topography (with slopes up to about 17°) usually allows the boundary layer to adjust without separation while for slopes exceeding about 17°, flow separation can occur (Oke, 1987). Figure 9 shows a typical example of flow over an obstruction with slopes greater than 17°. Separation from the top and both sides of a hill produces unsteady lee eddies. Therefore, in the immediate lee of the hill the wind direction near the surface may be counter to the general flow (i.e. upslope) and speeds are considerably reduced. The turbulent wake of the hill extends downstream for a considerable distance.

2.4.4. Available dispersion models

Dispersion models can be used effectively in two different ways. Firstly to assess the dispersion of odours and to correlate the results with complaints. Secondly to estimate the maximum odour emissions which can be permitted from a site in order to prevent odour complaints occuring. This second application is particularly useful if source emission information Is not available. Various models with varying capibilities are available to estimate the dispersion of pollutants from general stationary sources. Five models were chosen for investigation as part of this research. The folllowing is a brief review of the models being used.

a) Industrial Source Complex model (*ISC3*) (*USEPA*, 1995)

The *ISC3* model is a steady state, Gaussian plume model and is the most common and widely used dispersion model. It is specified as a regulatory model in the U.S. for use in most industrial applications.

Meteorological input is simple and *ISC3* only requires wind speed and direction, a single stability class specification (Pasquill-Gifford classification) and a mixing layer height. *ISC3* also requires specification of whether the area surrounding a facility is urban or rural. This establishes whether the Pasquill-Gifford (P-G) or McElroy-Pooler dispersion curves are used. It is recommended that the "Urban" dispersion mode be selected if the developed area (as indicated in land use maps) within 3km of the source is greater than 50 %, or if the population living within 3km of the source is greater than 750 persons/km^2.

Complex terrain can be modelled in a limited way in *ISC3*. Receptors can be placed at elevations above ground level to simulate ground level receptors in complex terrain. However, the model does not model any effect of terrain on plume shape or height. When receptors are placed above ground level, the 'screening mode' of *ISC3* (*COMPLEX1*) is used to formulate concentration predictions. Due to the fact that screening models are used only for preliminary studies, the results are usually conservative. Results of *ISC3* in complex terrain therefore usually overestimate concentrations.

b) *AERMOD* (*USEPA*, 1998a)

AERMOD is an update of the widely used regulatory model, *ISC3*. *ISC3*'s input/output formats were retained, but the *ISC3* algorithms were updated with new state-of-the-art modelling techniques. Additional functions, such as the incorporation of a complex terrain module, where also added. The end result was a dispersion model with two pre-processors, one for meteorology, *AERMET*, and the other for characterising the terrain named *AERMAP*.

AERMOD is a steady-state plume model. In the stable boundary layer, the concentration distribution is assumed to be Gaussian in both the horizontal and the vertical. In convective conditions (Unstable boundary layer), the horizontal concentration distribution is assumed to be Gaussian, but in the vertical *AERMOD* uses atmospheric boundary layer scaling to describe the distribution with a bi-Gaussian form. *AERMOD* also tracks any plume mass that penetrates into the elevated stable layer, and then allows it to re-enter the boundary layer when and if appropriate (See Cimorelli, 1998 for a full description of the model formulation).

AERMOD models complex terrain, and where appropriate, a plume is modelled as either impacting and/or following the terrain. *AERMOD* constructs vertical profiles of required meteorological variables based on similarity (scaling) relationships. *AERMOD* caters for point, area and volume sources.

c) Complex Terrain Dispersion Model PLUS algorithms for unstable conditions (*CTDMPLUS*) (Perry et al, 1989)

CTDMPLUS was formed on the basis of *CTDM*, with algorithms added for modelling daytime/unstable conditions. *CTDMPLUS* is a steady-state Gaussian plume model for point sources only. It was designed specifically for elevated point sources in complex terrain.

CTDMPLUS uses a meteorological pre-processor, *METPRO* that uses varying detail of information depending on the user requirements. *CTDMPLUS* can be run in one of four modes. The least capable mode uses only a few night-time hours of meteorological data and the most extensive mode (series of contiguous hours including daytime and night-time hours) requires on-site measurements of wind, temperature, turbulence and surface characteristics as well as off-site and upper air data.

While *CTDMPLUS* does model complex terrain, it does so in a limited way. The user must define individual terrain elements (e.g. individual hills) and prepare information on the location and shape (contours) of these elements. This information is then used to calculate parameters for an equivalent elliptically shaped terrain feature.

The major limitation of *CTDMPLUS* is that the path taken by a plume through an array of hills cannot be simulated. The influence of terrain features is reflected in the modelling only in the meteorological measurements. Any changes in the plume size caused by one hill are not carried forward to subsequent downwind terrain features.

d) *CALPUFF* (Scire et al, 1999)

Unlike the other four models under evaluation, *CALPUFF* is a non-steady state 'puff' model. *CALPUFF* contains three sub-sections (similar to *AERMOD*).

CALMET is a meteorological model that develops hourly wind and temperature fields on a three-dimensional gridded domain. Associated parameters such as mixing height, surface characteristics and dispersion properties are also included in the file produced by *CALMET*.

CALPUFF is a non-steady state Lagrangian Gaussian puff model that advects "puffs" of material emitted from modelled sources. *CALPUFF* has the ability to use complex time and space varying meteorological data produced by *Calmet* or single-station *ISC3* or *CTDMPLUS* data. *CALPUFF* has a host of features, the most important in the case of landfills includes the modelling of: wet and dry deposition; complex terrain; point, area, line and volume sources; time-varying emissions and coastal interaction effects. However, the most interesting feature of *CALPUFF* is its ability to model odour by allowing the input of emission rates and concentrations in terms of "odour units". *CALPUFF* uses a simple scaling factor to estimate short-term peak concentrations. This was discussed in section 2.3.10.

The drawback of *CALPUFF* is the manner in which terrain information has to be input. Similar to *CTDMPLUS*, (*CTDMPLUS* terrain information can be used in *CALPUFF* directly) individual features have to be identified and information on the location, orientation, size and shape of each feature must be specified.

Output files created by *CALPUFF* are processed by *CALPOST* to produce tables and summaries of the results.

e) Advanced Dispersion Modelling System (*ADMS™*)

ADMS™ is a steady state dispersion model and is regarded as one of the most advanced 'new-generation' dispersion models. *ADMS™* formulates predictions based on a description of the atmospheric boundary layer, not in terms of the single Pasquill-Gifford stability class but in terms of two parameters: the boundary layer depth, h and the Monin-Obukhov length, L_{MO}.

In *ADMS™* two different sets of equations have been developed for stable and neutral conditions as well as convective conditions. These equations have been formulated taking into account the state of the ABL height (h), the height of the source (z_s) and the height of the plume as it grows downwind. No theory or generally accepted empirically formulated expressions describing dispersion from all source heights in all stability conditions and over a wide range of distances from the source have been developed (Carruthers et al, 2000). The approach used in *ADMS™* was to use formulae developed for specific ranges of parameters z_s/h, h/L_{MO}, x/h and to construct interpolation formulae between these ranges. For a detailed review of the formulae used in *ADMS™*, see Carruthers et al, 2000.

ADMS™ has the capability to model wet and dry deposition; point, area, line and volume sources; time-varying emissions and coastal interaction effects. *ADMS™* incorporates algorithms to model the wind field and turbulence characteristics in complex terrain using a model known as *FLOWSTAR™* (Carruthers et al, 1988).

ADMS™ is by far the most 'user friendly' of the five models discussed here, especially with regard to the input of complex terrain. *ADMS*™ does not require any pre-processing of terrain data and accepts an *ASCII* file consisting of gridded height values.

ADMS™ also has the option of being able to calculate short-term fluctuations. A module dealing directly has been added to the latest version of *ADMS*™ (Version 3.1).

2.4.5. Review of exisiting dispersion model comparisons

Numerous studies have already been undertaken to quantify the differences in predictions of various dispersion models under various conditions. The following is a brief review of the results of six such studies involving the dispersion models under review in this section.

A comparison between *CALPUFF* and *ISC3* was conducted by the *USEPA* (Office of Air Quality Planning and Standards, 1998).

For all the point sources and all the meteorological conditions, the difference in concentrations was of the order 0.1 % of the mean values for the incident receptor.

Results were more scattered for ground level, area source emissions. The maximum residual was 33 % of the mean concentration at the incident receptors. No attempt to explain these differences is given.

For all the averaging periods (1, 3, 24 hours and annual averages) using the recorded meteorological data, the general trend showed that the greater the release height, the less consistent the predictions of the two models. The source type that was closest to a ground-level release was a point source modelled at two metres above the ground. *CALPUFF* predicted concentrations less than *ISC3* with the differences increasing as the distance from the source increased. The greatest difference between 1-hour average concentrations, within 5km of the source, were approximately 50% for the 2m source.

As part of the *AERMOD* validation process, observational data from ten data sets were compared with *AERMOD* predictions. Model comparisons were also done between *AERMOD, ISC3* and *CTDMPLUS*. The results were reported by Paine et al, 1998.

All ten sets of results from independent tracer experiments have been compiled and the ratio of predicted *AERMOD* concentrations to observed concentrations shown in Table 3.

It can be seen from Table 3 that *AERMOD* performed relatively worse with increasing averaging time. This was attributed to background concentrations that were not accounted for in the modelling. With reference to the 1-hour averaging period results, *AERMOD* performs within 25 % of the observed values in all cases. In all cases except one (moderately hilly terrain in rural setting), *AERMOD* outperformed *ISC3*. In four comparisons done with observational data sets compiled in complex terrain, *AERMOD* outperformed *CTDMPLUS* in all cases and for all averaging times. Overall, *AERMOD* had a slight tendency to over predict observed concentrations.

Table 3: Ratio of predicted *AERMOD* concentration to observed concentrations

	Low	High	Geometric mean
1-hr average	0.76	1.20	0.96
3-hr average	1.00	1.31	1.11
24-hr average	0.72	1.72	1.06
Annual average	0.30	1.64	0.73

A further study was carried out by the *USEPA* comparing *AERMOD, ISC3* and *CTDMPLUS* (Peters et al, 1999).

The comparisons were set–up in a similar manner to those in the *CALPUFF* vs. *ISC3* comparison. The key features of the analysis included one years meteorological data from two different sites, three point sources at different release heights, one ground-level area source release; 1, 3, 24 and annual average concentrations, and receptors placed at distances between 125 m and 16 km.

Comparisons were done between *AERMOD* and *ISC3* in flat terrain and between *AERMOD, CTDMPLUS, and COMPLEX1*, in complex terrain.

Results of this particular investigation where presented in ratios of average *AERMOD* concentration divided by average *ISC3* (or *CTDMPLUS*) concentration. I.e. a ratio greater than one means that *AERMOD* predicts higher average concentrations and vice versa.

Results in flat terrain show relatively little difference in predictions between *AERMOD* and *ISC3*. The greatest range in the ratios was for the 1-hour averaging period with a maximum of 4.25 and a minimum of 0.32. More specifically, for shorter stacks with non-buoyant release and in rural conditions, the ratio of *AERMOD* to *ISC3* was 0.5. This is similar to the result found in the *AERMOD* evaluation by Paine et al (1998).

In the case of area sources, *AERMOD* produced consistently higher average concentrations than *ISC3*. The 1-hour average concentrations predicted by *AERMOD* in a rural setting were 1.75 those of *ISC3*, and in an urban setting the difference was greater at 3.7 times *ISC3*.

Results of the complex terrain simulations showed fairly good agreement between *AERMOD* and *CTDMPLUS* but with *AERMOD* producing values slightly lower than *ISC3*. This is again consistent with the results found in the *AERMOD* evaluation (Paine et al, 1998).

A report was prepared by *CERC* (CERC, 2000a) as a supplement to the document discussed above (*USEPA*, 1999). The basis of the analysis was to compare concentrations of *ADMS™* with those of *AERMOD* and *ISC3*. The same source specifications, meteorological data and averaging times were used.

For point sources, it was found that the ratio of average *ADMS™* concentrations to average *AERMOD* concentrations was closer to unity than the *ADMS™/ISC3* ratios.

For area sources, *ADMS™* produced slightly higher concentrations than *AERMOD* with ratios of *ADMS™/AERMOD* ranging from 0.86 to 1.54 in a rural setting and ranging between 0.68 and 1.80 in an urban scenario. The ratio of *ADMS™* to *ISC3* in rural conditions ranged between 0.58 and 2.16 (c.f. 0.65 and 2.04 for *AERMOD/ISC3, USEPA*, 1999) and between 1.15 and 4.11 for an urban setting (c.f. 1.15 and 4.25, *USEPA*, 1999).

CERC (CERC, 2000b) have also done analysis as a supplement to the *USEPA*'s comparison of *AERMOD, ISC3* and *CTDMPLUS* (*USEPA*, 1999). On-site meteorological data was used in the *USEPA* comparison (*USEPA*, 1999), which was not available for this comparison, so an alternative annual data set was used. Data on only one of the four terrain cases modelled was available (Cinder Cone); so one more hill was added (Mt. St. Helens) for the analysis. Simulations were run for both of the two hills as well as for flat terrain.

For the Cinder Cone hill (peak 110 m), a slightly buoyant plume was released from a 35m stack (Ground level = 70m). *ADMS™* predicted much lower concentrations than *AERMOD* (The ratio of *ADMS™/AERMOD* ranged from 0.02 to 0.14) and *ISC3* (Ratio ranging from 0.11 to 0.15). The *ADMS™/ISC3* ratio is not surprising considering that the *COMPLEX1* mode of *ISC3* predicts very conservative concentrations.

Ratios were also calculated to compare results for each model in complex and flat terrain. The *ADMS™* ratio of Complex/Flat terrain was less than or equal to 1.4, which means that *ADMS™* predicts higher concentration in complex terrain than in flat terrain. This was unexpected, as it is believed that the greater turbulence created by variable terrain increases dilution and therefore lower concentrations. The *ISC3* ratios ranged up to 17 again due to inflated *COMPLEX1* concentrations. *AERMOD* showed quite remarkable results when complex terrain concentrations were compared to flat terrain concentrations. The ratio of complex to flat terrain results was 134 for the 1-hour average. This result is quite surprising bearing in mind that the top of the stack is only 5 m below the peak of the hill, which is approximately 300 m away. The release was also classified as slightly buoyant.

For the Mt. St. Helens simulation, both *ADMS™* and *ISC3* gave high complex/flat terrain ratios (*ADMS™* up to 5.3 and *ISC3* up to 84). *AERMOD*, ratios of

Complex/Flat terrain for Mt. St. Helens ranged from 18.7 to 79.9. As with the Cinder Cone simulations, *ADMS™* predicted much lower concentrations than *AERMOD* and *ISC3* (Ratios ranging between 0.1 and 0.22)

Hanna et al (1999) report comparisons between *ADMS™*, *AERMOD* and *ISC3* predictions and five sets of observational data.

The general conclusions of the study were that *ADMS™* and *AERMOD* performed more accurately than *ISC3*. *ADMS™* was slightly more accurate than *AERMOD* in general. *ADMS™* and *AERMOD* tended to underestimate the maximum concentration as well as the mean of all concentrations. This is contrary to the conclusion in the *AERMOD* model evaluation report that states that *AERMOD* tends to over predict observed concentration (Paine et al, 1998).

The objective of one experiment was to evaluate the performance of the models for near field impacts of low-level area source releases. For this particular experiment, *ADMS™* provided the most accurate results. *ADMS™* predicted the maximum concentration within 6 % (*ADMS™* prediction less than observed) and underestimated the mean by 40 %. *AERMOD* under predicted the maximum concentration by a factor of 2, and under predicted the mean by 80 %.

ADMS™, *AERMOD*, *ISC3*, *CTDMPLUS* and *CALPUFF* have been compared with each other and with observational data. *ISC3* is the most widely used available dispersion model and compared well with all models, in flat terrain, but consistently over-predicted concentration in complex terrain. *ISC3* will eventually be replaced by the more advanced *AERMOD*.

CTDMPLUS was designed specifically for modelling in complex terrain, but produced inconsistent results in the two comparisons reviewed. *USEPA* (1999) report a good agreement between *AERMOD* and *CTDMPLUS* predictions. In contrast, Paine et al (1998) found that *CTDMPLUS* performed worse than *AERMOD* when predictions were compared with four different sets of observational data. *CTDMPLUS* is tedious to use as it is a *MSDOS* based program and the terrin input requires approximations of individual terrain features.

No information was found on comparisons between *CALPUFF* predictions and observational data. This makes it difficult to conclude on the accuracy of *CALPUFF*. However, the fact that *CALPUFF* performed consistently with *ISC3* when run in '*ISC* mode' (Office of Air Quaity, Plannig and Standards, 1998) combined with *ISC's* outdated algorithms suggests that *CALPUFF* is best run at full capability (See section 2.4.4). Running *CALPUFF* at full capability requires extensive meteorological data which is not available for the case study site in this research. Terrain data is input in a similar manner as for *CTDMPLUS* which is tedious and time consuming.

AERMOD produced accurate results in flat terrain (Paine et al, 1998 ; Hanna et al, 1999). *AERMOD* out-performed *ISC3* in all but one of the comparisons done with observational data (Paine et al, 1998) and out-performed *CTDMPLUS* in all four comparisons done as part of the same evaluation. *AERMOD* produced inconsistently high results for artificial individual terrain features (Complex/Flat ratio <= 134) (CERC, 2000b). *AERMOD* is easy to use but the required format of terrain input is not available for the case study site used in this research.

ADMS™ predicted higher concentrations than *AERMOD* from ground level sources in flat terrain (*CERC*, 2000a), but predicted concentrations well below (0.02 – 0.14) those of *AERMOD* for artificially generated terrain features. For both terrain features modelled *ADMS™* suprisingly predicted higher concentrations in complex terrain than in flat terrain. Hanna et al (1999) reports that *ADMS™* and *AERMOD* perform better than *ISC3* for a wide range of scenarios. They also report that *ADMS™* is slightly more accurate than *AERMOD*. Therefore, *ADMS™* appears to be the most accurate available dispersion model. It is also the most user friendly. It is a *WINDOWS™*-based program which makes the setting up of simulations easy and it can also be run from a *MSDOS* command prompt. Meterological data input is flexible and not difficult to setup. Terrain data input is also easy to setup and the information is available in the correct format for the case study site.

2.5. Boundary layer climates and local meteorology

Most of the discussion thus far on dispersion has assumed either uniform, homogeneous terrain or local obstructions. Mesoscale (scale of kilometres) nonuniformity in terrain can cause winds to develop which influence dispersion. The local meteorological conditions and climate also affect dispersion. Section 2.5.1 provides a review of mesoscale effects on dispersion.

2.5.1. Land and sea breezes

Land and water surfaces possess contrasting thermal responses because of their different properties and energy balances. This is the driving force behind the land and sea breeze circulation system encountered near the ocean.

The difference in temperature between the land and water and their diurnal reversal (land warmer than water during the day and land cooler than water at night) produce corresponding land/water air pressure differences. These in turn result in a system of breezes across the shoreline.

Sea breezes are generated in the daytime and have higher wind speeds than the nocturnal land breeze. This is due to increased instability during the day. Sea breezes may result in a 'fumigation' plume pattern. This plume pattern occurs when an inversion above the plume obstructs upward dispersion, but is stable underneath such that there is mixing capable of bringing the plume contents to the ground. This phenomenon occurs when effluent is emitted into stable air of the offshore portion of the sea breeze. The 'fanning' plume drifts inland until it encounters the developing unstable boundary layer of the warmer land at which point it fumigates. Ground-level receptors receive high pollution concentrations under these conditions.

The land breeze is initiated in the evening due to the greater cooling and subsidence of air over the land. The land breeze is typically 1 - 2 m/s in strength (Oke, 1987).

2.5.2. Mountain and valley winds

Heating and cooling of valley sides can play an important role in the overall wind patterns of a valley.

By day the air above the slopes and the floor of the valley will be heated up by the underlying surface to a temperature well above that over the centre of the valley. As a result shallow, unstable upslope (anabatic) flow arises, and to maintain continuity a closed circulation develops across the valley involving air sinking in the valley centre. Commonly the uplift along the slopes is at speeds of 2 - 4 m/s (Oke, 1987). Flow up a valley is termed the valley wind.

On clear nights with light winds, vertical flow within a valley is dominated by the circulation generated by cooling of the valley slopes, and can be virtually isolated from the general airflow above the ridge. At night the valley surfaces cool by the emission of long-wave radiation (Oke, 1987). The lower air layers cool and slide down the valley under the influence of gravity. These katabatic winds usually flow gently downhill at about 2 to 3 m/s (Oke, 1987). The oldest (and densest) air settles to the lowest levels and therefore temperature increases with height above the valley floor producing a valley inversion.

2.5.3. Local climate

The climate of the Natal coastal belt is sub-tropical with a warm summer (Schumann, 1990). The southern sub-tropical high-pressure belt has its mean position at 30° and therefore plays an important role in this climatic zone (Preston-Whyte, 1980). The climate variability along the east coast is a result of the continuous procession of eastward moving alternate cells of high and low pressures. The passage of these cells past Durban may be regular thereby causing the weather along this stretch of coast to have a cyclic property. The weather patterns offer some insight into the presence or absence of landfill gas in the areas surrounding Bisasar road landfill site. A detailed review of the weather patterns along the Kwa-Zulu Natal coastline is given by Preston-Whyte (1980).

The atmospheric circulation's that influence the weather and climate in Durban fall into three scale categories (Preston-Whyte, 1980). Eastward moving cells of high and low pressure alternatively bring fine and disturbed weather to the east coast of South Africa (Preston-Whyte, 1980). By comparison mesoscale circulations are more confined and consist of land and sea breezes. On an even smaller scale, temperature and therefore pressure fluctuations in individual valleys cause winds.

With a high located offshore of Kwa-Zulu Natal, winds blow northeast and conditions are sunny. However, approximately every six days a trough of low pressure is witnessed (Preston-Whyte, 1980). The passage of high and low-pressure systems past Durban is associated with fluctuations in temperature, humidity, wind velocity and pressure. The frequent and rapid changes from warm, dry conditions to cool, moist conditions indicate that the weather-producing characteristics of these systems are distinctly different.

Low-pressure systems develop in two different ways. Coastal lows form as a result of the interaction between large-scale atmospheric flow and the marked South African escarpment. These systems propagate around South Africa moving northwards in an anticlockwise direction and are often associated with strong southwesterly gusts termed 'busters'. As a coastal low advances up the coast, the temperature rises and the pressure drops. The passage of the centre of the low is often associated with the arrival of a strong, gusty wind from the Southwest. Temperature then falls rapidly and the pressure rises.

Low-pressure systems are alternatively formed in the south Atlantic and Indian oceans. Climatic fronts form repeatedly in a well-developed polar front. Cyclonic storms (anti-clockwise in the southern hemisphere) develop along this polar front and move into the Indian Ocean. Only the cold front section of the cyclones is experienced in South Africa. These frontal low-pressure systems are most frequently experienced in Durban in winter and spring (Preston-Whyte, 1980).

The frontal characteristics of the low-pressure weather sequence occur so frequently that they provide a useful introduction for the discussion of the weather systems that influence Durban.

The passage of a front also has a major effect on the depth of the mixing layer and therefore the concentration of air pollutants at the surface (Preston-Whyte, 1980). The accumulation and dispersion of pollutants near the surface during the night and day respectively have already been discussed.

Both inversion and mixing depth characteristics are also influenced by the procession of low-pressure systems along the Kwa-Zulu Natal coast. The effect is best illustrated by Figure 10.

Fluctuations in mixing depth caused by the passage of low-pressure systems have a marked influence on the potential for the accumulation of air pollution.

The sequence begins with light northeasterly winds and a moderately stable atmosphere. Under these conditions the mixing depth at midday is able to provide effective dispersion of atmospheric pollution. With the approach of a low-pressure system, enhanced subsidence and lowering of the inversion causes increased near-surface atmospheric stability and contraction of the mixing layer. Atmospheric ventilation can be restricted and concentrations of pollution may increase near the surface. With the passage of the pressure minimum, strong southwesterly winds in an unstable atmosphere eliminate the low-level stable layer and allow pollution to be diffused through a deeper mixing layer (Preston-Whyte, 1980).

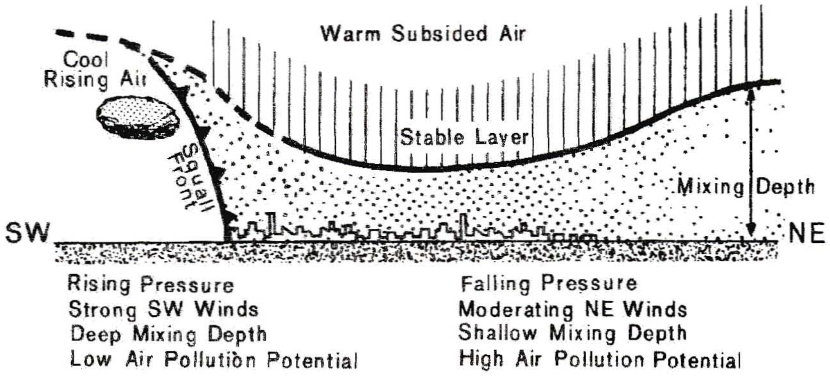


Figure 10: Variation in mixing depth due to passing frontal disturbance (Preston-Whyte, 1980).

2.5.4. Local meteorological conditions.

Mean monthly values of the maximum mixing depth over Durban show little seasonal variation about the mean annual depth of 788 m (Figure 11 - Preston-Whyte, 1980).

The air temperature field in Durban is characterised by a relatively low seasonal change, which is due to the damping effect of the adjacent ocean. The warm Agulhas current ensures that on average, temperature will be mild in winter and warm to hot in summer (Preston-Whyte, 1980). The mean annual temperature for Durban is 20,5 °C with an average range of 8,3 °C (Preston-Whyte, 1980).

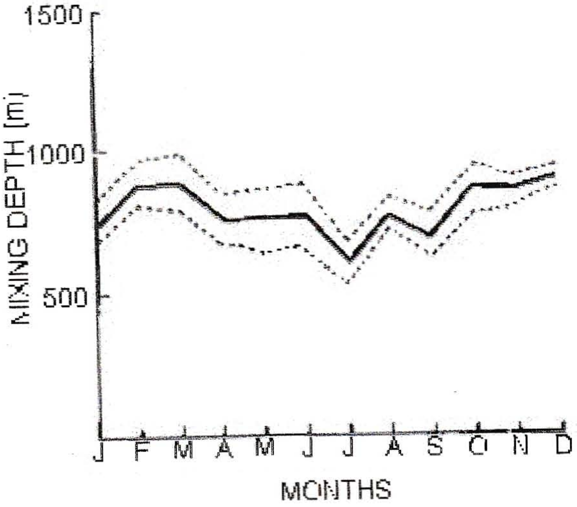


Figure 11: Monthly variation in afternoon mixing depth (m) (Preston-Whyte, 1980).

Precipitation reaches it's maximum in the summer months, November to March with it's peak in January (Whitmore, 1978). Sixty percent of the annual precipitation falls in the months November to March and only fifteen percent falls between May and august (Preston-Whyte, 1980). The mean annual precipitation in the Durban area varies between 1000 mm and 1100 mm (Whitmore, 1978).

The monthly mean atmospheric pressures in Durban are seen to be significantly higher in winter than in summer. This is due to an increase in the average intensity of the migratory highs, which also track closer to the Natal coast during the winter months (Schumann, 1990).

Table 4 shows the average seasonal values for selected meteorological parameters in Durban. Summer is classified as December, January and February while winter is considered May, June and July.

Table 4: Summer and winter average values for selected meteorological parameters in Durban (Whitmore, 1978)

	Summer average	Winter average
Temperature (°C)	23.9	17.1
Relative humidity (%)	71	58
Precipitation (mm/month)	120	43

The hot, humid conditions along the Kwa-Zulu Natal coast provide ideal conditions for the production of landfill gas. Summer generally provides more favourable conditions for odour generation than winter due to high temperature, high humidity, high rainfall and relatively lower pressure.

However, dispersion is more effective in the convective conditions developed in summer. In order to gain further information on the correlation between complaints and meteorological conditions, a detailed investigation into the wind speed and direction is necessary (refer section 3.1.2).

The coastline of Kwa-Zulu Natal lies roughly Northeast/Southwest, and the dominance of coastwise winds is apparent, especially in summer. In general, northeasterly winds dominate the summer wind rose (Schumann, 1980).

CHAPTER 3

3. DESCRIPTION OF CASE STUDY

This chapter introduces the case study site: Bisasar Road landfill. The general features of the site are highlighted. A detailed review of complaints recorded from January 1997 to July 2001 is given and possible explanations for the times and locations of complaints discussed. Results from flow visualisation experiments conducted on-site to investigate the effects of complex terrain on dispersion are reported. The effects of terrain were investigated quantitatively using a dispersion model. These results are also reported. Results of walkover surveys carried out on-site to determine the relative influence of possible sources of odour are discussed.

3.1. Bisasar Road landfill site

3.1.1. General description of site

Bisasar Road landfill is located in Springfield Park, 6 km Northwest of the Durban Central Business District (CBD). Durban is the main city in the province of Kwa-Zulu Natal, which lies on the eastern seaboard of South Africa.

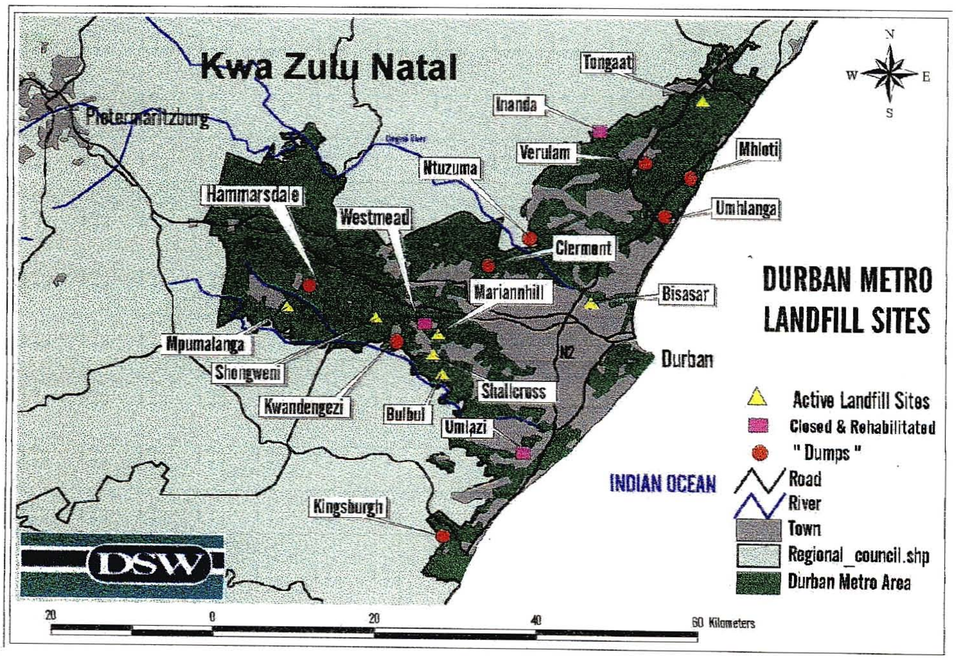


Figure 12: Map showing the location of Bisasar Rd. landfill (Courtesy of DSW)

Figure 12 shows the location of landfills and open dumps in Kwa-Zulu Natal.

The landfill is located in close proximity to the residential areas of Sherwood, Sydenham, Asherville, and Clare Estate. This is shown in Plate 1, with these four residential areas located southeast through southwest of the landfill (North is approximate). To the north of the landfill is industrial land (Not shown in Plate 2). Note the residences located on the west and south boundaries of the landfill. No buffer zone exists in practice around the edges of the landfill.

Plate 1: Aerial photograph of the Bisasar Rd landfill showing residential areas (Coutesy of DSW).

Bisasar Road receives on average three thousand tons of waste a day. It is typical of a South African landfill as it has an existing unlined waste body, around and over which a newly engineered landfill is being developed according to recent environmental regulations (Department of Water Affairs and Forestry, 1994). It has a capacity air space of twenty-one million cubic metres while at present approximately eight million cubic metres is landfilled. Bisasar Road is expected to serve the Durban Metro for another twenty years (Robinson and Strachan, 1999).

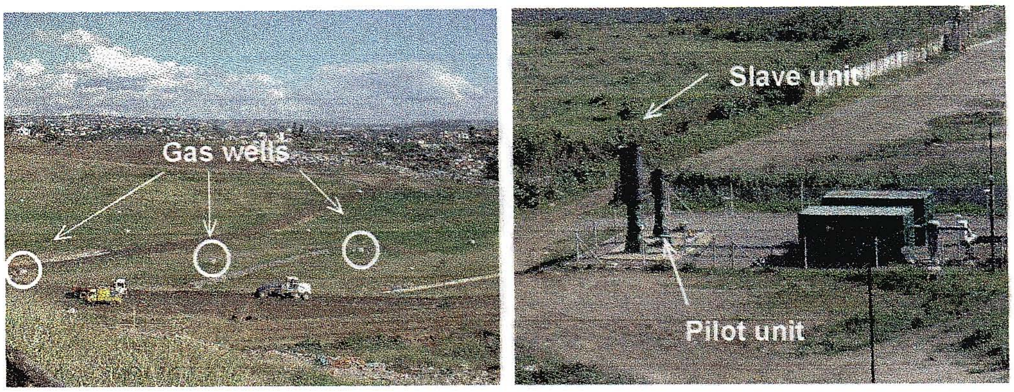


Plate 2 : (a) Gas well network, and (b) gas pump station and flares.

A degassing plant has been installed which includes twenty-four landfill gas wells (See Plate 2 (a)) and a purpose built pump and flare station which includes two Hofstetter flares – one is a 500 m^3/hr pilot unit and the other is a 2000 m^3/hr slave unit). Plate 2 (b) shows the pump and flare station. Although a flame cannot be seen above the slave unit, it is burning gas.

During the study period it was shown that the Bisasar Road landfill site, which had a planned forty year life span given the applicable deposition rates, would be extended by some seven to eight years if a gas extraction system were installed. This would result in a saving to the Municipal Operating Budget of almost sixty million Rand.

The terrain of the landfill is variable. Taking heights on a regularly spaced grid and using the central difference approximation, the slope between each grid point can be determined. The average slope across the site is 19% and the standard deviation of the slopes is 34% i.e. the coefficient of variance is approximately two. The height difference across the site is approximately 90m. Figure 13 is a 3-Dimensional plot of the Bisasar Rd landfill and the surrounding areas as it was in mid-2000.

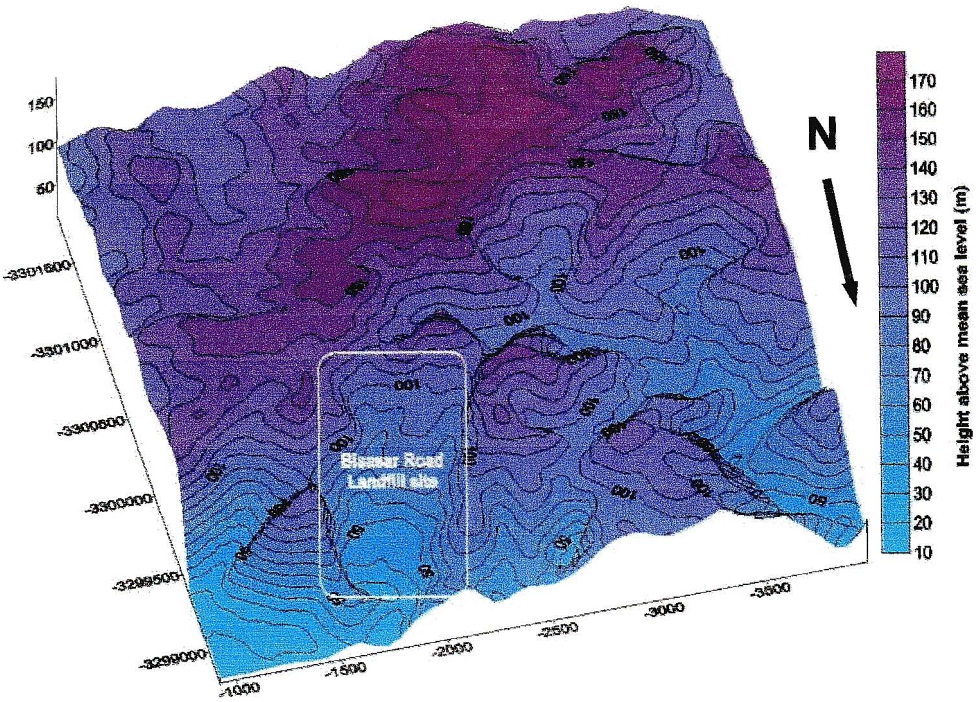


Figure 13: Three-dimensional plot of the Bisasar Rd landfill

Bisasar Road landfill site lies in a valley running along a northeast-southwest axis (See Figure 13). Local thermally generated winds may play an important role in the advection and diffusion of LFG. In the evenings, katabatic winds may lead to gas emissions collecting in the Umgeni valley, north of the landfill valley. The Umgeni valley north of the landfill (See Figure 13) is dominated by industry and thereffore katabatic flow may actually help advect LFG away from the residential areas.

On the other hand, in the morning, as the sun heats up the valley slopes, anabatic flows may be expected to carry the LFG into the residential areas south of the landfill. The low velocity of anabatic winds would not lead to much dilution of the LFG relative to convective daytime conditions.

Bisasar Road landfill has an unlined base with fully lined cells on top of the old waste body. The newly engineered cells also incorporate an underground leachate collection and transportation system.

3.1.2. Correlating complaints and weather

Complaints are lodged against the landfill for dust, airbourne litter, flies and general unsightliness. However, by far the most complaints are due to odour. A complaints log has been in operation at Bisasar Road since the beginning of 1996. Members of the public generally lodge complaints by telephone, by speaking directly to personnel at the Bisasar Road site offices. Complaints are also occasionally reported to other departments such as the Department of Water affairs and Forestry (DWAF) as well as the World Health Organisation (WHO). Complaints recorded at departments other than the landfill are relayed to DSW. When complaints are lodged, a specific form is completed with details of the complaint (See Appendix B). The complaint is then followed up by checking landfill operations, and checking odour control systems.

Figure 14 shows a distribution of complaints logged since the beginning of 1997. Complaints logged in 1996 are not shown as only six complaints were logged the entire year.

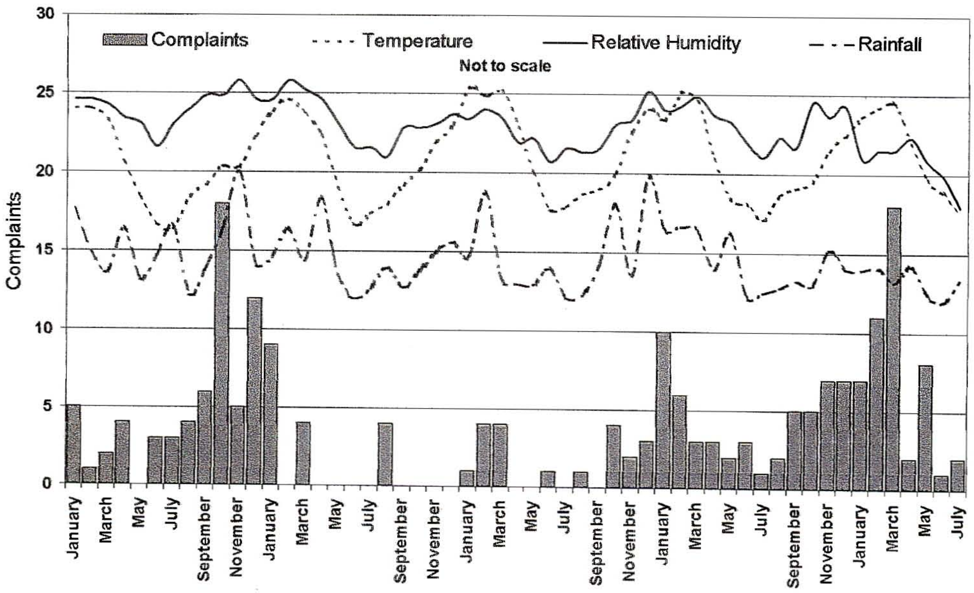


Figure 14: Complaints history and associated weather conditions from January 1997 to July 2001.

From Figure 14, it appears as though there is a peak in complaints in summer (November, December, January, February) and a dip in winter (May, June, July).

The summer peaks are shown clearly at the end of 1997, 1999 and 2000. Few complaints were logged in the summer of 1998. Associated weather conditions including temperature (°C), relative humidity (%) and rainfall (mm) are also shown in Figure 14.

The weather data are from an on-site weather station, which was erected in 1998 (data courtesy of DSW). The first readings were recorded in November of that year. Data from prior to November 1998 are from Durban International airport. The temperature profile is seasonal with a peak in summer (24.7°) and a trough in winter (16.3°). The profiles of relative humidity and rainfall are more erratic but also tend to increase in summer and decrease in winter. From this it can be concluded that complaints are more likely in hot, humid and wet conditions, typical of Durban summers.

This preliminary conclusion can be reinforced by analysis of the spatial distribution of complaints along with analysis of wind speed and direction. Figure 15 shows the spatial distribution of complaints around the landfill.

A hand-held Global Positioning System (GPS – Garmin model eTrex™) was used to obtain the co-ordinates where complaints were logged. These co-ordinates have been over-laid on a survey map as shown in Figure 15. It can be seen that the majority of the complaints are located south and west of the landfill. This is mainly due to the land-use distribution around the landfill. North of the landfill is the Springfield industrial area consisting of small to medium industrial sites and factories as well as large commercial retail stores. Residential areas dominate the south, west and east of the landfill. Despite the high density of residences east of the landfill, only one complaint has been logged from a location east of the landfill. Analysis of the wind speed and direction has been carried out in order to try to explain this distribution.

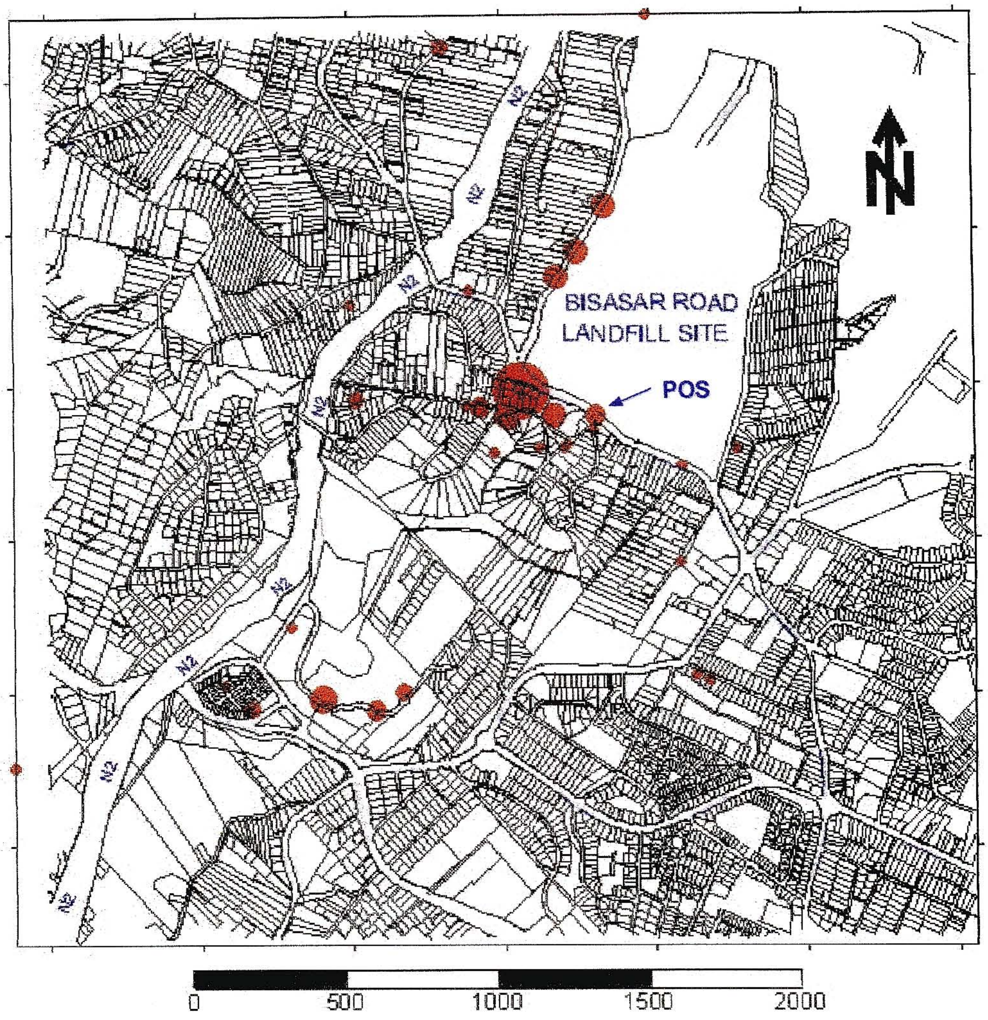


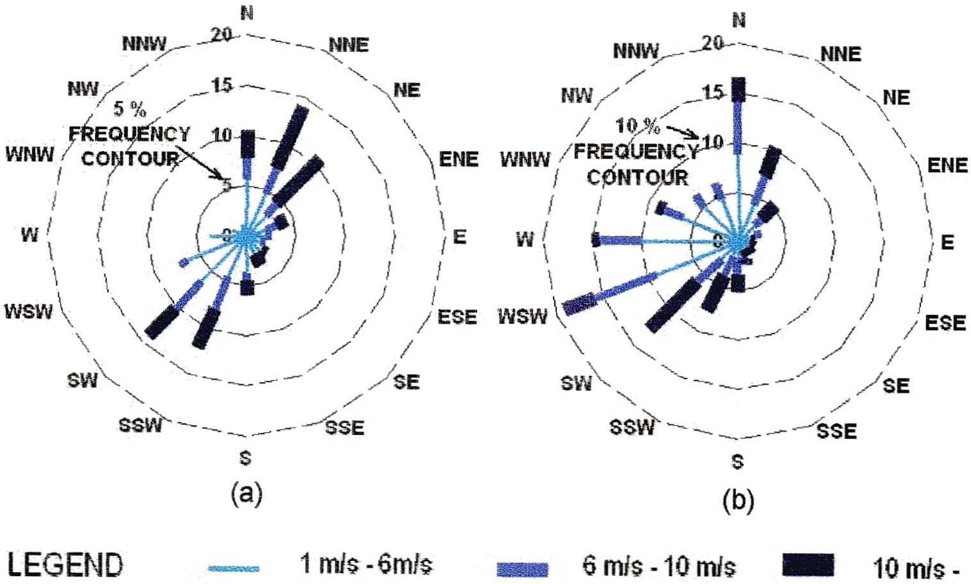
Figure 15: Spatial distribution of complaints around the Bisasar Rd. landfill with complaint locations shown as filled circles proportional to the square root of number of complaints

Analysis done by the South African Weather Bureau on fourteen years of data from Durban International Airport shows a high percentage of calms (36% of wind speeds less than one metre per second), as well as a fairly even distribution of winds blowing from the northeast and southwest. The wind blows from the northeast 22 % of the time and from the southwest approximately 25 % of the time. Winds from the Northwest account for only 1 %. This distribution is qualitatively consistent with the spatial distribution of complaints shown in Figure 15.

Wind roses are shown in Figure 16. A wind rose is a graphical illustration of the percentages of time that the wind is blowing from specific directions and for specific speeds. It is conventional to partition the wind direction into 16 sectors as in Figure 16. Wind roses also illustrate the percentages of time that the wind is blowing within chosen velocity ranges.

Wind analyses were done for weather data from the Bisasar Road station for summer months (November, December and January) and winter months (May, June and July). The wind in summer blows from an arc between north and northeast 35% of the time.

Complaint locations also appear to fall into two distinguishable distance arcs from the landfill centre. The majority of complaints (84%) are located within one kilometre of the landfill. Complaints logged from locations farther than one kilometre account for approximately 16%.



(a) (b)

Figure 16: (a) Wind rose for summer months (November, December and January), and (b) winter months (May, June and July).

3.2. Flow visualisation experiments

In order to formulate odour concentration predictions, dispersion modelling is required. One part of the modelling process is to accurately predict the wind field and turbulence characteristics in the area of interest. It is expensive to do field experiments to measure the flow to the required level of detail. However, it was decided that some qualitative field experiments would be carried out. In this way information could be obtained on the flow field across the actual case study site. The results could also serve as a validation of numerical model results.

3.2.1. Smoke flares

It was decided to discharge smoke flares around the landfill site and photograph the dispersing plumes.

The examination of the development of the visible size and shape of a smoke cloud is a simple and economical method of studying diffusion (Pasquill, 1983). By taking distant photographs of smoke clouds it is possible to draw conclusions about shape and size of the cloud, define the edges and even deduce quantitative information relating to concentrations within the plume.

A commercially available software package (*FLOWSTAR™* - Carruthers et al, 1988) was also used to compute the wind field across the landfill for conditions corresponding to those during the field experiments. This numerical model can compute mean flow and turbulence in complex terrain and therefore terrain was included in the simulations. Qualitative comparisons can be made between the path and spread of the smoke plumes and results compared to the numerical modelling. This can also act as a crude validation of the numerical computations.

Orange hand held distress flares were used as the source of smoke in the experiments. The burning time of one of these flares is approximately thirty seconds. Sixteen flares were set off in total in four individual experiments.

Each flare was attached to a two metre high wooden stake, which was driven into the ground.

Flares were simultaneously discharged and the results photographed from an elevated viewing location. Photographs were taken using a digital still camera that records pictures onto a 3 ½" floppy disk. Once a picture has been taken, it takes approximately eight seconds to save the picture to disk. With a discharge time of approximately thirty seconds, only a few pictures could be taken of each experiment.

The best visual results were achieved from the first experiment conducted on the 1st October 1999 at 7:30 am. Four flares were discharged and photographed from the southern boundary of the landfill (Place of Safety – POS. See Figure 15). The development of the plumes is shown in Plate 4.

The plumes in Plate 4 show some 'looping' behaviour (refer Chapter 2). This suggests that the atmospheric conditions may have been slightly unstable.

It is interesting to note the directions in which the individual plumes disperse. Flare one was placed in a fairly open section of the landfill and the direction in which the smoke from this flare dispersed is representative of the mean wind direction. The mean wind direction at the time of the experiment was measured at 20 degrees (clockwise from true North). The wind speed was 5 m/s.

Plume two followed a similar path. The section of the valley in which this flare was placed runs approximately parallel to the wind direction. The valley does not however, maintain this orientation. It is difficult to determine whether plume two is dispersing in the direction of the mean wind, as it is possible that the plume is being 'channelled' by the valley and dispersing due to local terrain influenced flow.

Plume three illustrates topographical effects the best. It is clear that the plume follows the contours of the hillside as it disperses.

Plume four dispersed initially in a southerly direction (i.e. towards the camera), then in a direction consistent with the recorded mean wind, and then again in a southerly direction. This may be due to a region of subsidence near the flare caused by the steepness of the terrain up to the southern boundary (30°).

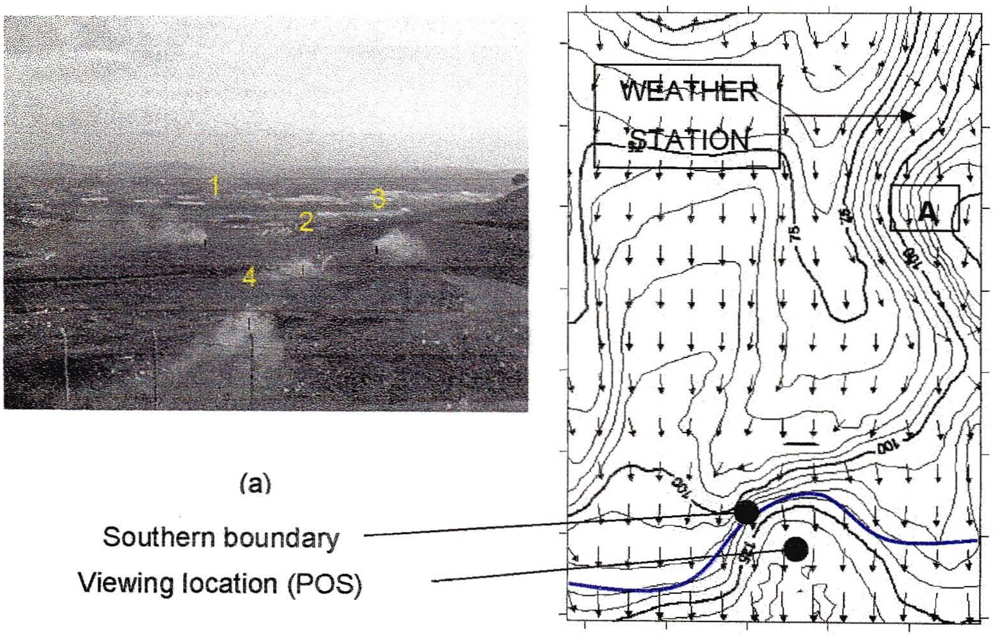
Results of the other three experiments have been included in Appendix D.

The results of the field experiments provided qualitative evidence that complex terrain does have an effect on the flow path and dispersion of smoke plumes. Our preliminary conclusion is that complex terrain effects at the case study site could be important for accurate short-range odour predictions.

Plate 3: (a) - (f) Time series of images taken of a dispersing smoke plume for experiment one conducted on the 30th October 1999.

FLOWSTAR™(Carruthers et al, 1988) was used to formulate the flow field in complex terrain. *FLOWSTAR™* links to a graphics package *SURFER™*, which is used to visualise the various flow parameters output by the model.

Figure 17 (a) shows an overlay of the images in Plate 3. Figure 17 (b) shows the predicted mean flow field across the landfill site at one metre above the ground. The direction of the arrows in Figure 17 (b) is representative of the wind direction and the length of the stem of each arrow illustrates the relative wind speed.



(a)

(b)

Figure 17: Comparison of flow experiment results, (a) and numerical simulations, (b).

Note the change in direction of flow as the wind flows around the hill marked "A" in Figure 17 (b). This is consistent with the direction of dispersion of the smoke plume (flare 3) on the right hand side of Figure 17 (a). Figure 17 (b) does show *FLOWSTAR™* predicting 'channelling' of the wind in the region of flare 2. In the region of flare 4, the numerical model does predict effects of the terrain on the wind speed and direction. The wind speed is lower in this region relative to the region around flare 1. The model also predicts non-uniform wind directions at the base of the southern boundary.

Similar comparisons can be drawn from experimental and numerical results for the other three tests conducted. These are discussed in Laister (1999).

The conclusion from the comparisons done is that the results of the field experiments and numerical modelling are qualitatively consistent.

Using smoke flares had three disadvantages:

a) The cost relative to funding available,
b) Smoke was only generated for thirty seconds, and
c) The hazard of discharging smoke flares on a landfill site where LFG emissions comprise approximately 50% CH_4.

In an attempt to combat these three disadvantages, it was decided to investigate the use of windsocks to map the mean flow across the site.

3.2.2. Wind socks

Windsocks are simple, low-tech devices, widely used at airports for determining wind speed and direction. Windsocks have low capital cost (approximately the equivalent cost of three smoke flares) and could remain as semi-permanent structures on-site and viewed on convenience.

Material was purchased and a windsock constructed. The windsock was placed next to the weather station on the northern side of hill "A" (See Figure 17 (b)). The windsock was photographed from the POS.

Unfortunately, results obtained from analysing the pictures of the windsock were inconsistent. This was possibly due to the slow response time of the windsock as well as the tail of the windsock being too light. The windsock fluctuated making the mean wind direction difficult to determine. Windsocks were thus not a viable option for accurately determining the mean wind speed and direction.

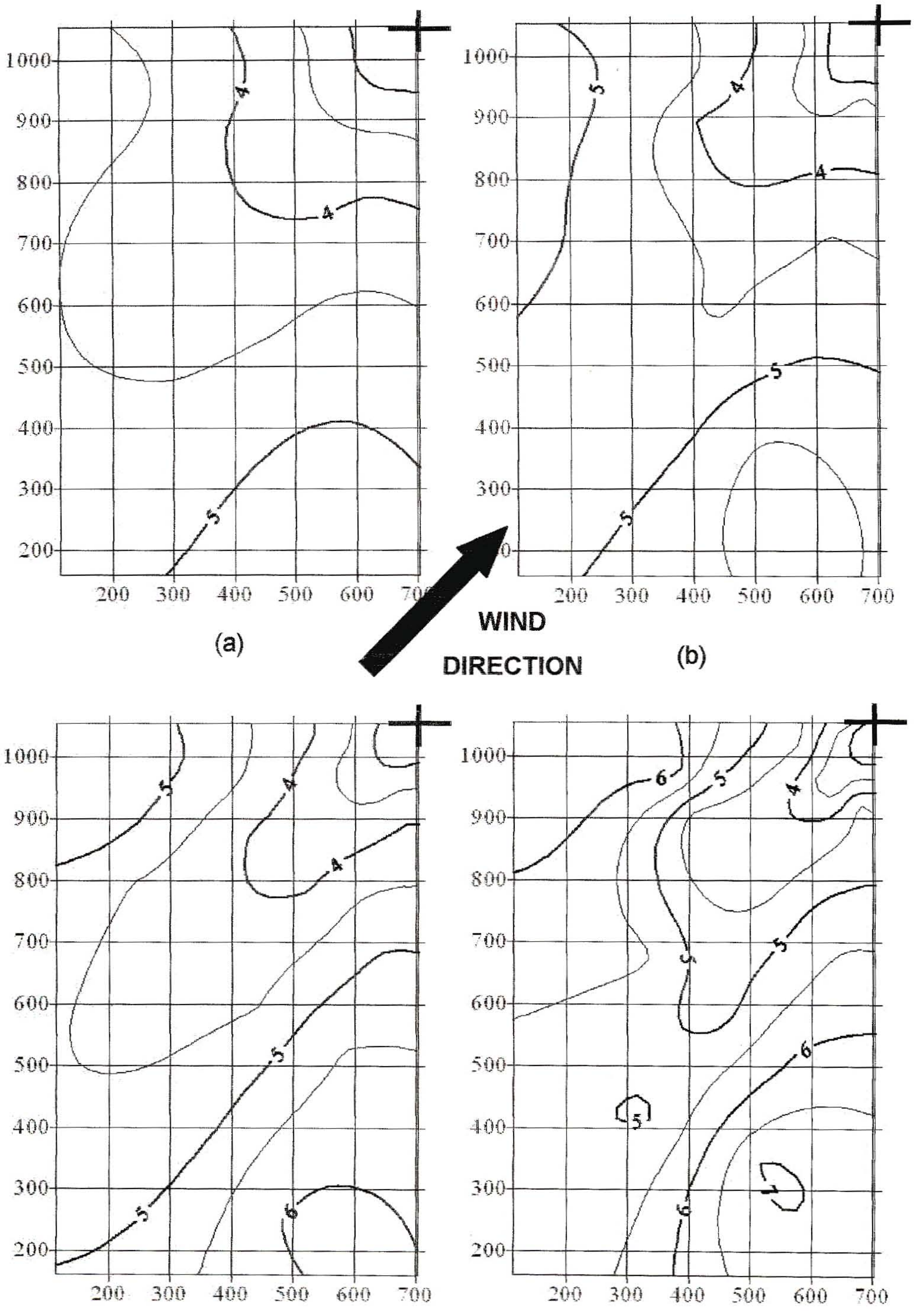
3.3. Quantitative assessment of complex terrain effects

A more quantitative illustration of complex terrain effects for our case study site is shown in Figure 18. These results were generated using the *ADMS™* dispersion model which utilises *FLOWSTAR™* for computing the flow field.

The contour maps show distributions of a normalised "dilution" on a logarithmic scale over the landfill site for two different reference wind speeds (same direction) and for a specified receptor location (co-ordinates (715, 1068) – shown by a cross in top right hand corner of each plot). The plots show the dilution (based on ground level concentrations averaged over 1 hour) that occurs between a particular source location and the receptor. For example a contour labelled *x* (say) in Figure 18, implies that the number of odour units which can be dispersed from those locations is given by 10^x ($U.D^2/Q$), where Q is the emission flow rate, U is the reference wind speed, and D is the source size.

It can be seen that complex terrain results in significant changes in the dispersion characteristics across this site, at least for short-range dispersion. The effect is less pronounced in lower wind speeds. Figure 18 (a) and (b) show the effects for complex terrain for a wind speed of 2.5m/s. Terrain causes an increase in dilution due to increased mechanical turbulence and therefore mixing. The increase in dilution is also due to interaction between a plume and the surface. The most noticeable difference between Figure 18 (a) and (b), is in the top left hand corner where the dilution is increased by approximately 3 times.

The effect of complex terrain is a lot more pronounced for a higher wind speed of 10m/s as shown in Figure 18 (c) and (d). Dilution is increased by more than ten times in certain places around the landfill.



(a) (b)

(c) (d)

Figure 18: Contour maps of predicted dilution for a receptor located at (715, 1068) (a) Flat terrain and wind speed = 2.5 m/s, (b) Complex terrain, wind speed =2.5 m/s, (c) flat terrain, wind speed = 10 m/s, and (d) Complex terrain, wind speed = 10 m/s

3.4. Odour sources at Bisasar Road landfill

Possible sources of odour at Bisasar Road landfill include the flare, the leachate and gas collection and transportation network, general emissions from the landfill surface (all biogas emissions), the transfer station and working face (fresh waste emissions).

A "Portable Odour Monitor" (Sensidyne™ model XP-329) was acquired (See Figure 19). The odour monitor is a handheld device that provides the user with a relative measure of the odour of a substance or mixture of substances. The pump draws a gaseous sample into the unit through the inlet and passes the sample over a solid-state sensor element. The result is a reading in arbitrary units, of the intensity of electrical and thermal effects that result from contact between the sample and the sensor. The monitor does not measure concentration directly.

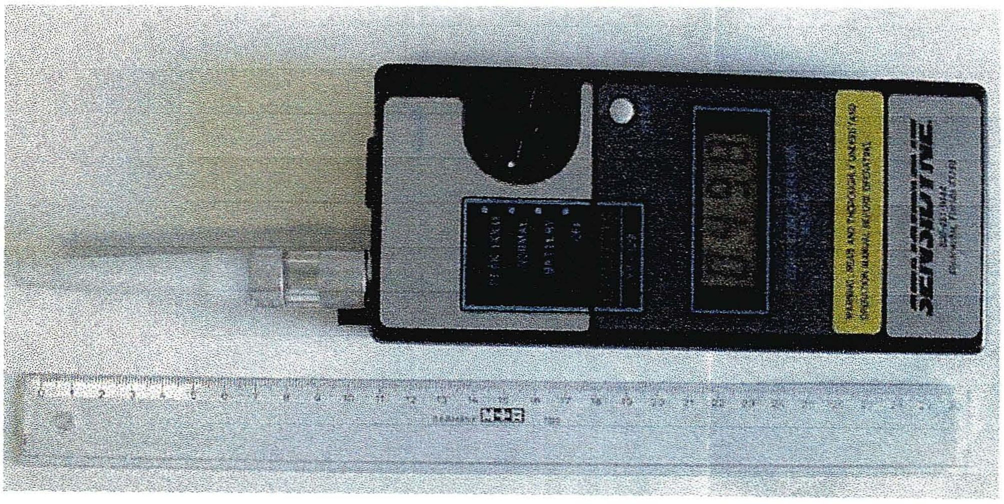


Figure 19: Portable odour monitor.

The monitor has been used for providing a relative intensity to the smell that would otherwise be difficult to quantify with descriptive words.

The odour monitor was used during walkover surveys in combination with subjective sense of smell to identify sources of odour on the landfill. A hand held GPS was used to track the path taken as well as to mark locations where the smell seemed particularly bad.

Visits to the landfill ('Walkover surveys) hinted that, besides a few secondary sources, the primary source of odour was the working face. Temporary sources of odour detected included leakage's in the gas collection system, a section where the gravel layer of the lining system intersected the top surface and an uncovered section of a junction in the leachate collection system. These sources emitted the distinctive biogas smell (as opposed to fresh waste gas). All of these latter problem sources were rectified and ceased to emit odour.

The transfer station located near the site office is a continuous daytime source of fresh waste odour. However, the size of the transfer station can be kept small enough so that the contribution from this source is low. No odour was detected downwind of the flare.

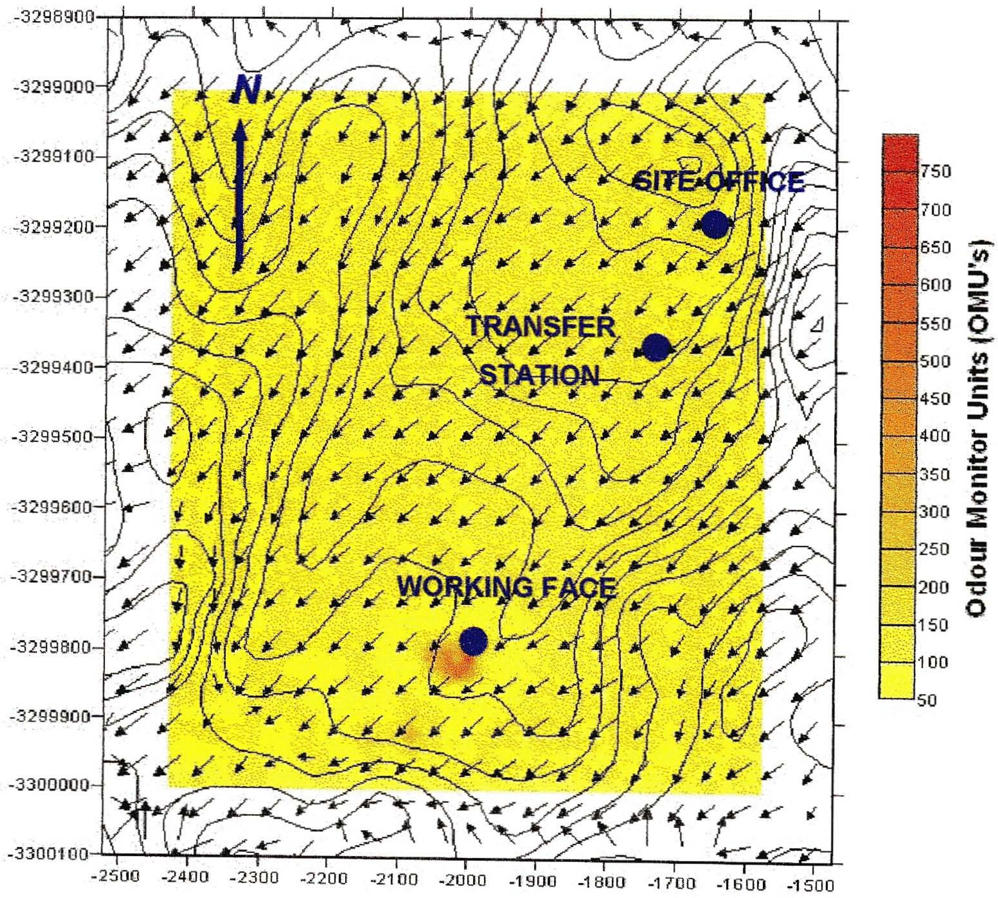


Figure 20: Results of walkover survey conducted on 30th January 2001

Despite qualitative nature of the above results, the portable odour monitor offered the opportunity to quantify the contribution of sources around the site. Seven of these 'walkover survey were conducted on separate days under differing weather conditions. The track taken and the points marked, differed from survey to survey.

Figure 20 Shows the results of a walkover survey conducted on the 30th January 2001. The results are in terms of odour monitor units (OMU's). Also shown in Figure 20, is a contour map of the terrain across the landfill as well as a vector map showing the wind field at one metre above the ground. *ADMS*™ was used to compute the wind field based on conditions at the time of the 'Walkover survey'.

The odour monitor was 'zeroed' in relatively non-odorous air by adjusting the reading on the display to 100. All values recorded during surveys are therefore relative to 100. As can be seen from Figure 20 readings below 100 were recorded (Lowest recorded reading was 68) due to lower odour levels than at the calibration location.

Figure 20 shows that, on this particular day, the only source with any noticeable odour is the working face. Low readings (less than 150 but greater than 100) were noted around the transfer station but it is difficult to notice this in Figure 20 because of the relatively higher values (maximum recorded value was 950) near the working face and the scale used. Besides the transfer station no other sources of odour were detected on the landfill. Temporary sources of odour (e.g. leakage's, uncovered leachate chamber, etc) were detected in other surveys, but on each survey conducted the working face was the primary source of odour.

Once it was established that the working face is the primary source of odour at Bisasar Road landfill, the source needed to be characterised. Efforts to sample the emissions are documented in chapter 4.

CHAPTER 4

4. SAMPLING

Once the working face had been established as the primary source of odour at Bisasar Road landfill, the emissions needed to be characterised in terms of source concentration and emission flow rate. This was attempted using four different methods. A portable odour monitor was used to characterise the source strength in terms of OMU's (See section 3.4). Results of sampling conducted over a year by an independent consultant are reported. A 'Static Accumulation Chamber' (SAC) was built, calibrated and tested on-site to determine the emission rate and concentration. Results are discussed in this chapter. Results of further sampling carried out using sorbent tubes are also discussed.

4.1. Quantification of source concentration using the portable odour monitor

The portable odour monitor outputs a reading in arbitrary units (OMU's). Despite the fact that this reading does not have any units, it may be possible to quantify concentration in odour units. This can be approximated by using the odour monitor to determine the dilution required for an odorous sample to reach its odour threshold. The dilution factor is the number of odour units in the original odorous sample.

In order to determine this factor of dilution, samples were taken from the working face. Samples were drawn into a container and then successively diluted until the odour monitor could no longer distinguish between the sample and clean air. An adaptation of the syringe method described in section 2.3.4, was first investigated. Unfortunately, it was not possible to acquire syringes larger than 100ml. A much larger sample would need to be taken in order to accurately dilute it significantly.

It was decided to try a flexible container that could be pumped up. Balloons were first used to contain samples, but it was found that the balloons had an inherent odour that was too strong for accurate readings of the actual sample to be taken. Condoms were therefore used as they have very little odour.

The procedure involved pumping up condoms with air samples from the working face using a handheld pump. The samples were then transferred to an area with minimal background odour. The odour monitor was zero-calibrated by exposing it to the background odour and the display reading adjusted to read 100. The dimensions of the condoms were noted in order to calculate the initial volume of the sample. The sample was released from the condom into the input to the odour monitor and the reading noted before the condom was resealed. The dimensions were re-measured. The condom was then pumped with fresh air to dilute the sample. The dimensions were again noted. More of the sample was released and the reading again noted. The procedure was repeated until the odour monitor no longer registered a change in reading between consecutive samples.

In total sixteen samples were taken and analysed. The length and the diameter of the condom were measured for the volume calculation by approximating the shape as a cylinder.

Therefore, with the volume prior to a reading taken, combined with the volume following the reading taken and the volume after filling with fresh air, the percentage relative concentration of the diluted sample could be calculated. Table 6 shows the results of one experiment conducted on the 13th February 2001.

Table 5: Example calculation of estimating factor of dilution required to reach the odour threshold

Reading OMU's	Original vol. (m^3)	Vol. After read. (m^3)	Vol. After fill. (m^3)	% Orig. conc. %
570	0.008291	-	-	100.000
320	0.008291	0.000944	0.013519	7.000
240	0.013519	0.000995	0.012776	0.500
200	0.012776	0.000870	0.011872	0.040
175	0.011872	0.000713	0.012479	0.002

Results from a total of ten experiments carried out on three different days have been plotted on a log scale in

Figure 21.

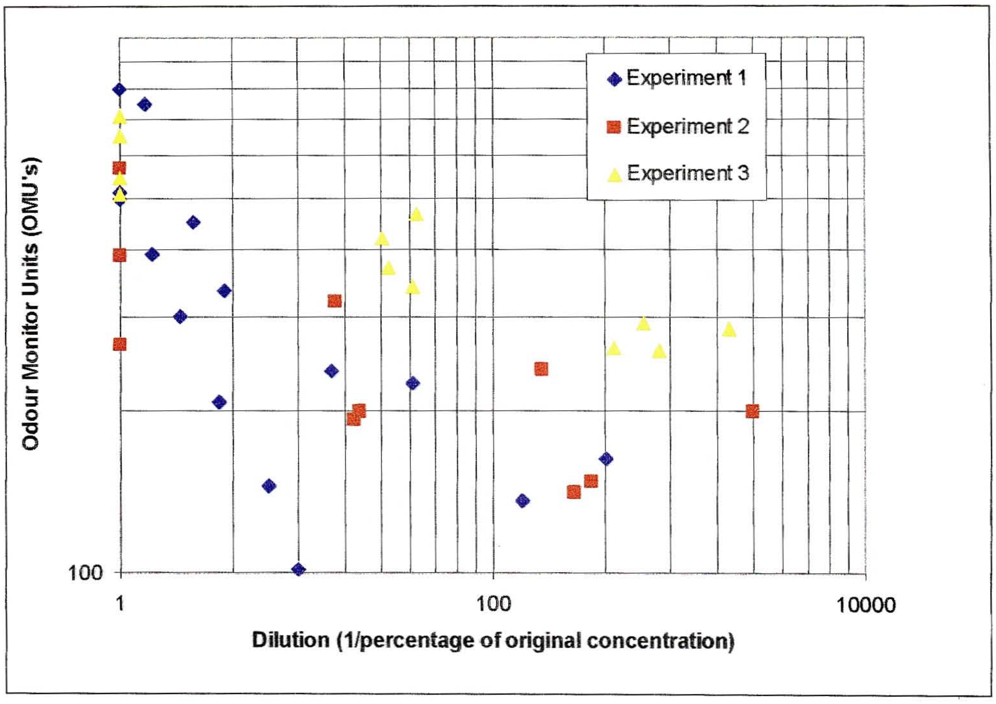


Figure 21: Log-log plot showing results of condom experiments used for determining the dilution required to reach threshold concentration from source concentration

Figure 21 shows the results with dilution plotted on the x-axis and the odour monitor readings (OMU's) plotted on the y-axis. The results are inconsistent between experiments and do not conform to any reasonable power law behaviour. However, the trend in the data suggests that the dilution required to reach the zero-calibration reading of 100, is of order 100 000. Further samples need to be taken to determine the relationship between the change in odour concentration and the change in odour monitor reading.

4.2. Field sampling

Sampling and analysis was carried out at Bisasar Road (by a third party) in October 1999, March 2000, and finally in November 2000 (HINDOC, 2000). Samples were taken using constant flow sorbent tubes (Activated charcoal was the adsorbent material used). Table 6 shows the results from the three sampling exercises. Table 6 also includes the Department of Environmental Affairs and Tourism (DEAT) Maximum Recommended Limit values (MRL) as well as the respective compound odour thresholds (OT's).

Table 6: Results of sampling and analysis done by independent consultant (HINDOC, 2000).

Sample date	Oct-99	Mar-00	Nov-00	Nov-00	DEAT MRL	OT
	Boundary	Boundary	Boundary	Work face		
Units	ppb	ppb	ppb	ppb	ppb	ppb
Benzene	BDL	12	BDL	BDL	50	12000
Toluene	77	316	72	673	1000	2900
Ethyl Benzene	112	201	70	420	2000	2300
Xylene	79	212	72	530	2000	56
Isopropyl Benzene	BDL	BDL	22	193	2000	NA
Mesitylene	BDL	BDL	BDL	40	500	550
Trimethylbenzene	116	47	4	173	500	1400
Tetramethylbenzenes	BDL	BDL	26	60	500	NA
Hexane	BDL	1050	28	40	10000	130000
Heptane	BDL	278	BDL	BDL	10000	150000
Nonane	BDL	BDL	BDL	BDL	4000	47000
Undecane	BDL	BDL	BDL	113	4000	NA
Dodecane	BDL	BDL	34	517	4000	NA
Naphthalene	BDL	BDL	22	483	100	84
Methylene Chloride	BDL	BDL	11	107	500	200000
Acetone	154	BDL	BDL	BDL	1000	5400
Ethyl Acetate	155	1230	BDL	BDL	8000	NA
Butyric acid	64	62	BDL	BDL	500	73
Propanoic acid	51	BDL	BDL	BDL	500	160
Trichloroethane	87	9	BDL	BDL	1000	28000
Ammonia	225	83	80	BDL	500	5200
Hydrogen Sulphide	BDL	BDL	BDL	BDL	200	8.1
Formaldehyde	25	18	18	BDL	20	830

Only once was the DEAT MRL limit exceeded in all the NMOC's tested. Naphthalene exceeded the MRL by over four times at the working face in November 2000. However, the concentration had dropped to below the MRL at the boundary of the landfill. Various compounds were detected for which odour thresholds are not available. For compounds with available odour thresholds, only Xylene and Naphthalene exceeded their respective odour thresholds. Xylene exceeded its odour threshold in all samples and in November 2000 exceeded the threshold by almost four times at the working face. Naphthalene only exceeded its threshold at the working face by approximately 5 times. Naphthalene has a 'moth-ball' or 'tar-like' smell (Ruth, 1986), while Xylene has a sweet smell (Ruth, 1986). The combination of Naphthalene and Xylene is probably not solely responsible for the overall smell emanating from the working face.

No Hydrogen Sulphide was detected on-site. Therefore, the overall odour must be due to compounds that were either not sampled or analysed for. Further sampling was therefore thought to be necessary to determine the odorous compounds.

4.3. Static Accumulation Chamber

In order to determine the emission rate and the emission concentration of the fresh waste gas, an area of the uncovered newly dumped waste needed to be enclosed and sampled. Sampling of area sources is usually achieved by using 'Flux Chambers'. It was decided to build a simpler 'Static Accumulation Chamber' (SAC) (Morris, 1999) in collaboration with Aiden Bowers (Bowers, 2002).

4.3.1. Design and testing of apparatus

The shape and size of the SAC was based on a similar chamber reported by Reinhart and Cooper (1985). A 700-mm diameter, 200-mm high SAC was constructed out of steel plate (Figure 22 (b)). A septum port was inserted in the roof of the SAC to draw out samples.

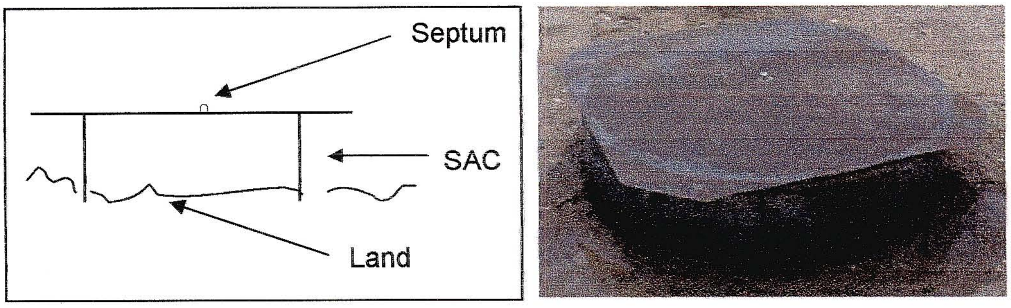


Figure 22: Static Accumulation Chamber (SAC), (a) Cross-section and, (b) In the field

It was decided to test and calibrate the flux box in the laboratory at the University of Natal, Durban (UND). This testing was based on similar calibration tests carried out by Morris (1999). In order to test the SAC, the conditions in the field needed to be simulated. A 1200mm x 1200mm testing bed was created (Figure 23) through which gas at a known flow rate was passed. Morris (1999) used a mixture of Carbon Dioxide and Methane as the test gas. The dangers of using Methane in confined areas led to the decision to use only pure Carbon Dioxide for testing the SAC.

The objective of the testing was two fold. Firstly, to determine how accurately the flux box measures a known flux of gas through the surface of the test bed. The input flow of CO_2 into the base of the bed was known and assumed to distribute evenly across the area of the bed resulting in a known output flux. More importantly than determining the accuracy, however, was to investigate whether consistent, repeatable results could be obtained. If the flux box could not measure flow accurately, but did measure a consistent ratio of measured to actual flow then this could be used as the flux box calibration constant. This constant could then be applied to results obtained in the field.

The testing bed consisted of an open-topped box built on legs 450mm high. The height of the sides of the box was 250mm. Forty-nine evenly distributed holes were drilled in the base of the box, and flexible rubber tubing inserted into each hole from underneath the box. The forty-nine lines of tubing converged into a 'splitter box' (Plate 4). Also shown in Plate 4 is the base of the splitter box, which has one exit hole to connect the splitter box to the gas source. The splitter box was constructed in order to split the flow of gas from the source evenly across the testing bed.

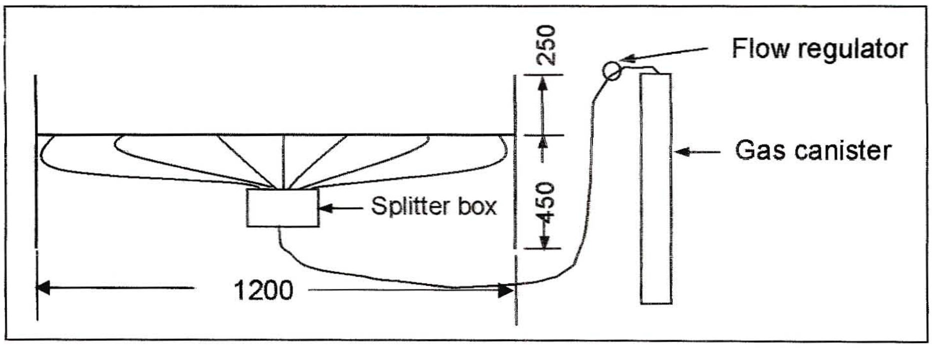


Figure 23: Testing bed for SAC

Unfortunately, not enough pressure drop was created in the splitter box for the gas to distribute evenly through the forty-nine exit holes. High flows were detected in the middle section of the testing bed and very little flow from the holes nearer the edge of the bed.

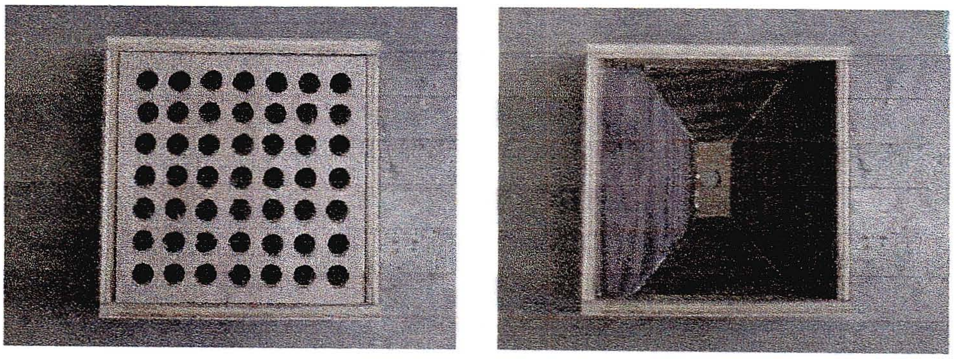


Plate 4: Splitter box

An alternative design for the testing bed was therefore required. This was undertaken by an undergraduate student in the department of Civil Engineering at UND as a dissertation project (Van Rooyen, 2001). The alternative design consisted of a solid base on which a 70mm layer of gravel was placed. Five layers of bidim geofabric was placed on top of the gravel. A false floor consisting of 169 holes was secured on top of the bidim. Gas from the canister was introduced into the bed through a single port into the side of the layer containing gravel. The purpose of the stone and bidim is to increase the pressure drop and hence produce a uniform flow of gas through the false floor. Above the false floor another layer of bidim was placed upon which approximately 120mm of uniformly graded Durban Berea Red sand was placed.

Twenty-one tests were conducted in total. Two different flow rates were used. Unfortunately, a large scatter was found between results of individual tests. The full set of results and detailed review of these results can be found in Van Rooyen (2001). Combining the results of tests for the two flow rates, the average ratio of actual flux to measured flux was 74. The standard deviation was 123 i.e. 1.66 times the average. This reflects unacceptable inconsistency in the results. The results of this testing were therefore insufficient to determine a calibration constant for the flux box (Van Rooyen, 2001).

4.3.2. Sampling

Despite these results, attempts were made to use the SAC on the fresh waste at Bisasar Road landfill. An area of the working face was selected where fresh waste had been laid down but not covered. The compactor was passed over the area a few times in order to level the surface and to crush any large objects and full rubbish bags. The SAC was then placed on the levelled surface and pushed into the waste to create a crude seal around the edge. Timing started once the SAC was fixed and samples were taken at various time intervals. Samples were drawn with a syringe from the SAC through the septum. The syringe used was a 100-mL gas tight syringe. Samples were transferred from the syringe into 2-mL vials that were then transported to the laboratory for analysis.

Four samples were taken on the 20th August 2001. Samples were taken at 1, 3, 7 and 16 minutes. Analysis was done at the UND Chemistry Department using a GC/MS.

4.3.3. Analysis and results

Unfortunately, the results of this set of samples were inconclusive. The concentration of gas in the vials was too small to identify any compounds. The low levels of concentration detected may have been due to minute traces of compounds remaining in the syringe or in the vials from previous tests.

The failure of this sampling and analysis procedure to determine emission rate or concentration of fresh waste gas emissions could be due to a number of factors including:

a) gas not accumulating or mixing within the flux box,
b) flow rate of the emissions could have been too low to fill the flux box sufficiently in the sampling time period,
c) gas could have leaked out of the vials or reacted within the vials forming compounds not analysed for,
d) Methods used to analysis the samples may not have been adequate.

Staff in the Chemistry department of UND advised that 'trapping' gaseous samples onto absorbent material could produce more positive results.

4.4. Sampling onto sorbent material

Following failure of the trial SAC tests, it was decided to try alternative methods of sampling. Unfortunately, the alternative methods do not allow for the calculation of the emission rate of gas from the working face, but only the detection of the constituents of the emissions.

Durban Metro Water Services (DMWS) had recently purchased a GC/MS and offered to do some preliminary analysis. Their preferred choice of sampling method was to sample atmospheric pollutants into sorbent tubes and then do the analysis according to *USEPA* compendium method TO-17 – "Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling Onto Sorbent Tubes" (*USEPA*, 1997b).

4.4.1. Equipment and sampling

As shown in Figure 5, the equipment to sample into sorbent tubes includes glass or stainless steel tubes containing absorbent material, connected to a hand held pump by flexible tubing.

According to TO-17, two samples are to be taken at the same time at different flow rates. This is made possible by the flexible tubing, which (attached to the pump at one end) forks into two *separate* lines at the other end. Each *separate* line has a valve, which is adjusted to give the required flow rates using a rotameter. The recommended flow rates of 16.7 and 66.7 ml/min were used. The suggested sampling duration of one hour was also used.

Various different types of absorbent materials are recommended for trapping different classes of compounds. As little information is available on the composition of fresh waste gas, a combination of commonly used materials were used to pack the stainless steel tubes. The materials used included Tenax™TA, Carbopack™B and Carboxen™1000.

The first sampling was conducted on the 23rd August 2001, at the working face on the Bisasar Road landfill. Two tubes, packed by DMWS, were sampled; one was taken to DMWS (Sample 1) for analysis and the other UND (sample 2). The pump used was the property of DMWS.

4.4.2. Analysis

The laboratory at UND has the capability to conduct quantitative analysis (determine concentration) whereas the laboratory at DMWS does not yet have the expertise to do this. This initial pair of samples taken were analysed at different laboratories to compare the results from two independent laboratories for consistency.

The instruments used for GC/MS analysis at DMWS consisted of a Hewlett-Packard 6890 Gas Chromatograph interfaced to a Hewlett-Packard 5973 Mass Spectrometer. The chromatographic column used was a 5 % phenylmethylsiloxane column with the dimensions 30-m long, 0.25-mm ID, and 0.25 μm coating. The GC oven was programmed to operate at 45°C for 5 minutes, then increased at 8°C/min up to 250°C until a total runtime of 31.63 minutes was reached. The column head pressure was set at 20 kPa and the carrier gas was Helium. The injector heater was maintained at 100°C and the flow path temperature maintained at 150°C.

A thermal desorption unit (Markes™) was used to desorb the samples from the tubes. The tubes were prepurged for 2 minutes. They were then desorbed for 5 minutes at 300°C and trapped for 3 minutes at a temperature between a minimum of 27°C and a maximum of 270°C.

4.4.3. Results

DMWS identified several compounds in the samples whereas the Chemistry department at UND detected nothing but background concentrations. This was a major disappointment, as quantitative analysis could not be done by DMWS. Figure 24 shows the spectrum of compounds determined by DMWS analysis (Sample 1). This is a section of the spectrum (time does not start from zero on the x-axis) to focus on the compounds that it was possible to identify. The spectrum outside of this time segment shows no identifiable compounds (Figure 47 in Appendix H shows the full time spectrum). The label 'Abundance' on the y-axis is a non-dimensional, unitless name given to the quantity of substance present. To calculate the concentration of the individual substances, pure samples of each individual substance must be passed through the GC/MS and the relative abundance's compared. The GC/MS at DMWS had not yet been calibrated.

Pure individual compounds do not have the same abundance as each other. Therefore the relative abundance's of each substance shown in Figure 24 cannot be used as a direct indication of the relative concentrations of individual substances present.

For example, in Figure 24, Toluene has a higher abundance than Decane, but this does not mean that Toluene was present at a higher concentration than Decane.

Classes of compounds identified in this sample include:

a) Aromatic Hydrocarbons (Alkenes): Xylene (two types), Toluene, Benzene (C3), Ethylbenzene, Diethylbenzene, Ethyltoluene, Naphthalene
b) Terepenes (Olefins): Limonene/Bornylene, Alpha-Pinene, Sabinene
c) Aliphatic Hydrocarbons (Alkanes): Decane, Undecane, Dodecane.

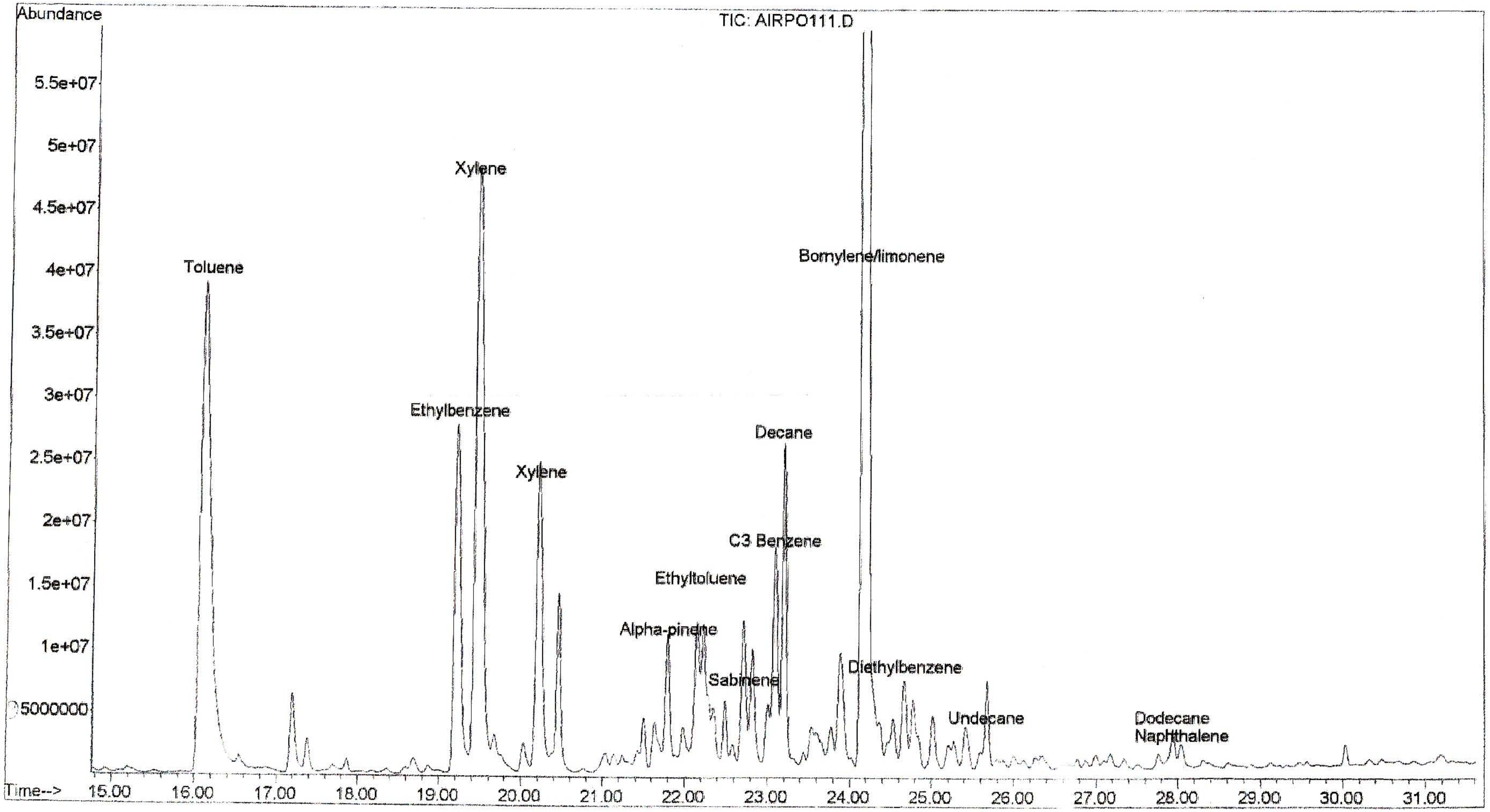


Figure 24: Partial spectrum of composition of fresh waste gas as sampled on 23rd August 2001 (Sample 1)

No sulphur compounds were detected in the analysis. It is difficult to trap sulphur compounds on absorbent material due to the high volatility of substances containing sulphur. The odour associated with the fresh waste could be due to sulphur compounds such as Mercaptans, Methyl sulphide, Dimethyl sulphide, Dimethyl disulphide, etc. As reported in Section 4.2, no Hydrogen Sulphide has been detected at the landfill.

It was decided to do further testing to determine the variability of the composition of the fresh waste gas. Further samples were taken on the 30th of October and the 2nd of November. Analysis of the sample taken on the 30th October at a flow rate of 16.7 ml/min (sample 3) failed to register any identifiable compounds for reasons unknown; therefore three further spectra were determined.

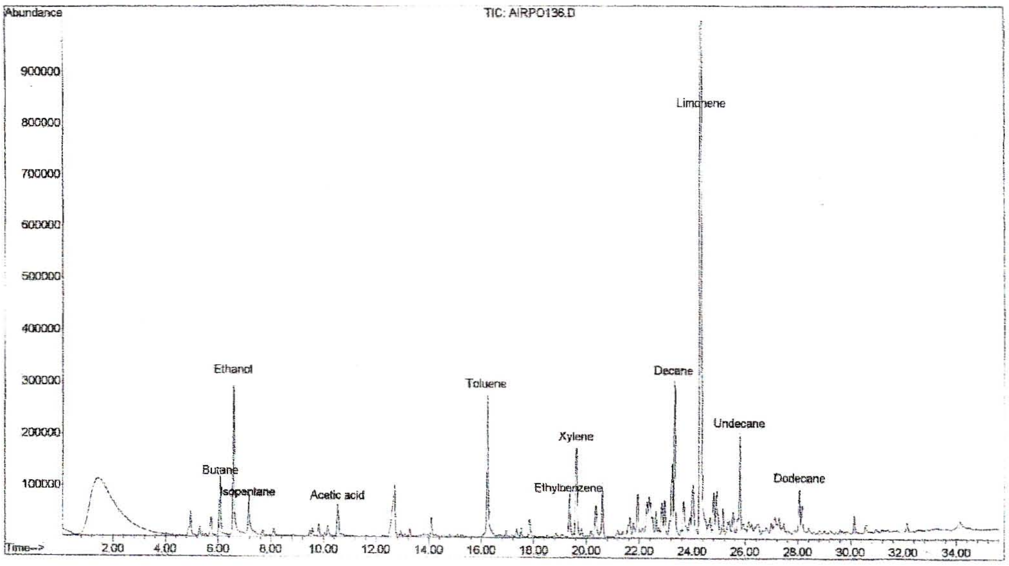


Figure 25: Full time scale spectrum of sample 4 taken on 30th October 2001 (Flow rate 66.7 ml/min)

The spectra of samples 4 and 6 are shown in Figure 25 and Figure 26. The spectrum for sample 5 has been included in Appendix H.

The spectra are qualitatively consistent in that similar compounds were detected in each sample and their relative abundance's in each test were also of similar magnitude. Additional classes of compounds appeared in the spectra of samples four (Figure 25), five (Figure 49 in appendix H) and six (Figure 26). These include:

a) Volatile Fatty Acids: Acetic acid,
b) Ketones: Butanone (MEK),
c) Alcohols: Ethanol, Butanol, and propanol.

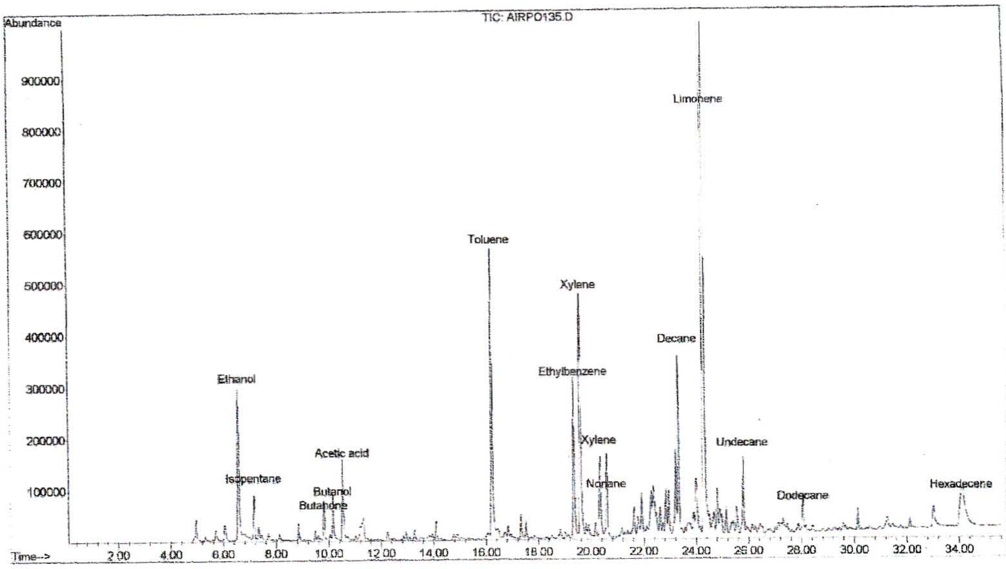


Figure 26: Full time scale spectrum of sample 6 taken on 2nd November 2001 (Flow rate = 66.7 ml/min)

4.5. Summary

The failure to achieve the two objectives of determining the emission rate and concentration of fresh waste emissions was due in part to:

a) Inherent difficulty in sampling area sources,
b) Difficulty in sampling the uncovered waste which has an uneven surface resulting in a poor seal around the base of the SAC,
c) Use of non-standardised sampling equipment which had inconclusive results,
d) Inconsistent results from the University laboratory,
e) Lack of equipment, facilities and expertise for analysing samples quantitatively.

The sampling experiments did gain information about the composition of fresh waste gas. The main groups of compounds detected were Hydrocarbons, and in particular, Terpenes. Volatile Fatty Acids, Ketones and Alcohols were also detected. No sulphur compounds were detected.

The composition of the fresh waste at Bisasar Road is consistent with results found by Termonia and Termonia (1999) that list Hydrocarbons, and in particular Monoterpenes, as the main cause of odour from fresh waste. However, the composition determined is in contrast to odorous compounds associated with aerobic composting facilities (Roberts and Sellwood, 1997). Roberts and Sellwood (1997) list sulphur compounds, nitrogen containing compounds, Volatile Fatty Acids, and Ketones as the main constituents of composting odour.

CHAPTER 5

5. DISPERSION MODELLING

Chapter five discusses the use of dispersion models. A dispersion model was used to investigate the effects of varying emission parameters. Results obtained from varying the source type specification (point or area source) are discussed. A comparison between four dispersion models assuming flat terrain is reviewed. Section 5.3.4 reviews a comparison made between predictions assuming flat and complex terrain using one of the dispersion models, ADMS™. ADMS™ was also used to predict conditions at the times of selected complaints recorded at Bisasar Road landfill.

5.1. Source characterisation

The parameters that need to be determined in order to characterise the source are the mass emission rate (mass per unit time) and the volume flow rate (volume per unit time). The mass emission rate divided by the volume flow rate is the source concentration (mass per unit volume).

The volume flow rate is equal to the area of the source multiplied by the emision exit velocity :

$$Q = V * A \tag{5.1}$$

where :

Q = Volume flow rate (m^3/s)
V = Exit velocity (m/s)
A = Area of source (m^2)

The area of the working face was determined using a hand-held GPS. The extremes of the working face were marked on different days and the average calculated. The average area of the working face was approximately $1000m^2$.

5.1.1. Exit velocity

In order to run a dispersion model it is necessary to provide a value for the emission exit velocity for which no measurements were available.

High exit velocities are expected to create additional turbulence and mixing. Therefore *ADMS™* was used to investigate the effect of changing the exit velocity whilst keeping the total source concentration ($C_0 = Q/E_m$) constant. Simulations were run for a single point source and for weather data characteristic of neutral and stable atmospheric conditions. One line of receptors were located downwind of the source at distances between 10 and 1000 metres. Simulations were run for exit velocities equal to 10%, 50%, 100% and 200% of the friction velocity, u_*. Two source sizes (2m and 45 m diameter) were used. The ratio of the downwind concentration at the receptor locations to the source concentration was calculated for each case and the results compared.

In neutral conditions, for both the small and the large source, the difference between all cases with exit velocity less than or equal to the friction velocity was less than one percent. The case with exit velocity of 200% of u_* differed by 2% and 6% for the 2m and 45m sources respectively.

It is in stable atmospheric conditions that the exit velocity has a greater effect. In stable conditions, an interesting trend was found. For an exit velocity of 1, 10 and 50 percent of the friction velocity, the predicted downwind concentration was almost identical in each case (varying by less than 1 percent). However, when the exit velocity was increased to equal the friction velocity, the predicted downwind concentration increased by a factor of ten.

From these results it can be concluded that, provided the exit velocity is less than the friction velocity, the exit velocity will have minimal effect on dispersion of the emissions in the region of interest.

5.1.2. Mass emission rate

The second parameter needed to characterise the source for modelling purposes is the strength or rate of emission of material from the source (units of mass per unit time). This parameter could not be determined from the sampling carried out (refer section 4.3). The value of this parameter therefore needed to be calculated theoretically or estimated. The *USEPA* have prepared a document recommending methods of estimating emission rates from a wide variety of sources and for a wide variety of applications (EPA, 1997a). Emissions from uncovered piles of waste are not included. The mass emission rate for the working face therefore needed to be assumed. For convenience the value of the total mass emission rate was assumed to be 1 g/s. Given that the size of the filling location is approximately 1000m^2, this mass emission rate equates to 1mg/s/m^2.

Since mass is conserved (in the absence of losses such as dry or wet deposition), the predicted concentrations downstream of the source simply scale in proportion to the mass emission rate. All predictions based on the assumed 1mg/s/m^2 rate will be refered to as 'normalised' values. When reliable information is obtained, these predictions can simply be scaled appropriately.

5.2. Source type specification

In dispersion models, sources can typically be modelled as point, area, line or volume sources. As the filling area at Bisasar Road landfill is generally about 1000 m^2 (See section 5.1), it should be modelled as an area source. Unfortunately with *ADMS™*, area sources cannot be modelled in combination with complex terrain. Therefore an alternative source description is required when incorporating complex terrain. The obvious choice would be a point source of equal area to that of the area source. Emissions from point and area sources are modelled with different algorithms and differences in predicted concentrations arise.

Analysis has been done to quantify the differences between modelling emissions from point and area sources as well as to investigate the effects of using multiple point sources whose total area equals that of a single area or point source. Simulations were run in flat terrain using an area source, single point source, four individual point sources and nine individual point sources.

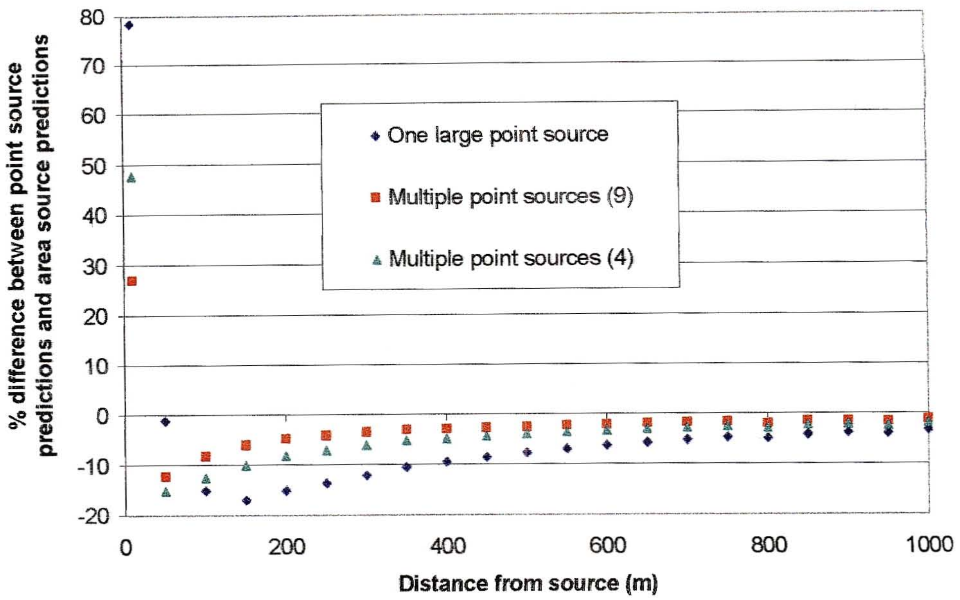


Figure 27: Comparison between modelling an area source versus a single or multiple point sources

Modelling the source as a single point source produced concentrations up to eighty percent higher than for an area source (Figure 27). Using four individual point sources reduced the difference in downwind concentrations to approximately fifty percent near the source. A larger improvement was noticed when nine individual point sources were used. The difference between downwind concentrations for an area source and nine point sources varied between four and 25 percent. At Bisasar Road, the separation between the landfill and receptors will always be greater than fifty metres. The difference in predicted concentrations at these and greater distances was less than twenty precent for all combinations of point and area sources.

Consistency of results has to be balanced with practicality. Therefore when simulations are run with complex terrain, area sources can be replaced by single point sources with the maximum difference in one hour average concentration remaining below twenty percent. Very little improvement was noticed in using multiple point sources as opposed to a single point source of equivalent area.

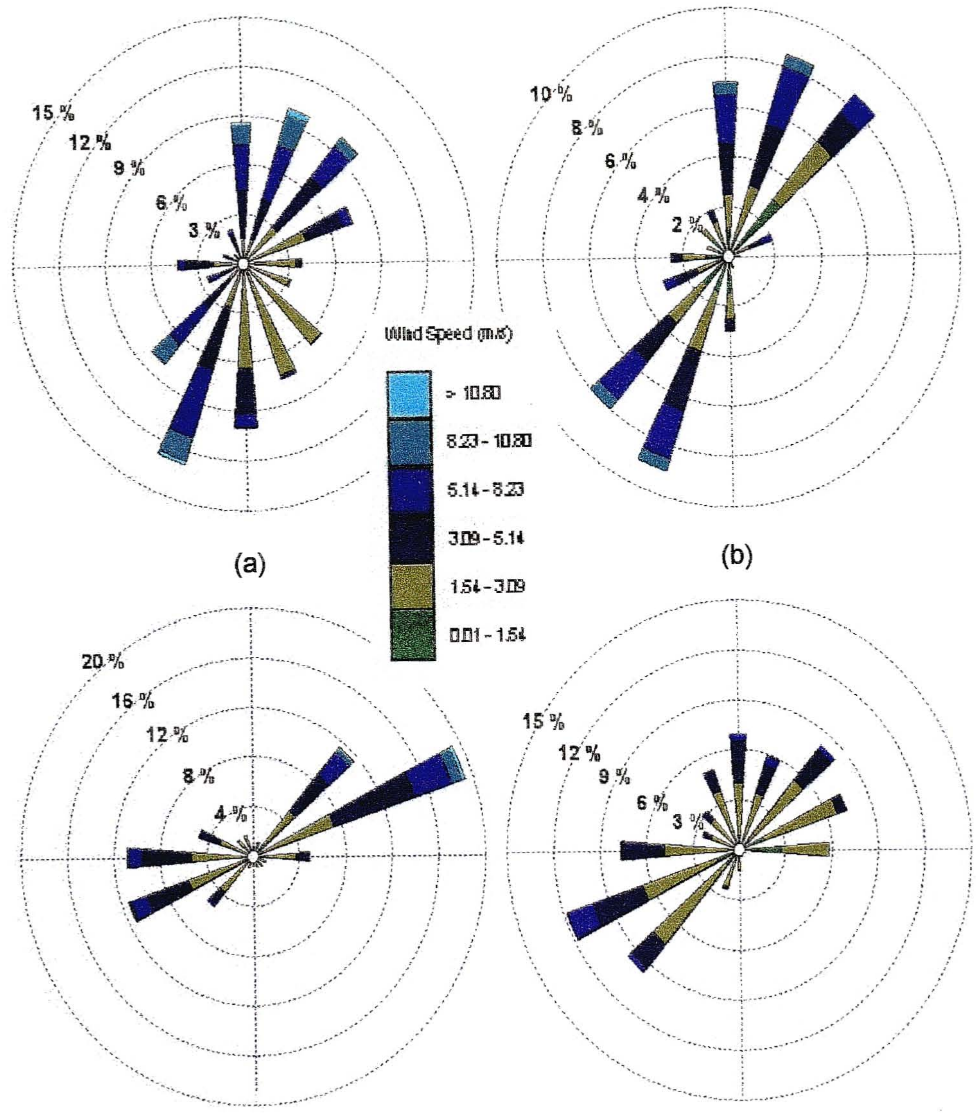
5.3. Comparison of dispersion models

The predicted concentrations of four models were compared against each other. The models used were *ADMS™*, *ISCST3*, *AERMOD* and *CALPUFF*.

The comparison between models was run for an area source of 1000m^2, with a total mass emission flux of 1 mg/s/m^2. The source was located near the middle of the landfill. Receptors were placed on a polar coordinate system at 15 degree intervals from fifty metres to 2450 metres from the source. One hour, three hour, 24 hour and annual averages were calculated. Various inconsistancies between the models were found and are highlighted in section 5.3.2.

5.3.1. Weather data

One year of weather data were used to do the comparisons. The data used were recorded from the on-site weather sation at Bisasar Road landfill. Ideally more than one year of historical data should be used. Unfortunately the weather station at Bisasar Road has only been operational for approximately two years. Portions of data during 2001 are inaccurate (temperature, humidity, solar radiation) due to technical difficulties with the power supply for the weather station. Wind speed and direction are not reliant on the same power supply, and this data are believed to be accurate. Data analysed for the year 2000 and the year 2001 produced similar wind roses. Therefore only data for the year 2000 were used for the model comparisons. Wind speed and direction is the most important parameter controlling the dispersion of pollutants in the boundary layer, therefore an assessment was made of the consistency of the wind data from Bisasar Road with other weather stations in the Durban area. The weather stations chosen for comparison were the Durban International Airport station (approximately 17 km south of Bisasar Road landfill) as well as the Mt. Edgecombe station (approximately 12 km north-north-east of Bisasar Road). The full two years of wind data from Bisasar Road were compared with data from Durban International and Mt Edgemcombe for the same time period (Data courtesy of the South African weather bureau). The wind rose for Durban International was also compared with fourteen years (1956 – 1970) of data from the same station. Figure 28 shows the four wind roses.



(a)

(b)

(c)

(d

Figure 28: Wind roses for (a) Durban International Airport (two years data) , (b) Durban International Airport (1956 - 1970), (c) Bisasar Road landfill (two years), and (d) Mt. Edgecombe (two years).

The most striking inconsistency between the wind roses, is the difference in 'calm' hours (wind speed < 1 m/s). For the fourteen years of data from the airport, 36 % of the hours recorded were calm. This compares to less than 1 % in the case of data recorded during 2000 and 2001 at the same station. The data from Mt Edgemcombe and Bisasar Road are more consistent regarding calm winds, with the fourteen years of data from the Ariport. Both Bisasar Road and Mt Edgecombe stations recorded 21 % calm winds.

Qualitatively, the wind roses appear inconsistent. The wind roses from the airport and Mt. Edgecombe have a greater spread across the sixteen different directions than the Bisasar Road wind rose. The Bisasar Road wind rose is more confined to wind blowing from a few particular directions. This may be due to the location of the weather station at Bisasar Road. The weather station is located on the side of a hill (See Figure 17). The local terrain near the weather station may be influencing the recorded wind pattern.

The wind roses are broadly consistent with regard to their distributions of wind speed. The percentages of time that the recorded wind speed was less than 5.4 m/s have been accumulated for each station (excluding calm hours). All three stations show this accumultive percentage to be approximtely 70%, with the maximum difference between Bisasar and Mt Edgecombe (67% compared with 76%). All three stations have the largest percentage of wind speeds recorded between 1.5 and 3.3 m/s.

In conclusion, despite some inconsistency, there appears to be enough consistency between the Bisasar Road data and other stations to support the use of this data in analysis.

5.3.2. Model setup

a) *ADMS™*

ADMS™ does not compute predictions during calm hours. For *ADMS™*, 'calm' conditions are defined as wind speeds less than 0.75 m/s. This definition of 'calm' differs between the various dispersion models and there is no way of altering this minimum wind speed. Concentration predictions will therefore be affected by this threshold.

b) *AERMOD*

AERMOD did not process the calm hours (defined in this case as wind speed < 0.5 m/s) or the missing hours. *AERMOD* has been formualted to set the concentration to zero for hours that are regarded as 'missing' or calm. This can lead to exagerated short term concentration predictions. All calm hours were therefore removed from the meteorological data set. *AERMOD* could then not be run in default mode due to the fact that the input data were no longer hourly sequential. *AERMOD* cannot be run in default mode with individual modules disabled (e.g. the sequential date checking algorithm). The only other default options that could not be incorporated were the algorithms for treating elevated terrain and stack-tip downwash. Neither of these are important in this particular comparison. *AERMOD* was run in both the 'Urban' and 'Rural' modes.

The *AERMOD* input file for this comparitive study is shown as an example of the *AERMOD* and *ISC3* style of keyword input in Appendix F.

c) *ISC3*

ISC3 uses Pasquill-Gifford stability classes to calculate the dispersion coefficients. These coefficients are normally calculated by a preprossessor such as PCRAMMET. PCRAMMET calculates the stabilities classes based on Turner (1964). The calculation requires the cloud cover, ceiling height and the solar radiation. The on-site weather station does not record cloud cover or ceiling height, but does record solar radiation. An alternative scheme for calculating the stability class using solar radation has been used for this comparison. The Solar radiation/delta-T method (*USEPA*, 1993) is based upon the method described by Turner (1964) but utilises the solar radiation to calculate the stability class during daytime hours and the vertical temperature gradient to calculate the stability class during nighttime hours. The vertical temperature gradient is not available, therefore the worst case scenario was assumed (i.e. stable conditions with negative temperature gradient).

The date checking algorithm cannot be disabled in *ISC3* therefore an hourly sequential meteorological data set needs to be input. This data set includes calm and missing hours. *ISC3* therefore needs to be run in default mode to include the calms processing routine. Default options in *ISC3* include the use of stack-tip downwash, buoyancy-induced dispersion, final plume rise (except for sources with building downwash), a routine for processing averages when calm winds occur, and default values for wind profile exponents and for the vertical potential temperature gradients. It is difficult to quantify the effects of running the model with these default options but it is reasonable to assume that they will have an effect on the predicted concentrations. *ISC3* has the same definition of 'calm' as *ADMS™*, but processes all hours with wind speeds greater than zero.

As with *AERMOD, ISC3* was also run in both 'Urban' and 'Rural' modes.

d) *CALPUFF*

CALPUFF is the most flexible model regarding the specification of meteorology input. Input can be in the simplest form (*ISC3* type) or can include complicated information describing the atmosphere in three dimensions. A large amount of input data is required to run *CALPUFF* to its full capability. This includes upper air data, which were not available for this study. Therefore, *CALPUFF* was run using the meteorology data prepared for *ISC3*.

5.3.3. Comparison between model prediction assuming flat terrain

Figure 29 shows the results of the comparative analysis assuming flat terrain. Each model predicted the average 1, 3, 24 hour, and annual average concentration at each receptor. The concentration at each receptor, and for each averaging time, was compared between the four models. The comparison was carried out by dividing the concentration at each receptor (as predicted by each model) by the concentration at the corresponding receptor for the other three models. The calculated ratios were then averaged for each set of model comparisons. The standard deviation, which represents the variability of ratios between receptors, was also calculated. Low standard deviation means that differences between model predictions are reasonably constant across the receptor grid.

For example, take the 1 hr average concentration at each receptor as predicted by *ADMS™*. The concentration at each receptor is divided by the *AERMOD* (Run in 'Rural' mode for this example) predicted concentration at the corresponding receptors. The average ratio of *ADMS™* to *AERMOD* concentration was then calculated for all receptors. The calculated average was 0.5 as shown by the first bar in Figure 29. The label on the x-axis represents *ADMS™* (Ad) divided by *AERMOD* (Ae) run in 'Rural' mode (R), forming 'AdAeR'. The same was done for all averaging times and between each of the four models.

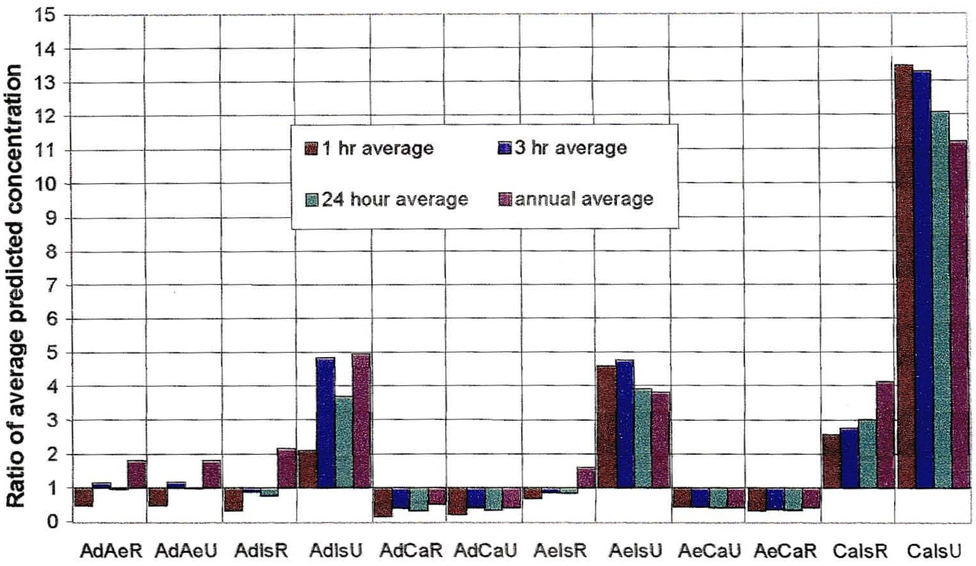


Figure 29: Results of comparitive analysis done between four dispersion models in flat terrain.

The urban module of *ISC3* appears to be under predicting by a factor of up to 13.5 relative to the other models as shown by the high values in Figure 29. Ratios of the *ADMS™*, *AERMOD* and *CALPUFF* normalised by *ISC3* range between two and fourteen. The *ISC3* under prediction was consistent across all averaging periods. These differences are due to *ISC3* calculating the dispersion coefficients (σ_y and σ_z) by characterising the state of the atmosphere using Pasquill stability coefficients. *ADMS™* and *AERMOD* do not use these stability coefficients. Interesting results were achieved in the *CALPUFF-ISC3* comparison. *CALPUFF* was run using *ISC3* weather data, which includes the stability coefficients. The large variation in predictions between these two models is not consistent with findings of the study conducted by the *USEPA* (*USEPA*, 1998b – see section 2.4.5 of this dissertation). These differences are difficult to explain based on the fact that *CALPUFF* was run using *ISC3* weather data and with similar default settings.

CALPUFF produced consistently higher average concentrations than both *ADMS™* and *AERMOD* for all averaging times. The standard deviation for both *ADMS™-CALPUFF* and *AERMOD -CALPUFF* ratios was relatively low. Concentrating on the 1-hr averages, the *ADMS™-CALPUFF* ratio ranged between 0.1 and 1.7, with an average of 0.2 and a standard deviation of 0.1.

Therefore, on average, *CALPUFF* consistently produces concentrations five times higher than *ADMS™*. The 1-hr *AERMOD-CALPUFF* ratio's range between 0.1 and 2.6, with an average of 0.4 and a standard deviation of 0.3. Only small differences were noticed between *CALPUFF* 'Urban' and 'Rural' modes when compared with *ADMS™* and *AERMOD*. This suggests that the results obtained from running *ISC3* in the 'Urban' mode are inconsistent with predictions from other modes and models. No previous work comparing *CALPUFF* with *AERMOD* or *ADMS™* was found.

Considering the 1-hr averaging time (rural setting), the *AERMOD-ISC3* ratios range between 0.4 and 3.7, with an average of 0.7. Similar results were obtained comparing *ADMS™* with *ISC3*. These differences seem to be due to the more advanced algorithms used in *AERMOD* and *ADMS™* to characterise the turbulent atmospheric boundary layer. These results are consistent with those reported by *USEPA* (1999).

The most important part of this investigation relates to the comparison between *AERMOD* and *ADMS™*, which are so called 'new generation' models. As with *CALPUFF*, *AERMOD* predictions in 'Urban' and 'Rural' were similar. The *ADMS™* 1-hr predicted concentrations are half of the *AERMOD* 1-hr concentrations. This is inconsistent with the results reported by *CERC* (2000a) for the Oklahoma meteorological data set (*ADMS™-AERMOD* = 1.4) but consistent with results using the Pittsburgh data set (*ADMS™-AERMOD* = 0.69). *CERC* (2000a) state that in general *ADMS™* predicts lower concentrations for releases at 20m or less, with the two models predicting similar concentrations for ground level sources.

ISC3 under-predicts concentration relative to *ADMS™*, *AERMOD* and *CALPUFF*. Of *ADMS™*, *AERMOD* and *CALPUFF*, *CALPUFF* consistently over predicts relative to *ADMS™* and *AERMOD*. *CALPUFF* weather data input is complex and using *ISC3* type data only allows *CALPUFF* to characterise the turbulent boundary layer using outdated stability categories. *ADMS™* and *AERMOD* produced similar results for all averaging periods.

5.3.4. Comparison in complex terrain

CTDM was designed specifically for use in complex terrain. However, its application is limited in that individual features of the terrain need to be identified and simplified into equivalent ellipsoid shapes. If multiple features are modelled, the effect of each feature on plume path or dispersion is not carried forward to other terrain features. *CALPUFF* operates in a similar way except that the effects of multiple terrain features are taken into account across the entire domain.

This method of modelling the effects of complex terrain has been superseded. More advanced methods using Digital Elevation Models (DEM's) are now used in models such as *ADMS™* and *AERMOD*. It was not possible to run *AERMOD* in complex terrain due to the required format of *AERMOD's* terrain data input. The required format is not consistent with terrain available for the case study site. Therefore only *ADMS™* was run incorporating terrain. The same input was used for this analysis as was used in the analysis assuming flat terrain except a terrain file was added in the input file.

ADMS™ predicts the average concentration in complex terrain to be approximately 68 % of the concentration assuming flat terrain in the region of interest. This is consistent for 1-hr, 3-hr and 24-hr averaging periods. Despite the average concentration being 32% lower, the 1hr maximum concentration predicted is 25% higher in complex terrain than flat terrain (1-hr averaging period). This may be due to the source being located in a region of relatively low flow compared with the mean wind speed. Dispersion could be less rapid in this region creating higher concentration predictions than if flat terrain were assumed.

These results are inconsistent with the results reported by *CERC* (2000b). In that study for the two sources and two terrain features modelled, *ADMS™* produced higher concentration in complex terrain than in flat terrain (up to a ratio of 1.4). The sources used in those two simulations were high stacks with buoyant effluent, so it is difficult to draw comparisons between these results and those obtained in this investigation.

The inconsistent results show that there is limited generality between results of individual studies. The scenarios modelled by CERC (2000b) used individual computer generated obstructions around which the flow was modelled and concentration calculated. This is in contrast to the site-specific data used in the case study simulations conducted for this investigation. The results obtained emphasise the need to incorporate terrain effects for accurate predictions.

Figure 30 and Figure 31 show the spatial variation of the predicted normalised dilution for a 1-hr averaging time. The normalised dilution is defined as the ratio of source concentration (C_0) to receptor concentration (C_m).

The effects of complex terrain on predicted dilution can be seen in Figure 30 and Figure 31. The colour scale used is the same for each plot. Qualitatively it can be seen that in the region of interest, the predicted dilution between the landfill and receptors in the area surrounding the landfill is greater in complex terrain. The opposite is true near the source as pointed out already. The most noticeable predicted impact of the terrain is along the eastern boundary of the landfill and in the surrounding areas northeast of the landfill. Land northeast of the landfill is dominated by industry so this area is of little interest in this study. However, residences dominate east of the landfill. The difference in predictions between assuming flat and complex terrain is noticeable in this area. If the land were assumed to be flat, the model predicts similar magnitudes of dilution in Asherville (and beyond) as in Clare Estate (See Figure 31). Based on the spatial distribution of complaints, and the fact that zero complaints have been received in five years from Asherville, the results shown in Figure 31 are inconsistent. Referring to Figure 30, the dilution between the source and receptors east of the landfill is approximately 10 times greater when complex terrain is incorporated in the modelling. The pattern of contours in Figure 30 is more consistent with the spatial distribution of complaints than if flat terrain is assumed.

The results shown in Figure 30 and Figure 31 corroborate the conclusion that it is important to incorporate terrain effects for accurate predictions.

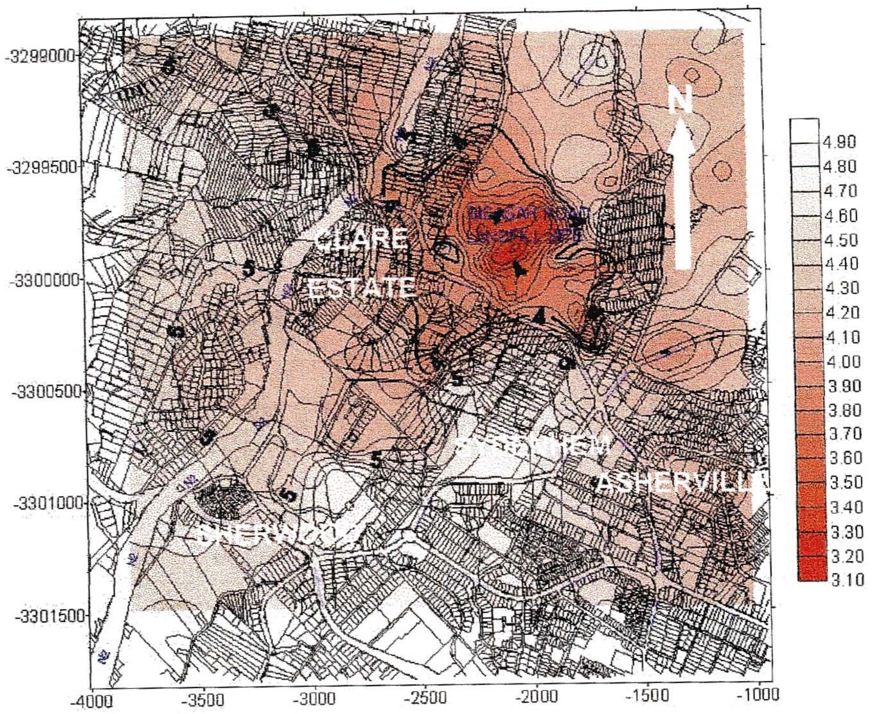


Figure 30: Predicted normalised dilution assuming Complex terrain by *ADMS*™ (1-hr averaging period)

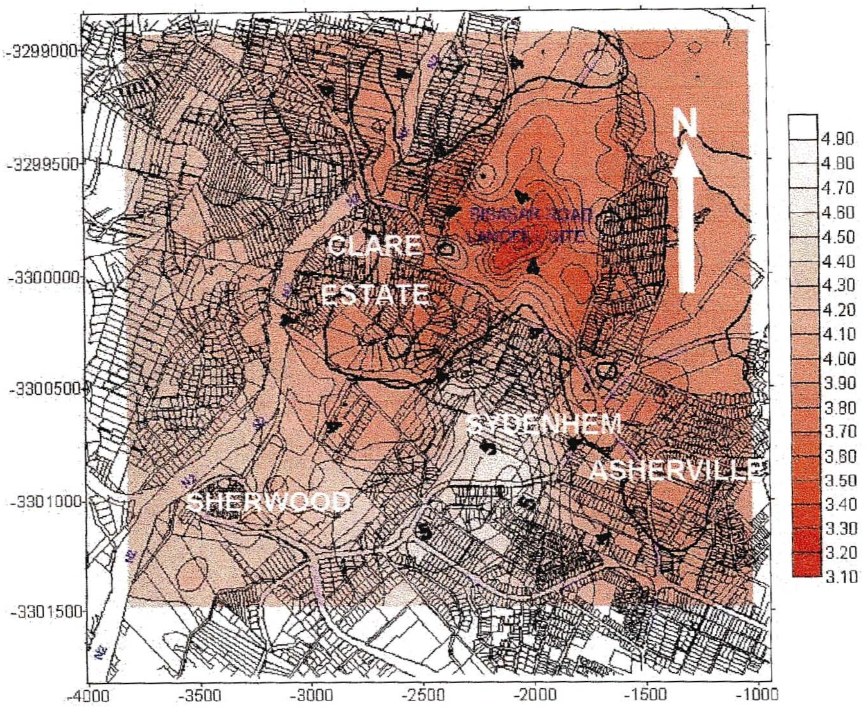


Figure 31: Predicted normalised concentration assuming flat terrain by *ADMS*™ (1-hr averaging period)

5.4. Use of dispersion modelling to analyse complaints

One method of validating results of dispersion model predictions is to run simulations for times and conditions when complaints were lodged. This excercise can also serve as a check that complaints due to odour were actually due to the landfill and not other sources.

The complaints log was analysed and days on which multiple complaints were logged were selected. Meteorological conditions at the times of the complaints were then taken from the onsite weather station records and simulations run. Complex terrain effects were included therefore the working face had to be modelled as a point source. As per section 5.1.2, a total mass emission flux of 1 mg/s/m^2 was used.

Eleven complaint days were analysed and the predicted concentration at the times of the complaints plotted in terms of dilution as in Figure 30 and Figure 31.

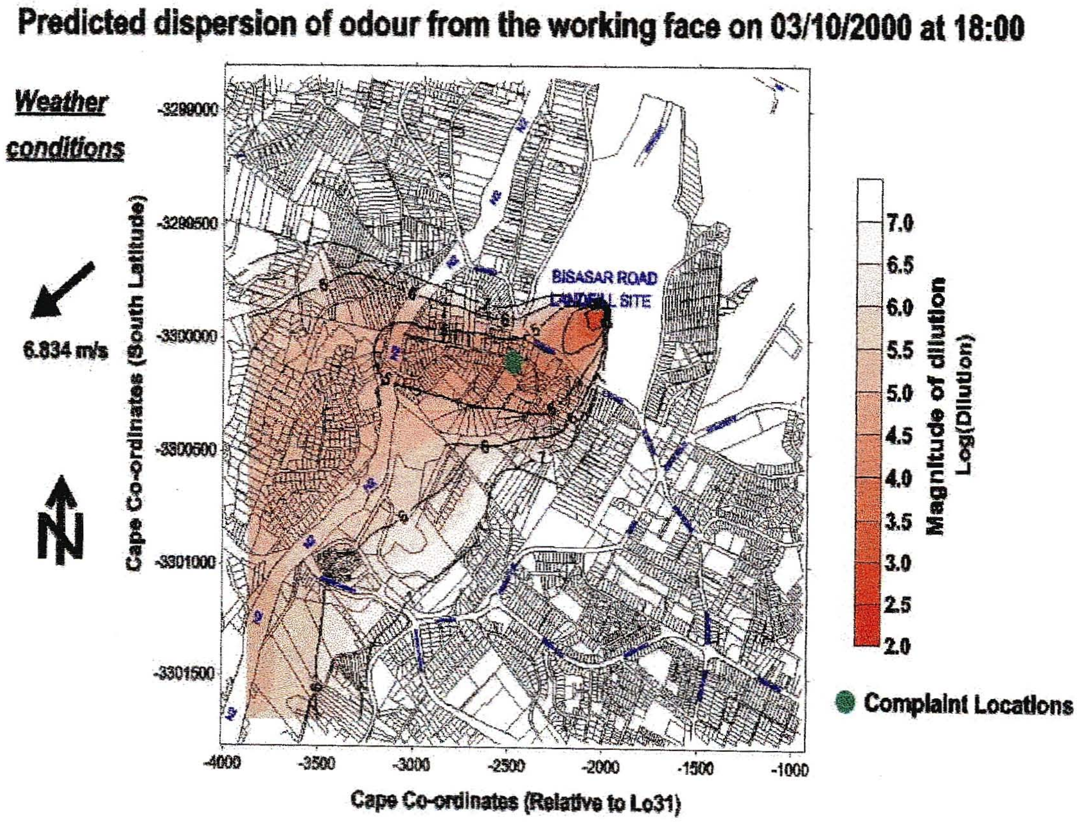


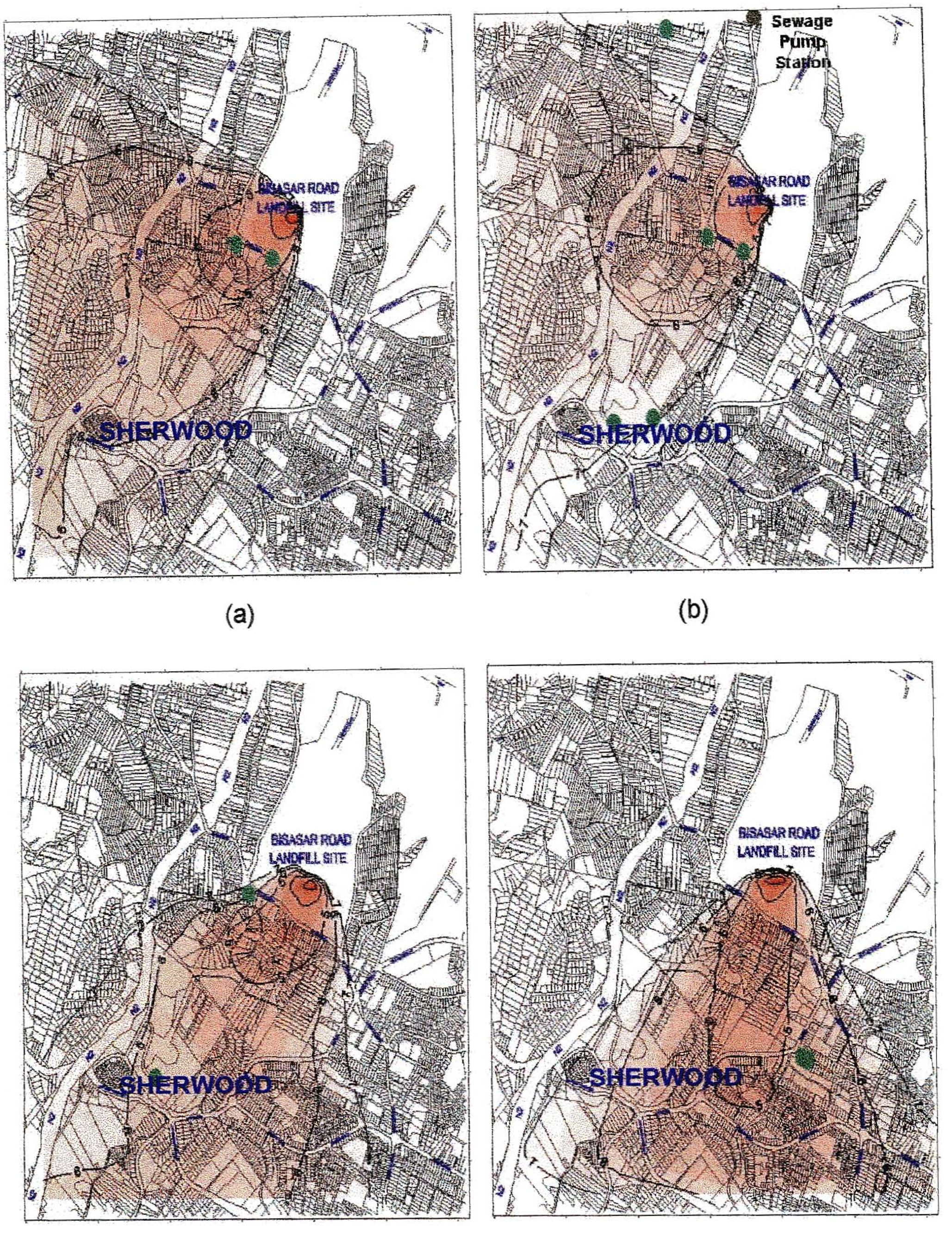
Figure 32: Predicted normalised dilution from source for a complaint logged at 18:00 on the 3rd October 2000

Figure 32 shows an example result of the predicted dilution from the working face at the time of a complaint. Also, shown in Figure 32 is the location of the complaint and the wind speed and direction at the time of the complaint. In this particular case the complaint was logged from two residents living close to the landfill. From Figure 32, the predicted dilution between the source and the complaint location is approximately $10^{4.5}$ or 32 000 ou/m^3. If the concentration at the receptor is assumed to have been at the odour detection threshold (1ou/m^3), then the approximate source concentration is 32 000 ou/m^3.

Further analysis has been done for ten other multiple complaint days. Figure 33 (a) –(d) shows the results for four of the cases analysed. The scale in these four plots is the same as in Figure 32. Figure 33 (a) shows two complaints logged from near the landfill in Clare Road. The complainants in this case were two residents who generate frequent complaints. The time of the complaints was 15:30 in the afternoon. As for the case shown in Figure 32, the predicted dilution is approximately 32000 implying a source strength of greater than or equal to 32 000ou/m^3. Figure 33 (b) shows an occasion when five complaints were logged in close succession. Two complaints were logged from near the landfill in Clare road; two were logged from approximately 2 kilometres away in Sherwood, and the fifth northwest of the site. Again, assuming that the receptor concentration is at the odour detection threshold of 1ou/m^3, the estimated source strength based on the complaint locations closest to the site is approximately 100 000, whereas the three farther away are in excess of this.

It is difficult to predict whether these three locations are detecting odour from the landfill or from another source. Looking qualitatively at Figure 33 (b), it is possible that the plume is affecting residents in Sherwood, while the complainant northwest of the landfill could have been affected by a source other than the landfill. There is a sewage pump station at the bottom of Kennedy Road (shown in Figure 33 (b)), which could be affecting the residents in this area. This speculation is based on the relative locations of the pump station and receptor as well as the direction of the wind.

Figure 33 (c) shows two complaints logged from locations approximately 1500m apart. The wind speed was approximately 7 m/s at the time of the complaints (13:30). Despite the difference in distance between the locations, the predicted dilution to both locations is approximately 1 000 000. This result illustrates the difficulty in predicting when residents are annoyed enough to complain.



(a) (b)

(c) (d)

Figure 33: Predicted normalised dilution between a source on the landfill and receptors for times of complaints logged.

Figure 33(d) shows model predictions at the time of two complaints logged in the early evening on 24th March 2001 when the wind speed was approximately 3 m/s. The predicted dilution to the complainant locations was approximately 180 000. This number is low taking into account the distance between the receptors and the source. This could be due to the relative lack of dispersion during early evening.

The remaining six analyses done on occasions of multiple complaints showed similar results to those included here. The complaint recorded and shown in Figure 33 (b) from west of the site, was the only complaint analysed that could have possibly come from another source.

This investigation of calculating the dilution between source and receptor for times of complaints was taken a step further. By running simulations to determine the dilution between source and receptors for a large number of complaints, the dilution at which complaints are likely or a 'threshold dilution' value could be calculated. In total, fifty complaint occasions have been analysed. Eight out of these fifty complaints were recorded from an area further than two kilometres from the site.. The predicted dilution to the locations of these eight complaints have therefore been separated from the much lower predicted dilution values for receptors closer to the site.

The mean predicted dilution to the eight complaint receptors further than two kilometres away is 4 400 000. The standard deviation (3 500 000) is roughly equal to the mean. The variability could be due to the relatively low number of number of data points. More complaints need to be analysed to determine a more precise value for the mean dilution.

Forty-two complaints were analysed in total from locations within two kilometres of the site. The mean predicted dilution between the site and these receptors was 155 000 with a standard deviation of 75 000. Based on the assumption that complaints are logged when the receptor concentration is at the odour detection threshold of 1 ou/m^3, this implies that provided the source concentration is kept below 155 000 ou/m^3, no complaints should occur. This value could be considered as a 'complaint threshold value' (CTV). Note however that this value is also based on an arbitrary emission rate of 1mg/s/m^2.

Based on the results presented in Figure 32 and Figure 33, *ADMS*™ consistently predicts similar dilution ratios for all the complaint locations analysed. The 'dilution threshold' was calculated as 155 000 for locations within two kilometres of the site and 4 400 000 for locations farther away although this value was calculated with less certainty.

CHAPTER 6

6. INTEGRATED ODOUR MANAGEMENT SYSTEM

Chapter six discusses the details of the 'Odour Management System' or OMS. The OMS was developed by writing original software applications to interface existing available software. Components of the OMS are discussed. The OMS is run on a "real-time" basis (every ten minutes) to produce predictions of dilution between source and receptors.

One of the main objectives of this research was to formulate and put in practice an 'Odour management System' (*OMS*). The aim was to produce real-time odour concentration predictions to enable the landfill operator to implement mitigation strategies to minimise the off-site odour impacts. Possible mitigation strategies have already been reviewed and are further discussed in chapter 7.

In this case, the definition of 'real-time' is the shortest time period necessary to run the *OMS* in each loop. The weather station can store data on time intervals as short as 1 minute. In this case the shortest time interval between predictions is limited by the software application cycle time.

As seen in chapter 5, a number of input parameters are necessary to run a dispersion model. In the case of real-time modelling, only two parameters (or groups of parameters) are dynamic (changing from run to run) and the rest are static. The one obvious dynamic group of parameters is the weather data for each run. The second parameter that may vary is the location of the working face. It will be up to the user of the *OMS* to change the location of the working face depending on where the filling will occur on any given day. A user interface to implement this is integrated into the *OMS*.

Note that the system was designed around the use of standard software packages: *ADMS*™ for the modelling and *SURFER*™ (Golden Software) for the graphics output. Several custom written software modules were developed to integrate the various components and automate the periodic updating of the predictions.

Figure 34 shows the various components of the *OMS*.

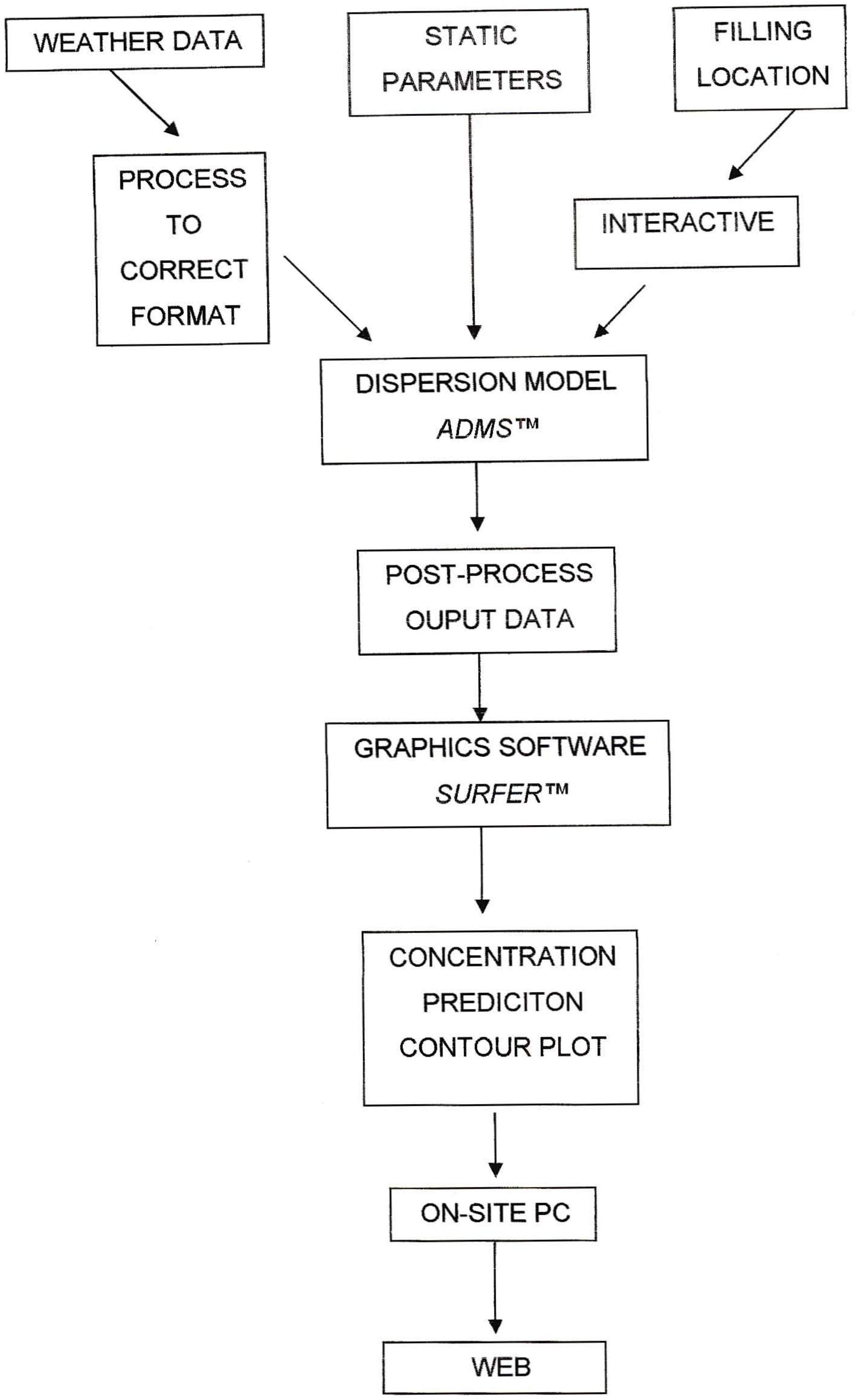


Figure 34: Flow chart showing interaction of components of *OMS*

Ultimately, it is hoped that the plots produced will be available on the Internet for viewing. The optimum situation would be for the public to be able to view the plots on a real-time basis. What may be more likely, is that the plots will be available for viewing only on the Durban Metro Water Services Intranet. This is yet to be undertaken.

The following is a review of each component of the management system.

6.1. Dynamic input data

6.1.1. Weather data

Weather data are captured from the on-site weather station. The weather station (and associated interface software) logs weather data comprising wind speed (m/s), wind direction, temperature (°C), relative humidity (%), pressure (Mb), solar radiation (W/m^2) and rainfall (mm). A recording of current conditions is logged every 20 seconds. A time average is recorded in an ASCII file on the air-monitoring computer. The time interval between time-averaged recordings can be varied and was set at ten minutes for the present investigation.

The data from the weather station are logged in one file that is continuously updated. For each run of the *OMS*, only the latest line of weather data is of interest. The format of the data in the ASCII file is not recognised by *ADMS*™, so the data has to be pre-processed into a compatible format (See section 6.4.3).

6.1.2. Filling location

The location of the filling area may change on a daily basis. Therefore, the user must be able to change the location in *ADMS*™. A contour map of the landfill has been constructed in *SURFER*™, which is opened on a prompt from the user. The map can be digitised in *SURFER*™ allowing the user to identify the location of the working face using a pointing device (e.g. mouse) and the co-ordinates saved to an ASCII file. The co-ordinates are then written to the *ADMS*™ input file, which is also an ASCII file.

6.2. Static input data

Various options are available in *ADMS™*, many of which are not applicable for this system. It is also only possible to run certain options in combination, which limits the scope in some cases. Table 7 shows the settings used for this case study.

Table 7: *ADMS™* settings for *OMS*

Terrain	Complex terrain used
Buildings	No buildings modelled
Fluctuations	Can't be modelled with complex terrain
Source description	Single individual point source
Source diameter (m)	33.85
Emission rate (m^3/s)	0.01
Emission concentration – total (g/s)	1
Emission temperature (°C)	23
Receptors	Gridded system with receptors up to 2000m from the landfill. Additional specific receptors.
Output	1-hr, Short-term average
Surface roughness - z_0 (m)	0.1

6.3. Existing software

6.3.1. Dispersion model (*ADMS™*):

A description of *ADMS™* has been given in 2.4.4 and the settings are shown in Table 7. Once *ADMS™* has run, two output files are created, one containing the concentration at each gridded receptor point and the other at specified receptors. This ASCII file needs to be processed into a format that *SURFER™* is familiar with.

6.3.2. Graphics software (*SURFER™*):

SURFER™ is a contour and 3D surface plotting software package produced by *Golden Software*. *SURFER™* takes columns of data in x, y, z format (x and y being co-ordinates and z being a variable such as height or concentration), interpolates the data and then creates a plot. *SURFER*™ also has it's own scripting program, so that tasks can be automated. A script has been written to create contour plots of concentration from the processed *ADMS*™ output data.

6.4. Custom software the *OMS*

6.4.1. Batch file

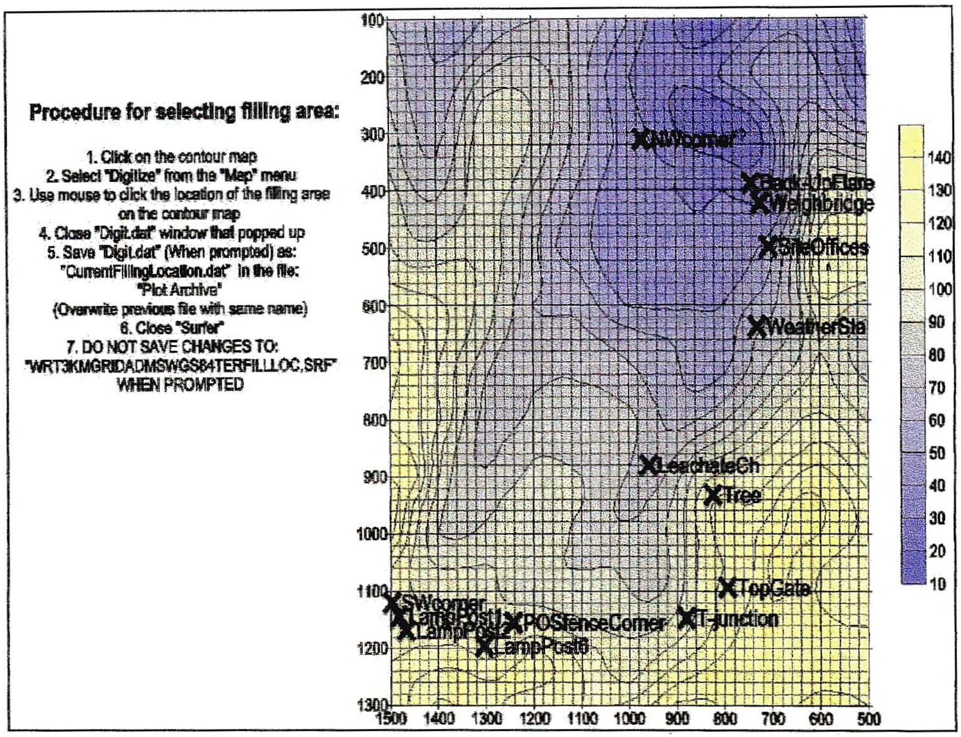
A batch file has been written in order to execute the various individual programs that comprise the *OMS*. The *WINDOWS*™ task scheduler runs this batch file at specified time intervals. Before *ADMS*™ can be run, the weather data needs to be processed and then the location of the filling area needs to be updated. A check is then run to see if the conditions are calm by searching for a file named '*ADMS*weathercalm.met'. If this file exists then the batch file exits. If the file does not exist, then the batch file continues and *ADMS*™ runs. Because conditions may be calm on one run and not on the next, the '*ADMS*weathercalm' file needs to be deleted at the beginning of the batch file. Figure 35 shows the pseudo code for the batch file (The code for the batch file can be found in Appendix J.1).

```
1. Delete the ADMSweathercalm.met' file from the previous run
2. Delete the file 'omsirec' from the previous run so that that new
     'omsirec.gst' can be renamed
3. Execute weather processing program
4. Update the filling location in the ADMS™ input file
5. Check to see if the conditions are calm, and if so exit the batch file
6. Run ADMS™
7. Rename the file 'omsirec.gst' as 'omsirec.dat, as an application on the
     computer already uses a file with the .gst extension'
8. Process ADMS™ output to import into SURFER™
9. Run SURFER™ script to plot the final graphic
10. Batch file is terminated
```

Figure 35: Batch file to run *OMS*

6.4.2. Filling location

A script has been written to open a graphic of the landfill in *SURFER™* on command from the user. Instructions or how to go about changing the location are also shown on the side of the landfill contour map (See Figure 36). The procedure involves identifying the location of the new working face and "digitising" the map. The co-ordinates of the location are saved.



Procedure for selecting filling area:

1. Click on the contour map
2. Select "Digitize" from the "Map" menu
3. Use mouse to click the location of the filling area on the contour map
4. Close "Digit.dat" window that popped up
5. Save "Digit.dat" (When prompted) as: "CurrentFillingLocation.dat" in the file: "Plot Archive" (Overwrite previous file with same name)
6. Close "Surfer"
7. DO NOT SAVE CHANGES TO: "WRT3KMGRIDADMSWGS84TERFILLLOC.SRF" WHEN PROMPTED

Figure 36: Contour map and procedure for obtaining co-ordinates of the filling area

On each loop of the *OMS*, the file containing the filling location is opened and the *ADMS™* input file is updated with the new location (See Appendix J.4 for details).

6.4.3. Processing of weather data

A program has been written in Visual Basic in order to process the weather data into a format suitable for use in *ADMS™*. The weather data is recorded from the weather station on successive lines of a data file. For each run of the *OMS*, only the last line of data in the file is required (See Appendix J.2).

In total, eight parameters are included in the weather data. These include wind speed (m/s), wind direction, standard deviation of the wind direction, temperature (°C), relative humidity (%), incoming solar radiation (W/m^2), rainfall (mm) and sensible heat flux (W/m^2). The date and time of the line of weather data is not used directly by *ADMS™*, but are used for display on the graphic.

Seven of the eight required parameters are recorded directly by the weather station. The only parameter that is not recorded is the sensible heat flux. This has to be calculated. The heat flux is obtained by following Holtslag & Van Ulden (1983).

The method uses certain parameters that are not recorded by the weather station (e.g. albedo and cloud cover). The albedo is a measure of the amount of reflection of heat at the ground surface. This was assumed to be 0.23 for this application which is the recommended value for a grass covered surface. Cloud cover is also required. The cloud cover is assumed to be 1 (100%) if the rainfall value is greater than zero and 0.2 (20%) for all other cases.

Following Holtslag & Van Ulden (1983), firstly the net radiation is calculated using:

$$Q^* = \frac{(1-r)*K^+ + c_1 * T^6 + c_2 N - \sigma * T^4}{1+c_3} \qquad (6.1)$$

where:

Q^* = net radiation
r = albedo
K^+ = incoming solar radiation
C_1 = 5.31 X 10^{-13}
T = temperature (K)
σ = Stefan-Boltzmann constant = 5.67 X 10^{-8}
N = total cloud cover
C_2 = 60
C_3 = 0.12

The sensible heat flux then follows from:

$$H = \frac{(1-\alpha)+\left(\frac{\gamma}{s}\right)}{1+\left(\frac{\gamma}{s}\right)}(Q^{*}-G)-\beta \tag{6.2}$$

where:

α and β are empirical parameters that depend on the surface moisture and were assumed to be unity and twenty respectively.

G = 0.1*Q*

The parameter, γ/s is based on values reported by Holtslag & Van Ulden (1983). These values for γ/s depend on temperature. A polynomial was fitted to the data by least squares to yield:

$$\frac{\gamma}{s} = 0.013*T^{2}-0.0802*T+1.4965 \tag{6.3}$$

where:

T = Temperature (K)

6.4.4. Post-processing of *ADMS*™ output

ADMS™ has been set-up to output two files. The first file contains values of predicted concentration for receptors on an evenly spaced grid across the entire terrain area. (The regions within 100 m of the boundary are excluded since *ADMS*™ does not compute predictions within 100m of the terrain file boundaries). The output is not in a format compatible with the graphics package, *SURFER*™. The output therefore needs to be processed. The output file from *ADMS*™ contains eight columns of data in a comma-delimited file. Only three of the eight columns of data are required, the x and y co-ordinates of the receptor and the concentration at each receptor. As the source emission rate and concentration is not known, an alternative form of expressing the data is used. Instead of plotting concentration directly (e.g. g/m^3), the dilution between source and receptor is calculated and shown on a log scale. A file containing the x and y co-ordinates as well as the log of the dilution is then written to a new, space delimited file. *SURFER™* then uses this new file to plot concentration contours.

A second file is output by *ADMS™* for each run. *ADMS™* has been set up to also output the concentrations at specific locations of interest. The locations of all the residences that have complained to the landfill more than once have been added. This second output file is in the same form as the first one with an extra column of data containing a receptor name. The same procedure is followed as for the gridded receptor concentrations to determine the log of the dilution at each specified receptor. The value of dilution is then compared against a specified threshold, and if less than this value (i.e. complaint is possible), then the x, y co-ordinate as well as the receptor name is written out to a new space-delimited file. *SURFER™* is programmed to use this file to plot locations of possible complaints.

6.4.5. Plotting graphics

SURFER™ (Version 6) is being used to plot the predicted dilution between source and receptor. *SURFER™* also has a scripting program, which allows the user to automate processes in *SURFER™*. A scripting program has been written to generate the required graphic outputs.

SURFER™ first creates a grid file from which to generate a contour plot. In generating the grid file, *SURFER™* interpolates the data in the original file to generate a smoothed version of the data. The user can select between different interpolation schemes. *SURFER™* grids the first output file created by *ADMS™*. *SURFER™* then opens the second *ADMS™* output file and checks if the file is blank or not. If the file is blank, then no individually specified receptor locations have concentrations greater than the threshold. If the file is not blank then a different subroutine within the script is run. The two subroutines are the same except for extra code added to the 'Threshold exceeded' subroutine, which plots the locations where the threshold has been exceeded.

The plot contains three layers including a contour map of predicted dilution and locations of specific exceedance (If applicable) as described above. The base layer is a cadastral map of the area around the landfill. The map consists of road reserves and cadastral lines. Road names for the more important roads are also shown. Figure 37 shows a typical plot produced by the *OMS*.

The header of the plot contains text as well as the date and time applicable to the weather data used. These parameters are read from files that are written out during the weather data processing.

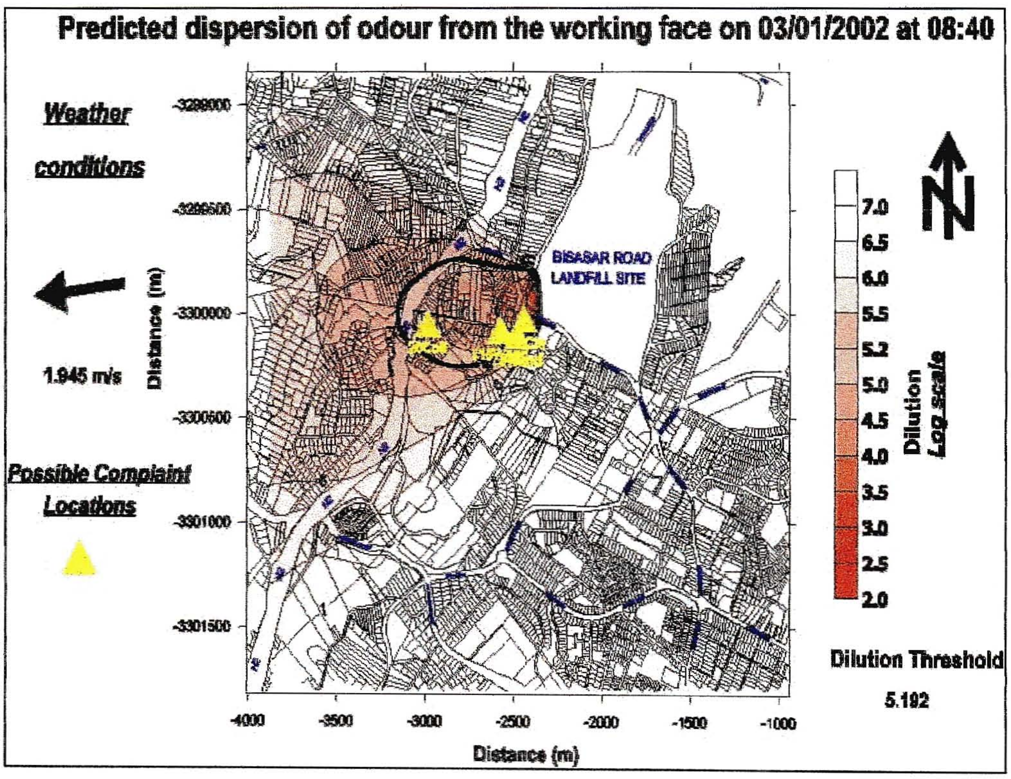


Figure 37: Typical plot produced by the Odour Management System.

Shown on the left of the map, is the wind speed and direction for the particular run. The arrow depicting the direction of the wind is rotated clockwise relative to the direction of north as shown.

The scale bar shows the scale used for the colour scheme in the contour plot. Shown below the scale bar is the approximate threshold value as calculated in section 5.4.

The plot is then saved with the date and time of the plot as the filename. The plot is saved in the proprietary *SURFER™* format (.SRF) file and exported as a .JPEG file. The *SURFER™* files are approximately 2 megabytes (MB) in size, so they are deleted every week to save space on the hard drive of the computer.

Extra code has been added to the 'Exceeded threshold' subroutine, to add the locations of the possible complaints for a particular run. The locations are plotted by a yellow triangle with the name of the receptor as it appeared in the dispersion model information. Each receptor name was based on the address of the residence.

6.5. Summary

In this chapter, the software elements that comprise the OMS that has been implemented at Bisasar road landfill are described.

CHAPTER 7

7. ODOUR MITIGATION STRATEGIES

Control or minimisation of odour from large area sources such as landfills is difficult. Chapter seven reviews the various operations that can assist in minimising odour. However well a landfill is operated, odour may still be a problem and additional odour control strategies may be needed. This chapter discusses various control measures and experiments carried out at Bisasar Road to determine the most applicable form of odour control. The original odour control system and the new system at Bisasar Road landfill are discussed. Two operational strategies were investigated using ADMS™. The first involves the pro-active use of the OMS to predict the location to fill on the landfill given a set of conditions to minimise the off-site odour impact. The second method involves the continuous availability of two working faces, with the cell causing the least off-site impact for given conditions, used as the filling location.

7.1. Odour control at Bisasar Road landfill

Operational procedures at a landfill can play a major role in odour minimisation. Daily operations at Bisasar road, which help to minimise the odour emanating from the landfill, are:

a) A gas collection/transportation system is in place at the North end of the landfill,
b) Operation of a transfer station at the North side of the landfill helps to minimise the size of the working area which is closer to the south/eastern boundary of the site,
c) The daily covering of waste prior to closure of the landfill,
d) The leachate collection and transportation has minimal exposure to the atmosphere.

One area of operational strategy of particular relevance is the covering of fresh waste. Cover of recently placed material is a simple and effective way of minimising odour from the working face. The following are important factors to consider regarding cover material (e.g. Gendebien et al, 1992):

a) Cover should be applied at least once a day (usually at the end of each working day) but it may be beneficial to cover more than once a day. For instance cover could be applied before lunch at midday and then again at the end of the working day.

b) Cover material should have an average particle size that is small enough to create an effective barrier against odour emissions escaping into the atmosphere. For instance, builder's rubble or demolition material is typically not good enough to use as cover material as it has a high porosity.

c) The depth of cover should also be substantial enough to minimise escape to the atmosphere. Regulations around the world (USA in particular) require a minimum of 6 inches (150 mm) of cover.

Covering the fresh waste once a day may not be sufficient to minimise off-site impacts of odour. Hence the use of supplementary control measures. The most common method of odour control is the use of chemicals either applied to the waste directly or sprayed into the air to either mask the odour with a more pleasant odour or alter the chemical state of the odorants.

7.2. Testing to determine most effective chemical

Initially five different possible odour counteractants were tested. Following relative success another six were tested. Table 8 shows the eleven chemicals that were tested.

The portable odour monitor as well as human assessors were used to determine the effect of spraying different counteractants onto piles of fresh waste.

The odour monitor does not distinguish between pleasant and unpleasant odours. It simply displays a reading representing the intensity of electrical and thermal changes that the gas causes on an internal sensor. Therefore counteractants that have their own smell will tend to produce high readings following application despite the fact that the smell may be more pleasant. Odour monitor readings were therefore assessed in the context of the type of counteractant being tested.

Table 8: Odour control chemicals tested at Bisasar Road landfill

Distributor	Product name	Product type
Vaporair	Mist Air	Chemical
Eco-sol	Odoreat	Chemical
Chempro	Ecosorb	Chemical
FPO tech.	Envirocure 100	Chemical
Emrosa	EM	Biological
Triad Ind.	Nu-Air	Chemical
Odorchem	Ona	Chemical
Nu-Tech environ.	Phantom 4	Chemical
Epoleon	N-11	Chemical
Vitacure CC	Ecolo	Chemical
Alliance Peroxide	H_2O_2	Chemical

Unpleasant smelling waste was collected from the working face and placed in the incinerator building. Individual piles of waste were constructed (300mm x 300mm x 150mm thick). Test solutions were made up for different concentrations of each counteractant. An odour monitor reading as well as the subjective opinion of a human assessor was recorded for each pile before application of the counteractants. The piles were then sprayed one at a time and readings taken and opinions noted at various time intervals following application.

Plate 5 shows an assessment being made of the smell emanating from one of the test waste piles.

Of the eleven counteractants tested, *ECOLO* and *ECOSORB* appeared to be the most effective based on these subjective tests. Details of the various agents tested and the results of the tests have been reported in Laister (2001b).

Plate 5: Testing countercatants

7.3. Direct treatment of waste with odour counteractants

It was decided that testing would be conducted at the landfill to determine the best method of applying odour control chemicals.

The optimum method of treating any odour problem is to treat the source. An experiment was conducted to test the effect of spraying chemicals directly onto the working face. Treating the working face on a permanent basis could be done either by using a water tanker, manual-spraying units or by high-pressure pump fitted to a vehicle.

The use of a water tanker was tested first. Prior to conducting the experiment, a walkover survey was conducted with the odour monitor to quantify the odour levels prior to testing. The waste was sprayed using the 15 000-L water tanker. The solution used to spray the waste was safe to handle and breathe, therefore operations at the working face continued during the spraying. The water tanker was capable of driving onto the working face (including uncompacted waste) and getting close enough to all the edges so that the side slopes were also treated.

Unfortunately this experiment failed in terms of assessing the long-term effect of this type of application. Bisasar Road processes a large volume of waste which meant that there was very little time during which the waste pile was static. It was intended that the walkover survey with the odour monitor be repeated after the initial chemical application. With continuous operation at the working face and 500 tons of waste arriving each hour, there was limited time to assess the effect of the counteractant. However, a less intense and more pleasant odour was subjectively noted following spraying.

The water tanker deposits 15 000-L into the landfill body every time it passes over the working face. The high flow rate of the spraying was considered too costly. Furthermore it introduced excessive amounts of liquid into the landfill body.

Following the limited success of using the water tanker, it was decided to try applying counteractant with hand-held spray units (Hudson knap-sacs). The knap-sacs are 17 litres in volume. Spraying commenced approximately one hour after having received a complaint of odour emanating from the landfill by a neighbouring resident. Three workers were equipped with knap-sacs and part of the working face sprayed. The idea of having solution sprayed directly onto the waste continuously is a good one, but is very labour intensive to do manually. Because of the size of the working face and the quantity of waste being handled, it would be necessary to treat the surface continuously. Manual spraying units would require approximately 5 workers on a permanent basis and the tanks would require refilling approximately every 30 minutes. This was considered impractical.

A better option would be to fit a pump system onto a vehicle (e.g. compactor) that sprays mist into the air as it operates. A tank can be placed on the compactor that holds enough mixture to spray for a working day and connected to a pump and set of nozzles.

7.4. Fence-line spraying systems

Fence-line misting systems are the most commonly used form of odour control on landfills and in other activities such as wastewater treatment plants. Fenceline misting systems are exactly as the name suggests; nozzles spaced as to produce a fine mist along the boundary of an odorous activity. Usually fenceline systems are run on a hydraulic pump, but can be run on compressed air if it is necessary to decrease the particle size of the individual droplets to less than 10 microns.

7.4.1. Original fenceline spray system

The original misting system at Bisasar Road was located within the landfill boundaries approximately 100 m from the south border. The system was run from a central pump station, which serviced 21 nozzle outlets. Approximately 65 m of HDPE piping ran either side of the centrally located pump station providing the chemical mixture to the equally spaced nozzles. There were 18 nozzles at 1 metre above the ground and 3 nozzles positioned on 3-m high poles (Plate 6).

Plate 6: Original odour control system

The nozzles produced droplet sizes between 100 and 500 microns in diameter. The Odour Control Station was connected by telemetry to the weather station with the system only operating when the wind was blowing between Northwest and Northeast (270-90°).

The counteractant used was a germicide/bacterial disinfectant. It was a viscous orange liquid generally used for disinfecting surfaces such as hospital floors and urinals.

The counteractant as well as the method of application in this original system were inadequate. Shortcomings of the system included:

a) The line of nozzles was not extensive enough (18 ground level nozzles extending in a straight line for 130 m),
b) The positioning of the system was also not optimal with relation to the position of the working face and the locality of complainants around the site,
c) The nozzles were not high enough off the ground (18 nozzles at 1 m off the ground and 3 nozzles approximately 3 m off the ground),
d) The 'Misting' system produced particles that were too large (droplet sizes of >100 microns) which resulted in a high settling velocity.

Due to these shortcomings combined with the dismantling of the original system due to the landfilling of the cell where the system was located, a new system was investigated.

7.4.2. Dispersion modelling to determine the height and location of a new system

One of the major faults with the original system was that the droplet size of the particles being sprayed was too large. The spray could actually be seen falling to ground within metres of the nozzles. Particles should be small enough to remain in suspension and be transported by the wind.

Analysis has been done using *ADMS™* to determine the vertical profile of concentration at the landfill boundary. This information can be used to determine the required height and location of a fenceline spraying system around the Bisasar Road landfill.

Complaints from Bisasar Road are located in an arc southwest of the landfill (See section 3.1.2). Therefore both the south and west fences of the landfill were considered for implementation of a fenceline system. The results from running *ADMS™* for one year of weather data in complex terrain were used to verify this (See section 5.3.4).

Figure 30 in section 5.3.4 shows the annual average predicted dilution between the landfill and surrounding areas. The severity of the odour problem can be seen in this plot. The most problematic area is southwest of the landfill. The predicted dilution at the southeast corner of the landfill is over 10 times less than that required to dilute the concentration to below the complaint threshold determined in section 5.4. Kaye and Jiang (1999) report that, in their experiments, complaints ceased when the concentration decreased below 23 ou/m^3. If the dilution required to reach the complaint threshold level is 155 000, then the dilution required to reach approximately 23 ou/m^3 is 6700. If this dilution contour is tracked in Figure 30 and the intercepts of this contour and the landfill boundary are identified, the places along the boundary where a fenceline system should be positioned can be determined. Based on Figure 30, a fenceline spraying system should be extended approximately 450m along the south border and 650m down the west border.

The landfill does not extend to Clare Road all the way along the southern boundary (See Figure 38). The POS is located on the north side of the Clare Road making it difficult to place a misting system along this section. If the misting system was placed on the southern border of the landfill (Northern border of the POS), the chemical could migrate into the POS. Placing the misting system on the south side of the POS along Clare Road is also a problem, as the POS is at a higher elevation than Clare Road.

Figure 38 shows the locations of the three points used to determine the vertical profile of concentration along the southern boundary of the landfill. Also shown is the location and approximate extent of the original spray system within the borders of the landfill.

The ground level at the original odour control station was approximately 110m above sea level, whereas the south fence is between 120 and 170m above sea level. The original spray system was set back approximately 70m from the boundary.

Figure 38: Location of the original spray system as well as the locations of the three points used to determine the vertical profile of concentration

One year of weather data were used and complex terrain modelled as described in section 5.3.4. The profiles in Figure 39 and Figure 40 are a result of emissions from a working face located in the middle of the landfill.

Figure 39 shows the vertical profile of concentration at the location of the original odour control system. The majority of the nozzles were located at 1m above ground level (Approximately 111m above sea level), with an additional three nozzles at each location at, 3m above ground level (114m above sea level). Due to the height and location of the system as well as the size of particles being produced from the nozzles, it is evident that the spray could only have had a limited effect (if any at all) on airborne compounds. This was confirmed by standing downwind of the system where little effect was perceived.

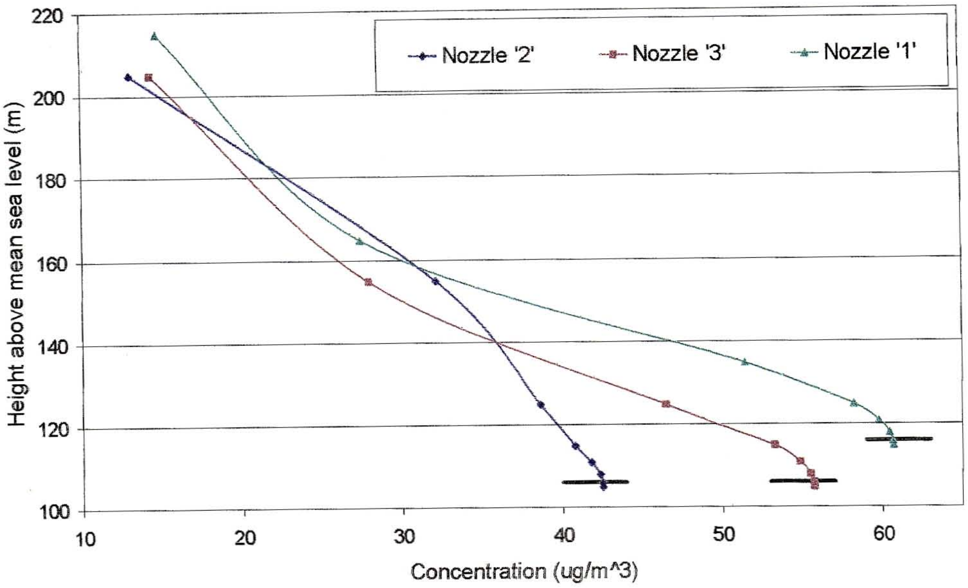


Figure 39: Vertical profile of concentration at first, middle and last nozzles on the original odour control station

Figure 40 shows the vertical profile of concentration for the three locations modelled for the new fenceline system. The ground level slopes down from nozzle 2, at the corner of the POS, to nozzle 1 at the corner of Clare and Kennedy Roads (Figure 38). The height of the wall along the southern boundary is 2m. The model did not take this into account; therefore the profile of concentration in the two metres closest to the ground is inaccurate. Figure 39 and Figure 40 show that concentration decreases from a maximum at ground level, down towards zero at well above 100m above ground level. At the boundary (Figure 40), the concentration remains fairly constant up to approximately 5m above the ground, and then begins to decrease. In order to encompass the entire plume as it passes over the boundary, a curtain of mist would have to be created up to a height of approximately 100m above ground level. This is not possible; therefore nozzles should be placed as high above the ground as possible whilst still creating enough of a mist below release level. The levels shown in Figure 40 are each 6m above ground level.

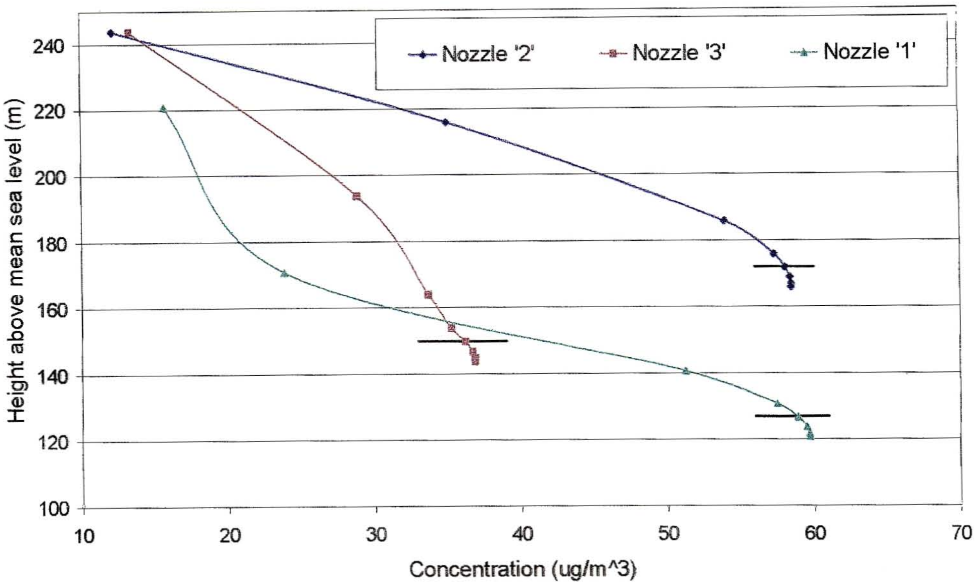


Figure 40: Vertical profile of concentration at three selected points along the southern boundary

Based on the concentration profiles shown and the amount of contaminant above the mist created by the fenceline system, it could be concluded that this type of system would be virtually ineffective in controlling odour. However, a fenceline spray system could be effective in treating the lowest few metres of the plume where the concentration is highest. These observations suggest that it may be more beneficial to have a fenceline misting system as close as possible to the working face to minimise the odour rising above the plume of the fenceline misting spray and to neutralise the odor while it still remains more concentrated.

7.4.3. New Odour control system

The results of the tests done at Bisasar Road were forwarded to Durban Solid Waste (Laister, 2001b). A decision was made to construct a fenceline misting system to cover the 300m of the boundary from the southwest corner to the edge of the Place of Safety. *ECOLO* was chosen to implement the fenceline odour control system. Plate 7 shows the new fenceline misting system in operation.

Plate 7: New odour control fenceline misting system

The system has subsequently been extended further east along Clare Road past the Place of Safety to the corner of Burnwood Road and Clare Road. The total length of the system is approximately 600m.

7.5. Relocating the working face to avoid complaints

Once the spatial distribution of complaints and the predominant wind directions had been determined, it was possible to identify areas of the landfill where filling may minimise odour impacts at complaint locations.

Typically dispersion models are used to determine the concentration emanating from a particular source. A different approach was used in this case. The landfill was modelled as an array of individual point sources and the concentration at only one receptor was determined. A plot displaying the relative influence of each individual point source across the landfill to the total receptor concentration could then be determined. Here 'dispersive power' is another term used for 'dilution' and is calculated in the same manner as in sections 5.3.3 and 5.3.4.

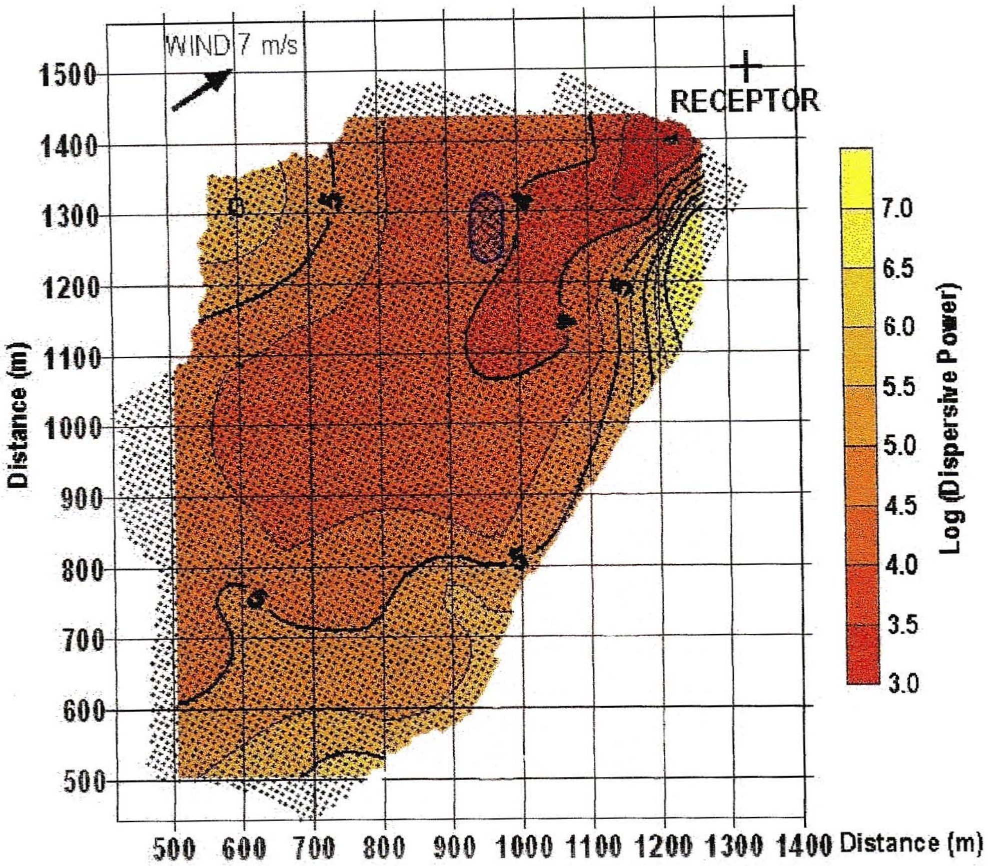


Figure 41: Relative influence plot for receptor at 78 Wandsbeck Road.

Figure 41 shows a plot of relative influence or 'dispersive power' across the landfill for a receptor located southwest of the landfill. The wind at the time of the complaint was blowing at 7 m/s out of the northeast. The approximate size and location of the working face on that day is also shown in blue. Based on the complaint threshold determined in section 5.4 (155 000), a complaint is predicted from this receptor in this case. Due to conditions on this particular occasion, there was very little area on the landfill that could have been filled in order to avoid a complaint from the specified complaint location. In other words, the complaint from this receptor could probably not have been avoided by relocating the working face. Figure 42 shows a slightly different scenario. A complaint was lodged from a receptor (191 Clare Road) in close proximity to that shown in

Figure 41. In this case, the filling area is located just within the contour labelled '5', again predicting that a complaint was likely.

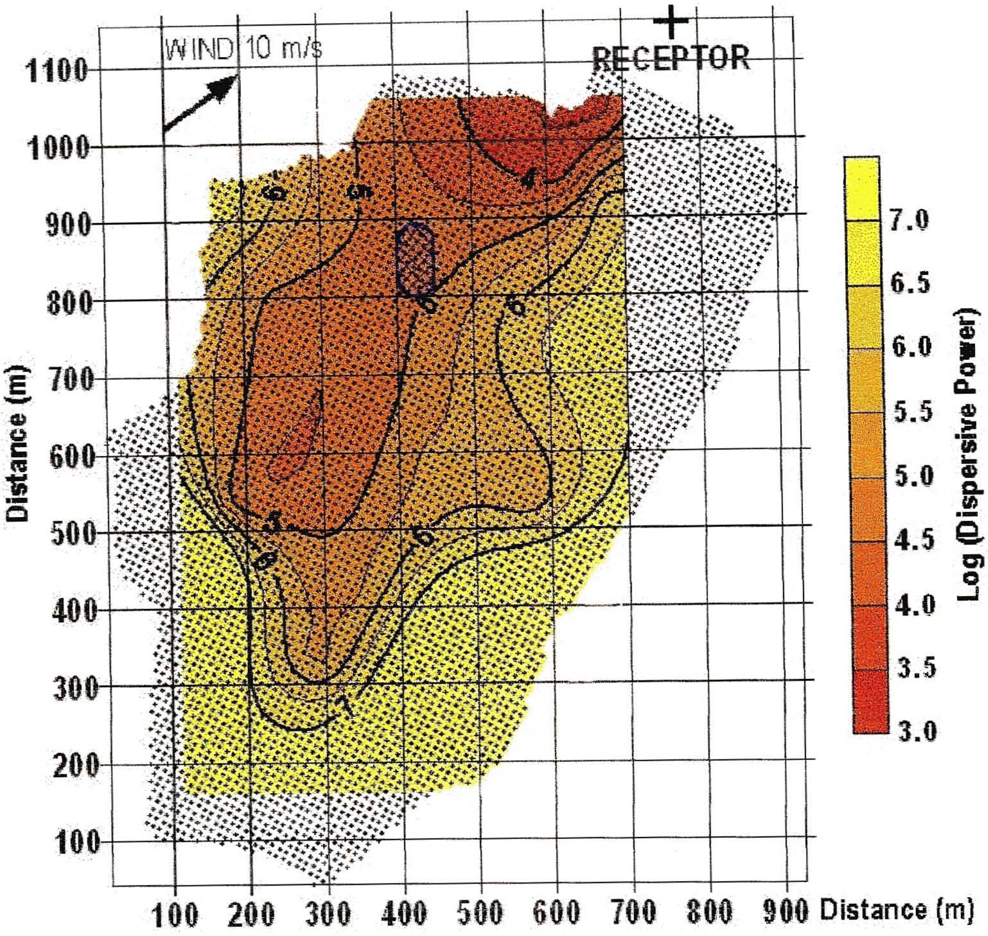


Figure 42: Relative influence plot for a receptor at 191 Clare Road.

Conditions were slightly different in this case, with the wind still blowing out of the northeast (65° as opposed to 55° in Figure 41), but at a higher velocity. From Figure 42, had filling taken place in an area outside the threshold contour, a complaint may not have been lodged from this particular receptor. It should be noted that this is only applicable for this particular receptor and moving the working face could result in a complaint being generated from a different location.

Figure 43 shows a third complaint occasion that has been analysed. This time, the wind was blowing from an unusual southeasterly direction (105°). The wind speed was also lower than in the two previous simulations at 4 m/s. As with the previous two, the working face is located in an area where a complaint is predicted. Figure 43 shows a large amount of the landfill that could have been used for filling which may have avoided a complaint being lodged from this particular receptor. Again, it is noted, that moving the working face 100m to the southwest may have avoided a complaint from the resident at 104 Kennedy Road but may have lead to a complaint from a resident elsewhere. However, with the complaint distribution as it is for Bisasar Road it may be possible to use the predictions that the *OMS* produces proactively to minimise complaints.

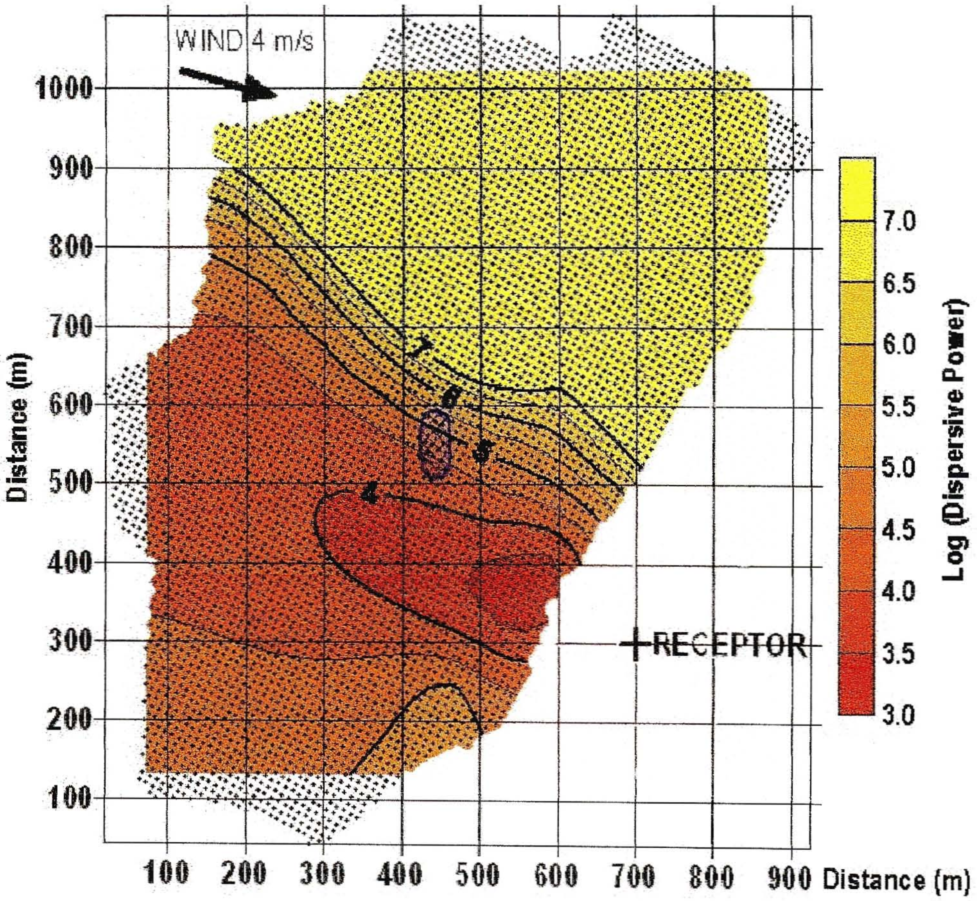


Figure 43: Relative influence plot for 104 Kennedy Road.

The objective this analysis was to illustrate that using predictions proactively and relocating the working face can possibly be used to avoid complaints. The location of the working face could be decided each day based on early morning predictions and weather forecasts. Moving the working face during the course of a day would take a reasonable amount of effort and co-ordination, and the time scale between moves would have to be varied to find the optimum. For instance, it may be worth changing the location of the working face every few hours, but a move twice a day may be more feasible. This could be determined on a 'trial-and-error' basis on-site.

7.6. Multi-cell cell strategy

Following on from the results presented in section 7.5, one possible mitigation strategy could be to have two *separate* working areas available for use at all times. For the purposes of this example we shall refer to them as the "Randle" and "Kennedy" cells (See Figure 44). Depending on current weather conditions, the area that causes minimal odour nuisance for specified receptors can be utilised while the other is covered to reduce its emissions. Simulations of this type of operational strategy have been conducted to examine its effectiveness. Complex terrain effects were included.

Half-hourly weather data for January 2000 were used for the simulations. Only working hours were simulated. The model calculated the effects of the two source areas working independently as well as in combination. The change in receptor concentration due to selective operation of only the area that minimised the receptor concentration could thus be determined.

Figure 44 shows exceedance probabilities for hourly mean concentrations at a specific receptor. Contributions from each of the Randle and Kennedy cells operating continuously are shown. Also shown is a minimum impact strategy where only the cell that had the smallest effect on the receptor concentrations was utilised at any given time. Note that for nearly 50% of the time period, neither area contributed to the receptor in this example.

In this particular case, significant benefits are predicted for this type of mitigation strategy. A reduction in mean concentration at the specified receptor (averaged over the duration of the simulation) of approximately 90% was achieved in comparison to using only the Randle cell i.e. in this case, the prevailing wind directions during the simulation period strongly favoured use of the Kennedy cell. In general, such large benefits would be difficult to achieve, and further work on the effectiveness and practicality of this type of strategy is required.

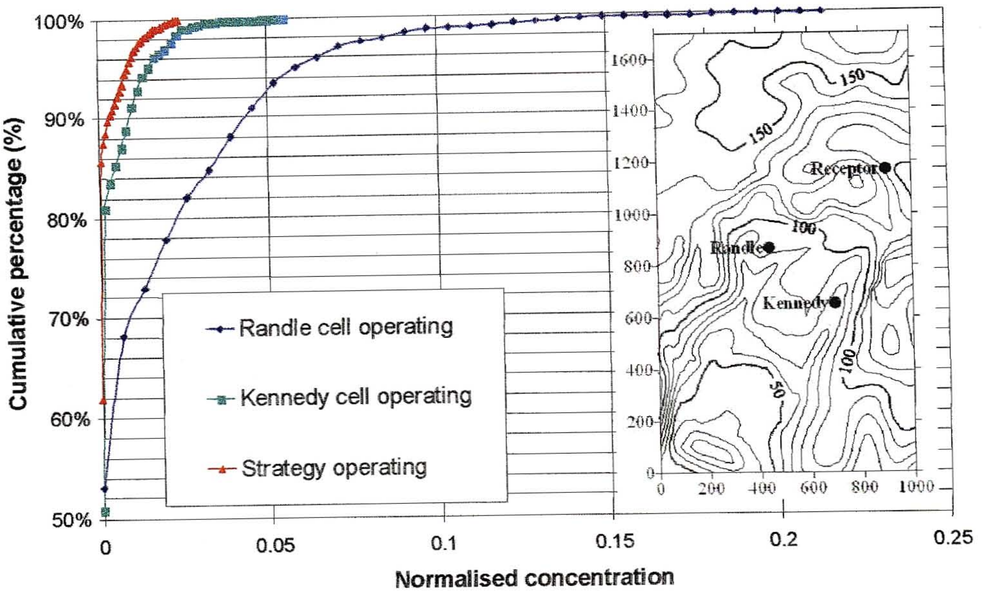


Figure 44: Exceedance probabilities for hourly mean concentrations at a specific receptor.

CHAPTER 8

8. CONCLUSIONS

The research conducted for this project concerned the prediction, management and control of odour from landfills. The results obtained from experiments conducted and analyses done are applicable to landfills in general, but the focus has been on a particular case study site: Bisasar Road landfill in Durban.

The Bisasar Road landfill complaints register was reviewed and a temporal and spatial analysis of the data carried out. It was found that, based on three and half years worth of data, complaints are more likely in summer than in winter. This may be due to the hot, humid and wet conditions typical of Durban summers. It may also be due to the wind, which blows predominantly from the northeast and the southwest. The spatial analysis showed that the majority of complaints (ninety-seven percent) were reported from locations within an arc southwest of the landfill. Eighty-four percent of the complaints were logged from residences within one kilometre of the site.

Flow visualisation experiments provided qualitative information on the effects of terrain. The experiments showed significant effects of the terrain on the path of the smoke plumes.

Numerical simulations carried out using *FLOWSTAR™* are qualitatively consistent with results obtained from the smoke flares, thereby qualitatively validating the *FLOWSTAR™* algorithms. Further analysis carried out using *ADMS™* (Incorporating *FLOWSTAR™* algorithms) showed that complex terrain generally assists in the dispersion and the dilution of emissions. It was therefore decided to incorporate complex terrain effects in the modelling process.

Five available dispersion models were obtained and reviewed. ISC3 provides reasonable concentration estimates in flat terrain but appears to grossly overpredict concentration in complex terrain. Algorithms dealing with complex terrain have been updated in the replacement for ISC3, AERMOD. AERMOD produces accurate estimates in flat and complex terrain, however the format of terrain input was unavailable for the case study site. CTDMPLUS is a MSDOS based model that was formulated specifically for predictions in complex terrain. According to studies carried out by the USEPA, CTDMPLUS produces less accurate results than AERMOD. This is probably due to the fact that terrain input into CTDMPLUS is in the form of artificially generated approximations of terrain features. These approximations are time consuming to produce. It is difficult to assess the accuracy of CALPUFF as only one previously reported study comparing CALPUFF with ISC3 was found. CALPUFF employs the same terrain input format as CTDMPLUS. In order to run CALPUFF to its full capacity requires complex meteorological data, which was not available for the case study site. *ADMS™* was chosen as the most accurate and most user-friendly model. Meteorological and terrain data are simple to include.

The working face was identified as the primary source of odour at Bisasar Road landfill. Sampling was conducted at the working face and the composition of fresh waste gas emissions was determined. The primary groups of compounds found include; hydrocarbons (Xylene, Toluene, Benzene, Naphthalene, Decane, Undecane and Dodecane) and terpenes (Limonene and Alpha-Pinene). These results are consistent with Termonia and Termonia (1999). The emission rate or concentration of fresh waste gas could not be determined.

Due to the fact that site specific data on the emission rate and concentration is still not available for Bisasar Road, predictions using *ADMS™* have been presented in a dimensionless form of dilution between source and receptor. Conditions for forty-two complaints have been analysed using *ADMS™*, and it was found that the average dilution between the source and the respective receptors was approximately 155 000. This factor of dilution could be used as a 'Complaint dilution threshold' i.e. if a dilution factor less than 155 000 is registered at a receptor then a complaint is likely.

The main objective of the project was to develop and Implement a management tool that could be used to assist in minimising the negative impact of odour from landfills. This has been achieved in the form of an 'Odour Management System' (OMS) which has been implemented on-site at Bisasar Road landfill site. The OMS produces 'real-time' (every ten minutes) graphical predictions of dilution from the working face. The OMS incorporates existing software (*ADMS™* and *SURFER™*) with additional software applications written specifically for producing the graphical predictions. The OMS contains code to process calm conditions (wind speed <0.75m/s) as well as invalid output data produced by *ADMS™*. The main application of the OMS is in assisting the landfill operator when conditions are either not conducive to dispersion and/or complaints are likely. If the OMS predicts that complaints may be likely, management and control strategies can be implemented pro-actively to minimise the off-site impacts of odour.

Unconfined odours, as is the case with fresh waste emissions from landfills, are difficult to eliminate or even reduce. Sound engineering practice can assist in minimising the impact of odour. Two operational strategies have been investigated using *ADMS™*. From these investigations it has been shown that utilising more than one filling location can help reduce the impact of odour offsite depending on the weather conditions.

Landfill working faces are usually large (approximately 1000m^2) and continually changing shape and size as new waste arrives. This makes it difficult to treat the waste at the source for odour. Landfills may also have multiple sources of odour and treating each source individually is not practical. Based on common practice and on results from the experiments carried out, fenceline-misting systems appear to be the most effective form of odour control for landfills. However, the effectiveness of fence-line misting control systems is largely unproven and analysis done suggests that these systems may still be largely ineffectual.

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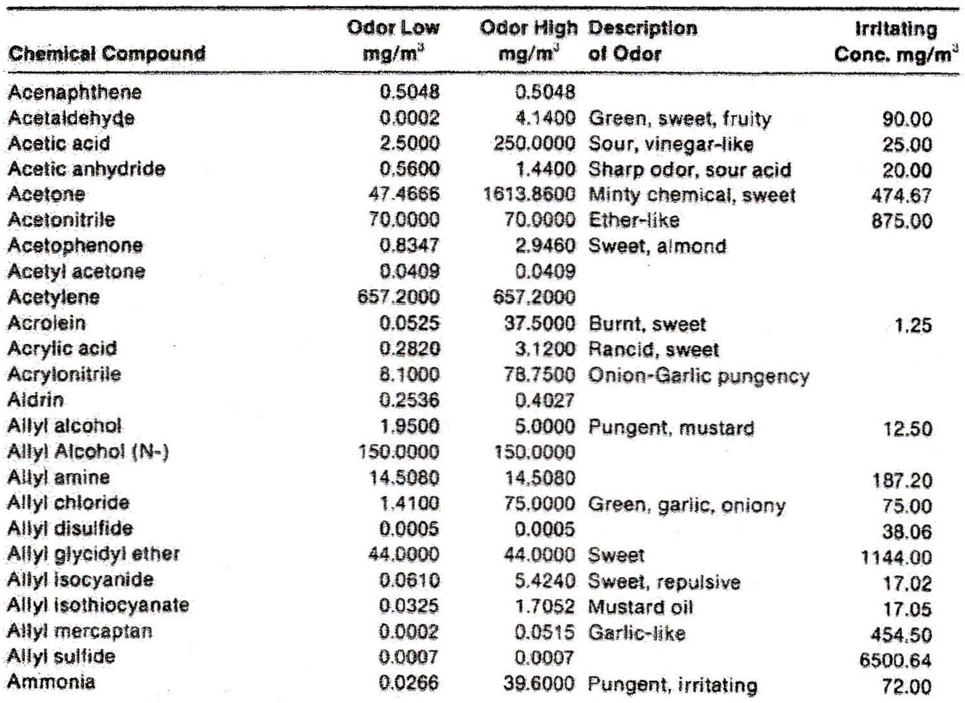
APPENDIX A: COMPILATION OF ODOUR THRESHOLDS

This table of odour thresholds and irritation concentrations of chemicals was compiled and reported by Ruth (1986).

Table 9: Compilation of odour thresholds and irritation concentrations for chemicals (Ruth, 1986)



Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Acenaphthene	0.5048	0.5048		
Acetaldehyde	0.0002	4.1400	Green, sweet, fruity	90.00
Acetic acid	2.5000	250.0000	Sour, vinegar-like	25.00
Acetic anhydride	0.5600	1.4400	Sharp odor, sour acid	20.00
Acetone	47.4666	1613.8600	Minty chemical, sweet	474.67
Acetonitrile	70.0000	70.0000	Ether-like	875.00
Acetophenone	0.8347	2.9460	Sweet, almond	
Acetyl acetone	0.0409	0.0409		
Acetylene	657.2000	657.2000		
Acrolein	0.0525	37.5000	Burnt, sweet	1.25
Acrylic acid	0.2820	3.1200	Rancid, sweet	
Acrylonitrile	8.1000	78.7500	Onion-Garlic pungency	
Aldrin	0.2536	0.4027		
Allyl alcohol	1.9500	5.0000	Pungent, mustard	12.50
Allyl Alcohol (N-)	150.0000	150.0000		
Allyl amine	14.5080	14.5080		187.20
Allyl chloride	1.4100	75.0000	Green, garlic, oniony	75.00
Allyl disulfide	0.0005	0.0005		38.06
Allyl glycidyl ether	44.0000	44.0000	Sweet	1144.00
Allyl isocyanide	0.0610	5.4240	Sweet, repulsive	17.02
Allyl isothiocyanate	0.0325	1.7052	Mustard oil	17.05
Allyl mercaptan	0.0002	0.0515	Garlic-like	454.50
Allyl sulfide	0.0007	0.0007		6500.64
Ammonia	0.0266	39.6000	Pungent, irritating	72.00

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Amyl acetate (N-)	0.0265	37.1000	Fruity, banana, pear	530.00
Amyl acetate (sec-)	0.0107	0.0107		
Amyl alcohol (iso-)	25.2000	25.2000		
Amyl alcohol (N-)	0.4332	72.2000	Sweet	
Amyl alcohol (tert-)	0.8303	0.8303		
Amyl amine (N-)	56.6040	132.0760		
Amyl mercaptan	0.0001	0.0018		
Amyl mercaptan (iso-)	0.0018	0.0018		
Aniline	0.0002	350.0000	Pungent, amine-like	
Anisole	0.2210	0.2210		
Apiole	0.0570	0.0570		
Arsine	0.8400	2.0000	Garlic-like	
Azetidine	51.9200	169.9200		
Azine	31.6480	66.2400		
Azole	134.2600	295.9200		
Benzaldehyde	0.0008	0.1823	Pleasant, bitter	20.01
Benzene	4.5000	270.0000	Sweet, solventy	9000.00
Benzene hexachloride	0.0015	142.8000		
Benzenethiol	0.0012	279.0000		
Benzothiazole	0.4424	2.2120		
Benzyl chloride	0.2350	1.5500	Solventy	41.00
Benzyl mercaptan	0.0132	0.2028	Unpleasant	22.81
Benzyl sulfide	0.0184	0.0184	Sulfidy	
Biphenyl	0.0062	0.3000		7.50
Boron trifluoride	4.5000	4.5000	Pungent, irritating	
Bromine	0.3290	24.5000	Bleachy, penetrating	2.10
Bromoacetophenone	0.1221	1.3838	Unpleasant	0.33
Bromochloromethane	1680.0000	1680.0000		
Bromoform	5300.0000	5300.0000	Similar to chloroform	
Butadiene (1,3-)	0.3520	2.8600		
Butadiene dioxide	17.6000	17.6000		35.20
Butane	2.8500	14.6300		
Butenethiol (2-)	0.0001	0.0001		
Butyl acetate (iso-)	0.0090	90.0000	Pleasant, fruity	1350.00
Butyl acetate (N-)	33.1333	94.6666	Fruity	473.33
Butyl acrylate (iso-)	0.0110	0.0660	Sweet, musty	
Butyl alcohol (iso-)	0.3600	225.0000	Mild, non-residual	300.00
Butyl alcohol (N-)	0.3600	150.0000	Sweet	75.00
Butyl alcohol (secondary-)	131.1500	131.1500	Strong, pleasant	
Butyl alcohol (tertiary-)	219.0000	219.0000	Camphor-like	
Butyl amine (N-)	0.2400	6.0000	Ammonical	30.00
Butyl cellosolve	0.4800	288.0000	Sweet, ester	
Butyl cellosolve acetate	0.7194	1.3080	Sweet, ester	
Butyl chloride (N-)	3.3352	6.3293	Pungent	
Butyl ether (N-)	0.3731	2.5051	Fruity, sweet	
Butyl formate	70.8900	83.4000		
Butyl furan (2-)	50.8000	50.8000		
Butyl lactate (N-)	35.0000	35.0000		
Butyl mercaptan	0.0016	0.0033	Stinks!	
Butyl sulfide	0.0897	0.0897		
Butyl toluene (P-, tertiary-)	30.0000	30.0000	Gasoline-like	48.00
Butylamine	3.0000	378.0000	Ammonia, fishy	30.00
Butylene	54.9600	54.9600	Gassy	
Butylene oxide	0.2058	2.0874	Sweet, alcohol	
Butylthiazole (2, iso-)	0.0202	0.0202		
Butyraldehyde	0.0136	26.5500	Sweet, rancid	
Butyric acid	0.0010	9.0000	Sour, perspiration	
Butyric acid (iso-)	29.1600	29.1600		
Camphor (synthetic)	7.8000	1200.0000		10.62
Caprolactam	28.0000	28.0000		
Capryl alcohol			Sweet, pungent	
Carbitol	1.1508	6.0280	Sweet, musty	
Carbitol acetate	0.1872	1.8936	Sweet	
Carbon disulfide	0.0243	23.1000	Disagreeable, sweet	
Carbon tetrachloride from CS_2	60.0000	128.4000	Sweet, pungent	

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Carbon tetrachloride from CH_4	300.0000	1500.0000	Sweet, pungent	
Caryophyllene	0.5350	0.5350		
Cellosolve	2.0350	185.0000		
Cellosolve acetate	0.3024	270.0000	Sweet, musty	
Cellosolve solvent	1.1040	2.0240		
Chloral	0.2825	0.2825	Sweet	
Chlordane	0.0084	0.0419		
Chlorinated Camphene Toxaphene	2.3689	2.3689		
Chlorine	0.0300	15.0000	Bleachy, pungent	9.00
Chlorine Dioxide	0.3000	0.3000	Sharp, pungent	15.00
Chloroacetaldehyde	3.0000	3.0000	Sharp, irritating	3.00
Chloroacetophenone (alpha-)	0.1020	0.1500	Sharp, irritating	0.05
Chlorobenzene	0.9800	280.0000	Sweet, almond-like	933.33
Chlorobenzylidene malonitrile (ortho-)			Peppery	1.52
Chlorobromomethane	2100.0000	2100.0000	Sweet	
Chloroform	250.0000	1000.0000		20480.00
Chlorophenol	0.0189	6.5224	Medicinal, empyrumatic	6801.18
Chloropicrin	5.4600	7.7000	Sharp, penetrating	2.10
Chlorotoluene	0.2350	0.2350	Pungent, irritating	
Citral	0.3738	0.3738		
Coumarin	0.0020	0.0120	Pleasant, vanilla	
Cresol	0.0012	22.0000	Sweet, creosote, tar	
Crotonaldehyde	0.1050	3.0000	Pungent, suffocating	23.01
Cumene	0.0392	6.3700	Sharp, aromatic	
Cyanogen	500.0000	500.0000	Pungent	32.00
Cyanogen chloride	2.0000	2.0000		
Cyclobutylamine	97.1750	340.8600		
Cycloheptylamine	309.2600	573.4000		
Cyclohexane	1.4350	1.4350	Sweet, aromatic	1050.00
Cyclohexanol	400.0000	400.0000	Camphor-like	200.00
Cyclohexanone	0.4800	400.0000	Sweet, pepperminty	100.00
Cyclohexylamine	106.0000	448.0000		
Cyclopentadiene	5.0667	5.0667		
Cyclopentyl acetate	0.1031	0.1031		
Cyclopentylamine	676.4000	2278.4000		
Cyclopropylamine	153.5170	153.5170		
DDT	5.0725	5.0725		
Decaborane	0.3600	0.3600		
Decalin	565.0000	565.0000		565.00
Decanoic acid	11.9510	112.4800		
Decanol	0.0006	43.2820		
Diacetone alcohol	1.3440	480.0000	Sweet	240.00
Diacetyl	0.0035	0.0880		
Diallyl sulphide	0.0005	0.1491	Garlicky	
Dibenzofuran	0.7752	1.6150		
Diborane	2.0000	4.0000	Repulsively sweet	
Dibromo-3-chloropropane (1,2-)	0.0965	0.2895		1.93
Dibutylamine	0.4224	1.4256		
Dibutylamine (N-)	0.4232	2.5392	Fishy, amine	
Dichloroacetic acid	1.2144	1.2144		
Dichloroanisole (2,6-)	0.0003	0.0003		
Dichlorobenzene (ortho-)	12.0000	300.0000		150.00
Dichlorobenzene (para-)	90.0000	180.0000	Mothballs	240.00
Dichloroethane	445.5000	810.0000	Chloroform-like	
Dichloroethyl ether	90.0000	2160.0000		600.00
Dichloroethylene (1,2-)	0.3358	1975.0000	Acrid, ethereal	
Dichlorophenol (2,4-)	1.4007	1.4007		
Dicyclo pentadiene	0.0297	0.0540	Sharp, sweet	2.70
Diethyl disulfide	0.0195	0.0195		
Diethyl ethanolamine	0.0536	0.1948	Amine	
Diethyl ketone	3.1725	49.3500		
Diethyl pyrazine (2,5-)	0.0336	0.1120		
Diethyl selenide	0.0617	0.0617	Putrid	

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Diethyl sulphide	0.0177	0.0117	Foul, garlickly	
Diethyl trisulfide	0.0044	0.0044		
Diethylamine	0.0600	114.0000	Fishy, ammonical	150.00
Diglycidyl ether	25.0000	25.0000		50.00
Diisobutyl carbinol	0.1885	0.9424	Sweet, alcohol	
Diisobutyl ketone	0.6600	1.8600	Sweet, ester	150.00
Diisopropyl amine	0.5200	3.4000	Fishy, amine	100.00
Dimethoxy dimethyl pyrazine	1.2366	1.2366		
Dimethyl acetamide	161.0000	163.8000		
Dimethyl amine	0.0846	0.0846		174.60
Dimethyl disulfide	0.0001	0.3465		
Dimethyl ethanolamine	0.0546	0.1638	Amine	
Dimethyl formamide (N,N-)	300.0000	300.0000		
Dimethyl napthalene	0.0428	0.0428		
Dimethyl sulfide	0.0025	0.0508	Decayed cabbage	
Dimethyl trisulfide	0.0062	0.0062		
Dimethyl trithiocarbonate	0.0331	0.0331		
Dimethylacetamide (N,N-)	163.8000	163.8000	Amine, burnt, oily	
Dimethylamine	0.0378	55.8000	Fishy, ammonical	
Dimethylformamide (N,N-)	300.0000	300.0000	Fishy, pungent	
Dimethylhydrazine (1,1-)	12.0000	20.0000	Ammonical, amine-like	
Dioxane (1,4-)	0.0108	612.0000	Ether-like	792.00
Dioxane (para-)	20.1600	972.0000		720.00
Dioxolane (1,3-)	44.5400	335.3600	Sweet, musty	
Dipentene			Lemon-like	
Diphenyl ether (perfume)	0.6950	0.6950	Pleasant, geraniums	
Diphenyl sulfide	0.0026	0.0358	Burnt, rubbery	
Dipropylamine	0.0826	227.1500	Ammonical, amine	
Dipropylamine (N-)	0.4140	0.8280	Ammonical, amine	
Dipropylene glycol methyl ether	210.0000	6000.0000	Ether-like	450.00
Dodecanol (1-)	0.0152	0.0533		
Dodecyl Mercaptan (N-)	4222.8000	4222.8000		
Dowtherm A	0.7000	7.0000	Aromatic, disagreeable	21.00
Endrin	0.2808	6.3963		
Epichlorohydrin	50.0000	80.0000	Chloroform-like	325.00
Ethane	184.5000	1105.7700		
Ethanolamine	5.3333	10.6666	Ammonia	13.33
Ethoxy 3,4 dihydro 1,2 pyran (2-)	3.1440	3.1440	Sweet, fruity	
Ethoxy 3,4-dihyro 1,2 pyran	0.1048	3.1440	Sweet, fruity	
Ethyl acetate	0.0196	665.0000	Fruity, pleasant	350.00
Ethyl acrylate	0.0008	32.0000	Earthy, acrid, plastic	16.00
Ethyl alcohol (synthetic)	0.3420	9690.000	Sweet, alcoholic	9500.00
Ethyl amine	0.4860	396.0000	Sharp, ammonical	180.00
Ethyl amyl ketone	31.2000	31.2000	Mild, fruity	260.00
Ethyl benzene	8.7000	870.0000	Aromatic	870.00
Ethyl benzoate	3.8068	3.8068		
Ethyl bromide	890.0000	890.0000	Ether-like	28925.00
Ethyl butanol (2-)	0.2919	3.2109	Musty, sweet	
Ethyl ether	0.9900	3.0000	Sweet, ether-like	300.00
Ethyl formate			Fruity	990.00
Ethyl hexanol (2-)	0.3990	0.7342	Musty	
Ethyl hexyl acetate	0.5132	1.4763	Sweet	
Ethyl hexyl acrylate (2-)	0.5497	1.3554	Sharp, musty	
Ethyl isothiocyanate	6.0520	6.0520	Mustard, unpleasant	65.15
Ethyl lactate	67.6200	67.6200		
Ethyl mercaptan	3.2×10^{-5}	0.0920	Garlic	
Ethyl methyl disulfide	0.0487	0.0487		
Ethyl methylamine	21.6900	79.5300		
Ethyl morpholine (N-)	0.3680	1.1500	Ammonia	184.00
Ethyl phenylacetate	4.3615	4.3615		
Ethyl propyl amine	60.5200	181.5600		
Ethyl selenide	0.0003	0.003		
Ethyl selenomercaptan	8.0×10^{-6}	0.0054	Foul	
Ethyl silicate	722.5000	722.5000	Alcohol-like, sharp	5950.00
Ethyl sulfide	0.0009	0.0103		

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Ethyl valerate	0.0266	0.0266		
Ethyl vinyl ketone	0.0004	0.0069		
Ethylene	299.0000	4600.0000	Olefinic	
Ethylene diamine	2.5000	28.0000	Ammonical, musty	250.00
Ethylene dibromide	76.8000	76.8000	Mild, sweet	
Ethylene dichloride	24.0000	440.0000	Sweet	
Ethylene glycol	62.5000	62.5000	Sweet	
Ethylene glycol dinitrate				0.18
Ethylene oxide	520.0000	1400.0000	Sweet, olefinic	
Ethylenediamine	25.0000	28.0000	Musty, ammonical	500.00
Ethyleneimine	4.0000	4.0000	Ammonical	200.00
Ethylidene norborene	0.0700	0.3650	Sweet, aromatic	30.00
Fluorine	6.0000	6.0000		50.00
Formaldehyde	1.4700	73.5000	Pungent, hay	1.50
Formamide	150.0000	150.0000		
Formic acid	0.0450	37.8000	Pungent, penetråting	27.00
Furfural	0.0240	20.0000	Almonds	48.00
Furfuryl alcohol	32.0000	32.0000		
Glycol diacetate	0.5552	1.8626	Fruity, acid	
Heptachlor	0.3060	0.3060		
Heptanal	0.0140	0.0932		
Heptane	200.0000	1280.0000	Gasoline-like	
Heptyl alcohol (N-)	98.3250	98.3250		
Heptyl isobutyrate	0.0989	0.0989		
Heptyl propionate	0.0281	0.0281		
Hexachlorobutadiene	12.0000	12.0000		
Hexachlorocyclopentadiene	1.5000	3.3000		
Hexadiene	1.6750	127.3000		
Hexane (N-)				1800.00
Hexanol (1-)	0.0417	21.6840	Sweet, alcohol	
Hexyl acetate (secondary-)	0.0120	600.0000	Unpleasant	600.00
Hexyl isobutyrate	0.0422	0.0422		
Hexyl propionate	0.0514	0.0514		
Hexylene glycol	250.0000	250.0000		250.00
Hydrazine	3.0000	4.0000	Ammonical, fishy	
Hydrochloric acid	7.0000	49.0000	Irritating, pungent	49.00
Hydrofluoric acid	0.0333	0.1333	Strong, irritating	4.17
Hydrogen bromide	6.6667	6.6667	Sharp, irritating	10.00
Hydrogen cyanide	0.9000	5.0000	Bitter almond	
Hydrogen peroxide			Slightly sharp	150.00
Hydrogen selenide	0.0016	12.0000	Decayed horseradish	6.00
Hydrogen sulfide	0.0007	0.0140	Rotten eggs	14.00
Iodine	9.0000	9.0000		2.00
Iodoform	0.0062	0.0833		
Ionone	4.63×10^{-7}	573.0500		
Isoamyl alcohol	36.0000	126.0000		360.00
Isobutyl 2-methoxypyrazine	13.5800	13.5800		
Isobutyl 3-methoxypyrazine	1.3×10^{-5}			
Isobutyl 3-methyl pyrazine	0.2146	0.2146		
Isobutyl butyrate	12.3690	17.6700		
Isobutyl mercaptan	0.0020	0.0020		
Isobutyl pyrazine (2-)	2.2080	2.2080		
Isodecanol	0.1292	0.2713	Musty, alcohol	
Isopentanoic acid	0.0209	0.1084	Goaty	
Isophorone	1.0000	50.0000	Sharp, objectionable	50.00
Isopropyl acetate	0.1900	1520.0000	Fruity	380.00
Isopropyl alcohol	7.8400	490.0000	Pleasant	490.00
Isopropyl amine	0.5040	480.0000	Pungent, ammonia	24.00
Isopropyl ether	0.0714	1260.0000	Sweet, sharp, ether	1260.00
Isopropyl glycidyl ether	1440.0000	1440.0000		
Kerosene	0.5517	0.5517		122.60
Ketene			Sharp	41.40
Lauraldehyde	0.0151	0.0151		
Linalyl acetate	50.5260	50.5260		
Malathion	13.5000	13.5000		
Maleic anhydride	1.8400	1.9600	Acrid	5.48

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Mercaptobenzothiazole	12.0208	12.0208		
Mercaptoethanol	0.3828	2.0416		
Mesityl Oxide	0.0680	100.0000	Sweet	100.00
Methyl 2, cyanoacrylate	4.0000	12.0000		12.00
Methyl acetate	610.0000	915.0000	Fragrant, fruity	30496.90
Methyl acetylene-propadiene MAPP gas	180.0000	180.0000	Foul, objectionable	
Methyl acrylate	70.0000	70.0000	Sharp, sweet, fruity	262.50
Methyl acrylonitrile (alpha-)	6.0000	42.0000		6.00
Methyl alcohol	13.1150	26840.0000	Sweet	22875.00
Methyl amine	0.0252	12.0000		24.00
Methyl amyl acetate	0.4123	2.3560	Sweet, ester	
Methyl amyl alcohol	1.3761	2.1684	Sweet, alcohol	
Methyl anthranilate	0.0581	0.0581		
Methyl benzyl alcohol	7235.5000	5235.5000		
Methyl bromide	80.0000	4000.0000	Sweetish	
Methyl butanol (2-)	0.0450	0.8280	Sour, sharp	
Methyl butenoic acid (2-)	0.0528	0.0528	Body odor	
Methyl butyl acetate	0.0266	0.0266		
Methyl cellosolve	0.2380	288.0000	Mild, non-residual	368.00
Methyl cellosolve acetate	1.6320	240.0000	Sweet, ester	
Methyl chloride	21.0000	21.0000	Sweet, ethereal	1050.00
Methyl chloroform	542.8570	3800.0000	Chloroform-like	5428.57
Methyl cyclohexane	2000.0000	2000.0000	Faint, benzene-like	
Methyl cyclohexanol	2350.0000	2350.0000	Weak, coconut oil	2350.00
Methyl disulfide	0.0012	0.0039		
Methyl ethanolamine	3.0700	10.4380	Musty, ammonical	
Methyl ethyl ketone	0.7375	147.5000	Sweet, acetone-like	590.00
Methyl ethyl pyridine	0.0297	94.0500	Sour, pungent	
Methyl formate	500.0000	6875.0000	Pleasant	8750.00
Methyl furan (2-)	90.4500	90.4500		
Methyl glycol	186.6000	279.9000		
Methyl heptanoate	0.0236	0.0236		
Methyl hexyl ketone	1299.5200	1299.5200		
Methyl hydrazine	1.7500	5.2500		
Methyl iodide				21500.00
Methyl isoamyl alcohol	0.2919	0.8340	Pungent	
Methyl isoamyl ketone	0.0576	0.3360		
Methyl isobutyl carbinol	2.0800	200.0000	Sweat, mild odor	100.00
Methyl isobutyl ketone	0.4100	192.7000	Sweet, sharp	410.00
Methyl isocyanate				5.00
Methyl isopropenyl ketone	1.0222	1.0222		
Methyl mercaptan	4.0×10^{-5}	0.0820	Sulfidy	
Methyl methacrylate	0.2050	1.3940	Arid, fruity, sulfidy	697.00
Methyl n-amyl carbinol	0.0989	0.3378	Sweet, alcohol	
Methyl n-amyl ketone	0.0940	0.0940		
Methyl n-propyl ketone	28.0000	45.5000		
Methyl naphthalene (2-)	0.0581	0.2905		
Methyl parathion	0.1328	0.1328		
Methyl pentaldehyde (2-)	0.3681	0.5562	Sweet, rancid	
Methyl pentane (2-)	0.2886	0.2886		
Methyl propanol (2-)	0.0027	0.1303		
Methyl propene (2-)	45.8000	45.8000	Gassy	
Methyl pyrazine (2-)	231.0000	231.0000		
Methyl salicylate	0.6220	0.8708		
Methyl styrene (alpha-)	0.2496	960.0000	Sweet, aromatic	960.00
Methyl thiocyanate	0.7475	0.7475	Sweet, unpleasant	480.19
Methyl vinyl ketone	0.5720	0.5720		
Methylamine	0.0252	12.0000	Fishy, pungent	30.00
Methylene chloride	540.0000	2160.0000	Sweet	8260.00
Methylene chlorobromide	2120.0000	2120.0000		
Methylene glycol	76.2000	76.2000		
Mineral spirits	157.5000	787.5000		
Monochlorobenzene	0.9800	0.9800	Chlorinated, mothball	
Morpholine	0.0350	0.4900	Fishy, amine	

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Musk oil	3.8×10^{6}	0.0487		
Mustard gas	0.0150	0.0150		
Myrcene	0.0723	0.0723		
Naphthalene	1.5000	125.0000	Mothball, tar-like	75.00
Nickel carbonyl	0.2100	21.0000	Musty	
Nitric acid	0.7500	2.5000		155.00
Nitric oxide	0.3600	1.2000		
Nitrobenzene	0.0235	9.5000	Shoe polish, pungent	230.00
Nitroethane	620.0000	620.0000	Mild, fruity	310.00
Nitrogen dioxide	2.0000	10.0000	Sweetish, acrid	20.00
Nitromethane	250.0000	250.0000	Mild, fruity	500.00
Nitropropane (1-)	1080.0000	1080.0000	Mild, fruity	360.00
Nitropropane (2-)	17.5000	1029.0000		
Nonane	3412.5000	3412.5000		
Nonanol (2-)	0.0005	20.6150		
Octadiene (1,3-)	54.0000	90.0000		
Octane	725.0000	1208.3300	Gasoline-like	1450.00
Octyl alcohol	0.6916	0.6916		
Oxygen difluoride	0.2000	1.0000	Foul	
Ozone	0.0010	1.0200	Pleasant, clover-like	2.00
Parathion	0.4760	0.4760	Garlic-like	
Pentaborane	2.5000	2.5000	Strong, pungent	
Pentachlorophenol			Pungent when hot	10.90
Pentane	6.6000	3000.0000	Gasoline-like	
Pentanedione (2,4-)	0.0409	0.0982	Sour, rancid	
Pentanol (n-)	0.7560	1.1160	Sweet, alcohol	
Perchloroethylene	31.3560	469.0000	Chlorinated solvent	1340.00
Perchloromethyl mercaptan	0.0075	0.0075		
Perchloryl fluoride	46.6666	46.6666	Sweet	
Phenol	0.1786	22.4200	Medicinal, sweet	182.40
Phenyl ether	0.0070	0.7000	Disagreeable	21.00
Phenyl ethyl alcohol (beta-)	35.0000	35.0000		
Phenyl sulfide	0.0026	0.0358		
Phenylacetaldehyde	0.0010	0.0196		
Phosgene	2.0000	4.0000	Musty hay, green corn	8.00
Phosphine	0.0280	3.6000	Oniony, mustard, fish	10.67
Phthalic Anhydride				30.00
Picoline (2-)	0.0532	0.1748	Sweet	
Picric acid	0.0005	0.0005		
Propane	1800.0000	36000.0000		
Propionaldehyde	0.0225	0.4029	Sweet, ester	
Propionic acid	0.0840	60.0000	Sour	
Propyl acetate (n-)	0.2100	105.0000	Sweet, ester	
Propyl alcohol	75.0000	500.0000		13750.00
Propyl alcohol (n-)	0.0750	150.0000	Sweet, alcohol	
Propyl mercaptan	0.0002	0.0746		
Propyl nitrate (n-)	210.0000	210.0000	Ether-like	
Propyl sulfide	0.0531	0.0531		2801.40
Propylene	39.5600	116.2720	Aromatic	
Propylene diamine	0.0424	0.2030	Sharp, amine	
Propylene dichloride	1.1667	606.6660	Sweet	
Propylene glycol dinitrate	1.2000	1.5600		
Propylene glycol isobutyl ether	60.5000	60.5000		121.00
Propylene glycol methylether	360.0000	360.0000		3600.00
Propylene oxide	24.7500	500.0000	Sweet, alcoholic	1125.00
Pyridine	0.0090	15.0000	Burnt, sickening	90.00
Pyrrolidine	58.0000	187.3400		
Quinone	0.4000	0.4000	Acrid	2.00
Rotenone	5.7960	5.7960		
Safrole	1.4586	1.4586		
Silicon tetrafluoride	4.2500	4.2500		42.50
Skatole	4.0×10^{7}	0.2680	Perfume	
Stoddard solvent	5.2500	157.5000	Kerosene-like	2100.00
Styrene (inhibited)	0.4300	860.0000	Solventy, rubbery	4300.00
Styrene (uninhibited)	0.2021	860.0000	Solventy, rubbery	430.00
Styrene oxide	0.3093	1.9640	Sweet	

Chemical Compound	Odor Low mg/m^3	Odor High mg/m^3	Description of Odor	Irritating Conc. mg/m^3
Sulfur dichloride	0.0042	0.0042	Sulfidy	
Sulfur dioxide	1.1750	12.5000	Yech!	5.00
Sulfur monochloride			Nauseating	12.00
Sulfuric acid	1.0000	1.0000		1.10
Tetrachloroethane (1,1,2,2-)	21.0000	35.0000	Sickly sweet	1302.00
Tetrachloroethylene	31.3560	469.0000	Chlorinated solvent	710.20
Tetraethyl orthosilicate	30.6360	61.2720	Sweet, alcohol	
Tetrahydrofuran	7.3750	177.0000	Ether-like	
Tetralin	97.2000	97.2000		
Tetramethylenediamine	79.2000	79.2000		
Thiophene	0.0026	0.0026	Aromatic	
Thiophenol mercaptan	0.0012	382.5000		
Toluene petroleum	8.0250	150.0000	Rubbery, mothballs	750.00
Toluene from coke	17.5500	262.5000	Floral, pungent	750.00
Toluene 2,4 diisocyanate TDI	3.2000	17.1200	Sweet, fruity, acrid	4.00
Toxaphene	2.3660	2.3660		
Trichloro fluoromethane Freon 11	28.0000	1170.4000	Sweet	
Trichloro trifluoroethane Freon 113	342.0000	1026.0000	Sweet	
Trichlorobenzene (1,2,4-)	24.0000	24.0000		40.00
Trichloroethylene TCE	1.1340	2160.0000	Solventy	864.00
Trichloropropane (1,2,3-)			Strong, acrid	300.00
Tricycloketone	1.8660	870.8000		
Triethyl amine	0.3600	1.1200	Fishy, amine	200.00
Trimethyl amine	0.0008	0.0008	Fishy, pungent	
Trimethyl phosphite	0.0005	0.0005	Pyridine-like	
Trimethylenediamine	3757.2000	11968.5000		
Trinitro tert-butylxylene musk oil	3.8×10^{-6}	0.0487		
Turpentine	560.0000	1120.0000		560.00
Valeric acid	0.0026	0.0026		
Vanillin	2.0×10^{-7}		Perfume	
Vinyl acetate	0.3600	1.6500	Sour, sharp	
Vinyl amyl ketone	0.5150	0.5150		
Vinyl butyl ketone	0.0321	0.0321		
Vinyl propyl ketone	0.0201	0.0201		
Vinyl pyridine	1.1670	1.9450	Nauseating	
Vinyl toluene	240.0000	240.0000	Disagreeable	240.00
Vinylidene chloride	2000.0000	4000.0000	Sweet, chloroformish	
VM&P naphtha	3.8700	3.8700		
Xylene	0.3480	174.0000	Sweet	435.00
Xylidene	0.0240	0.0240	Weak, amine-like	

APPENDIX B: COMPLAINTS LOG FORM

NAME			
ADDRESS			
TELEPHONE		CELL NO.	

DATE		TIME	
NATURE OF COMPLAINT			

DESCRIPTION OF ODOUR BY COMPLAINANT:

DATE OF ODOUR		TIME	
WEATHER CONDITIONS (Ensure weather station data is attached)	WIND DIRECTION		
	WIND SPEED		
	GENERAL		
	DATE & TIME OF PRINTOUT		

ACTION TAKEN		TIME	

NAME & SIGNATURE: ....

APPENDIX C: WIND ROSE FOR DURBAN INTERNATIONAL AIRPORT

Table 10: Wind rose for Durban International Airport for forteen years worth of data

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	TOTALS
0-1																	36.65
1-1.5	0.64	0.45	0.36	0.15	0.19	0.13	0.23	0.21	0.16	0.28	0.78	0.38	0.17	0.04	0.14	0.30	4.61
1.5-3.3	1.63	1.64	1.37	0.66	0.77	0.47	0.76	0.72	0.92	1.18	2.89	1.18	0.60	0.12	0.17	0.47	15.55
3.3-5.4	1.11	2.42	2.22	1.15	0.95	0.32	0.46	0.85	1.68	2.17	2.80	0.58	0.15	0.03	0.03	0.07	16.99
5.4-7.9	0.43	2.44	2.22	1.03	0.37	0.06	0.07	0.37	1.82	2.54	1.70	0.33	0.04	0.01	0.01	0.01	13.45
7.9-10.7	0.16	2.10	1.77	0.57	0.11	0.01	0.01	0.12	1.78	2.32	0.90	0.12	0.01	0.01	0.01		10.00
10.7-13.8	0.02	0.50	0.40	0.13	0.01		0.01	0.01	0.42	0.62	0.20	0.02					2.34
13.8-17.1		0.03	0.03	0.03					0.10	0.12	0.04	0.04					0.39
17.1-20.7									0.01	0.01							0.02
20.7-24.4																	
TOTALS	3.99	9.58	8.37	3.72	2.40	0.99	1.54	2.28	6.89	9.24	9.31	2.65	0.97	0.21	0.36	0.85	63.35

APPENDIX D: RESULTS OF SMOKE FLARE EXPERIMENTS

Plate 8: (a) - (e) Time series of images taken of a dispersing smoke plume for experiment two conducted on the 4th October 1999.

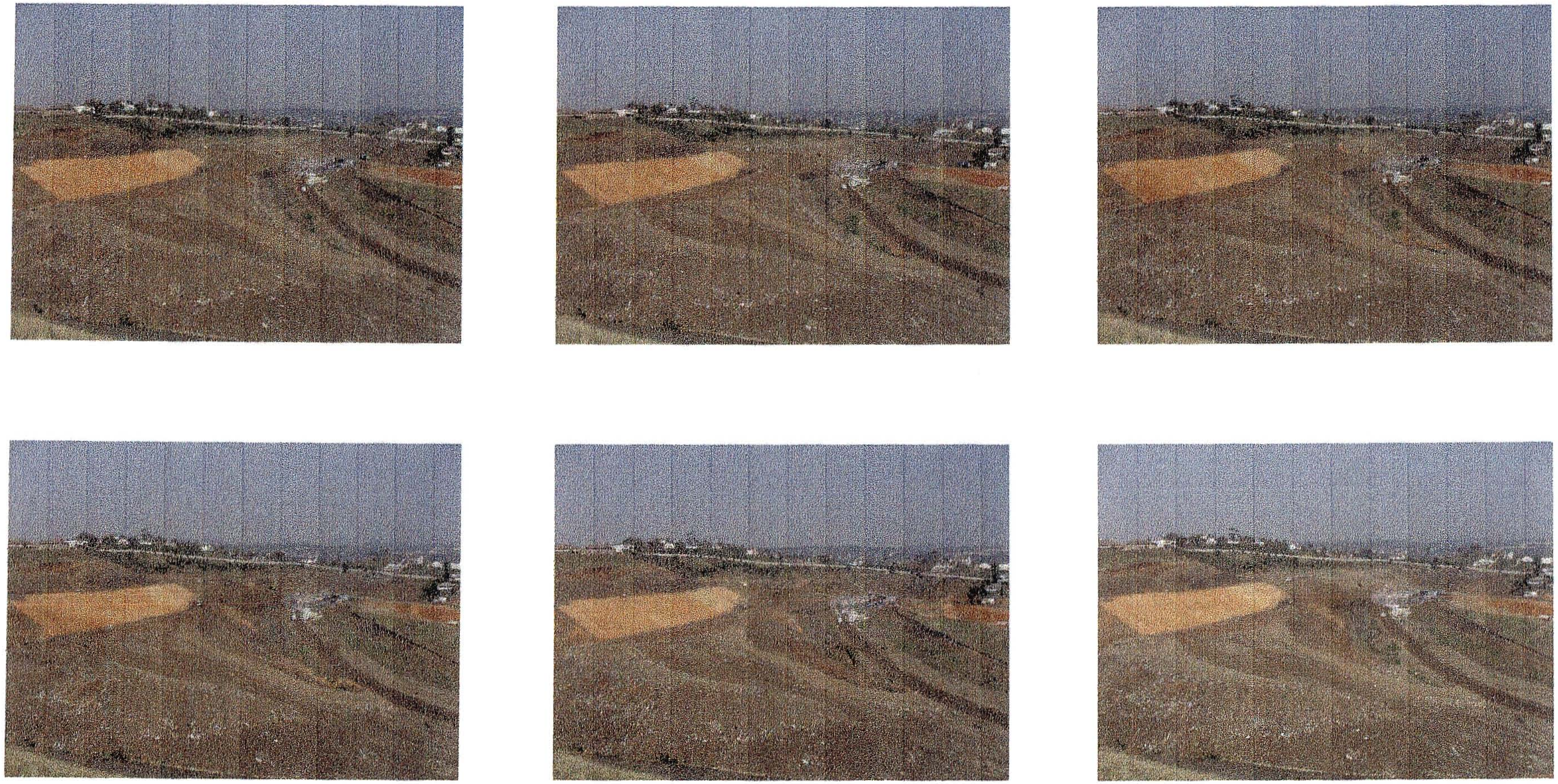


Plate 9: (a) - (b) Time series of images taken of a dispersing smoke plume for experiment three conducted on the 4th October 1999.

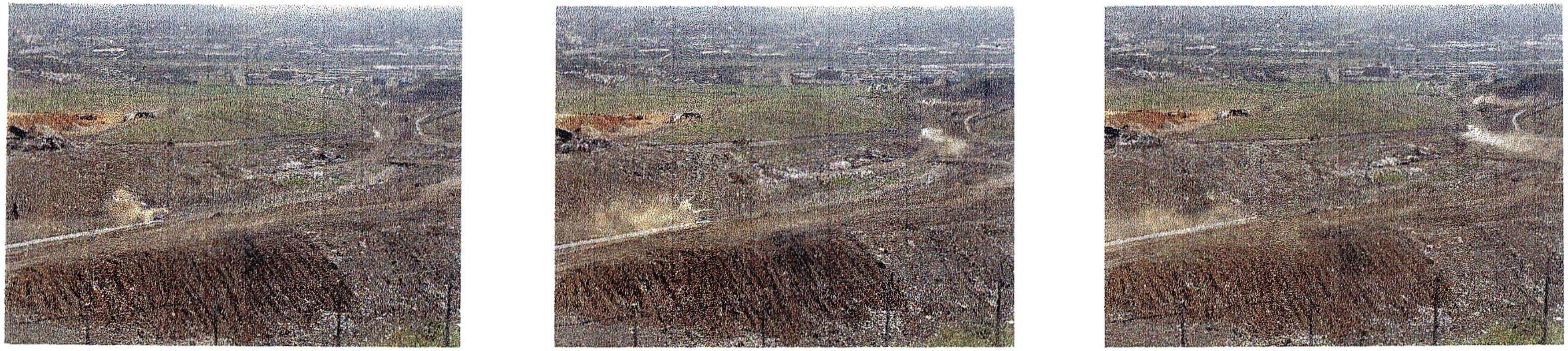


Plate 10: (a) - (c) Time series of images taken of a dispersing smoke plume for experiment four conducted on 8th October 1999.

APPENDIX E: NUMERICAL WIND FIELD SIMULATIONS.

Figure 45 shows the predicted wind field based on conditions at the time of testing on the 4th October 1999. The dashed lines in Figure 45 and Figure 46 symbolise the boundaries of the surveyed terrain data. The shape of the terrain outside of the bounded region is a result of the Kriging interpolation performed by *SURFER™*.

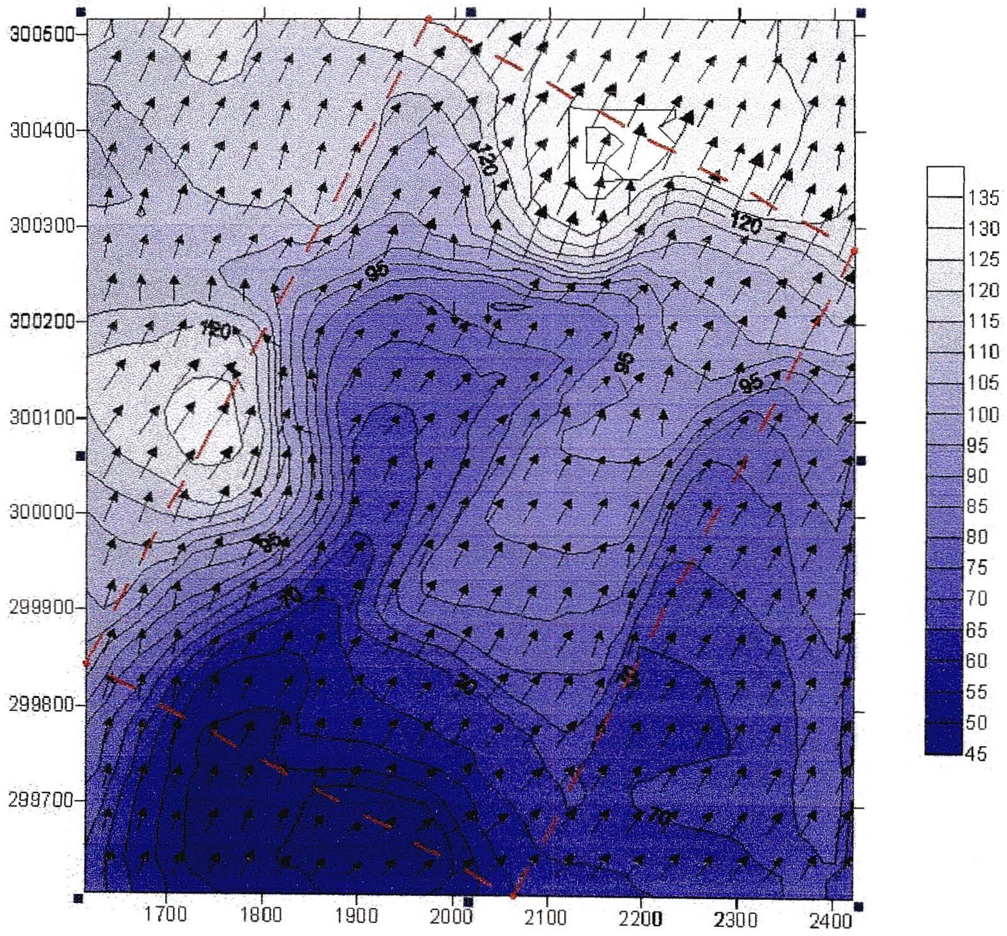


Figure 45: Predicted wind field at 1m above the ground for conditions at time of testing on 4th October 1999

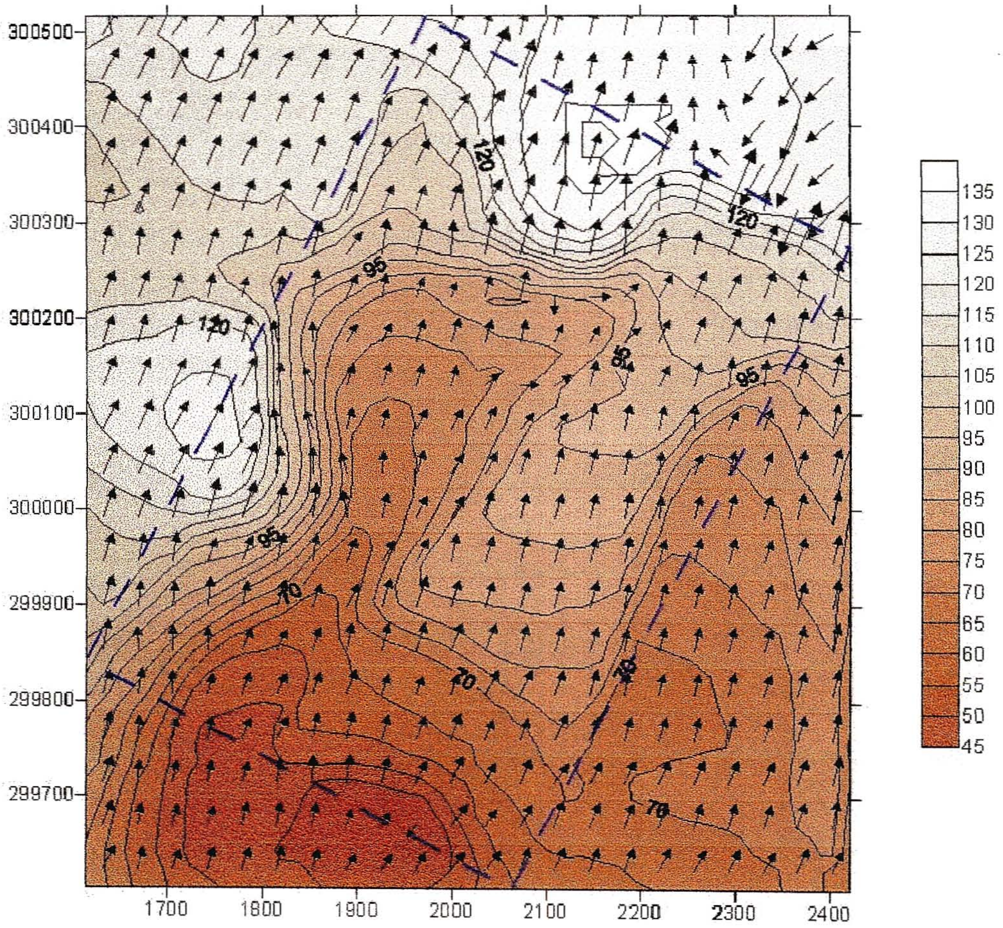


Figure 46: Predicted wind field at 1m above the ground for conditions at time of testing on 8th October 1999.

APPENDIX F: *AERMOD* INPUT FILE FOR MODEL COMPARISON STUDY

```
** This input run stream file corresponds to the model evaluation involving
** 4 other models in order to assess the capabilities and the differences in
** predicted concentration of each.
** This evaluation is for an annual set of weather data
** The output file has been named (General) Aeflannu.txt
** To run the example, type (General):
**
**  AERMOD Aeflanru.inp Aeflanru.dat

** This is line 10 including all quoted lines
CO STARTING
  TITLEONE  Bisasar Road landfill site
  TITLETWO  Model Evaluation: Flat Terrain, Annual set of weather data
  MODELOPT  CONC nochkd
  AVERTIME  1 3 24 PERIOD
  POLLUTID  SO2
  RUNORNOT  RUN
  ERRORFIL  EAEflanru.txt
CO FINISHED
** line 20
SO STARTING
  LOCATION  FILL_LOC  AREA  998.0  757.0  0.0
** Point Source          QS      HS  Xint
** Parameters:           ----    ---- ----
  SRCPARAM  FILL_LOC  0.0006  0.0  40.0
  EMISUNIT  1.0E3  GRAMS/SEC  MILLIGRAMS/M**3
  SRCGROUP  ALL
SO FINISHED

** 30
RE STARTING
  GRIDPOLR  FILL_LOC  STA
        FILL_LOC  ORIG  FILL_LOC
        FILL_LOC  DIST  50.  150.  250.  350.  450.  550.  650.  750.  850.  950.
1050.
  FILL_LOC  DIST  1150.  1250.  1350.  1450.  1550.  1650.  1750.  1850.  1950.
 2050.
```

```
        FILL_LOC DIST 2150. 2250. 2350. 2450.
        FILL_LOC GDIR 24 0. 15.
        FILL_LOC END
** 40
RE FINISHED

ME STARTING
  SURFFILE Aeflannu.SFC
  PROFFILE Aeflannu.PFL
  SURFDATA 11111 2000 BISASAR
  UAIRDATA 00011111 2000 BISASAR
  SITEDATA 0 2000 BISASAR
  PROFBASE 0.0 METERS
** 50
ME FINISHED

OU STARTING
  RECTABLE ALLAVE FIRST SECOND

  PLOTFILE 1 ALL 1ST   PLFLANr1.FIL
  PLOTFILE 1 ALL 2ND   PLFLAr12.FIL
  PLOTFILE 3 ALL 1ST   PLFLANr3.FIL
  PLOTFILE 3 ALL 2ND   PLFLAr32.FIL
  PLOTFILE 24 ALL 1ST  PLFLAr24.FIL
  PLOTFILE 24 ALL 2ND  PLFLr242.FIL
  PLOTFILE PERIOD ALL  PLFLANru.FIL

OU FINISHED
```

APPENDIX G: DISPERSION MODEL COMPARISON RESULTS

Ad = *ADMS™*
Ae = *AERMOD*
Ca = *CALPUFF*
Is = *ISC3*
R = Rural mode
U = Urban mode

The ratio's shown represent the first model labelled divided by the second model labelled. E.g. AdAeR = *ADMS™* divided by *AERMOD* (rural)

Table 11: Results of comparisons between four dispersion models

AdAeR	1 hr	3 hr	24 hr	annual
min	0.2	0.1	0.2	0.1
max	3.9	18.5	17.4	27.4
average	0.5	1.2	1.0	1.8
std dev	0.3	1.2	1.1	2.5

AdAeU	1 hr	3 hr	24 hr	annual
min	0.2	0.1	0.2	0.1
max	3.9	18.6	17.7	27.3
average	0.5	1.2	1.0	1.8
std dev	0.3	1.2	1.1	2.5

AdIsR	1 hr	3 hr	24 hr	annual
min	0.1	0.1	0.1	0.1
max	3.0	15.9	21.4	38.5
average	0.3	0.9	0.8	2.2
std dev	0.2	1.1	1.2	3.0

Table 11 continued

AdIsU	1 hr	3 hr	24 hr	annual
min	0.8	0.7	0.3	0.2
max	11.8	67.6	90.3	117.0
average	2.1	4.8	3.7	4.9
std dev	1.0	5.0	5.4	7.6

AdCaR	1 hr	3 hr	24 hr	annual
min	0.0	0.0	0.0	0.0
max	1.7	6.7	9.6	11.0
average	0.2	0.4	0.3	0.5
std dev	0.1	0.5	0.6	0.7

AdCaU	1 hr	3 hr	24 hr	annual
min	0.1	0.0	0.0	0.0
max	1.4	6.1	8.2	8.0
average	0.2	0.4	0.3	0.4
std dev	0.2	0.5	0.5	0.6

AeIsR	1 hr	3 hr	24 hr	annual
min	0.4	0.2	0.2	0.2
max	3.7	3.7	2.8	5.6
average	0.7	0.9	0.8	1.6
std dev	0.3	0.5	0.5	1.5

AeIsU	1 hr	3 hr	24 hr	annual
min	2.5	1.2	0.9	0.4
max	11.9	11.7	12.2	14.1
average	4.6	4.7	3.9	3.8
std dev	1.3	2.1	2.6	3.2

Table 11 continued

AeCaU	1 hr	3 hr	24 hr	annual
min	0.1	0.1	0.1	0.0
max	2.6	2.3	2.8	2.6
average	0.4	0.4	0.4	0.4
std dev	0.3	0.3	0.3	0.4

AeCaR	1 hr	3 hr	24 hr	annual
min	0.1	0.1	0.0	0.3
max	1.7	1.5	1.8	22.7
average	0.3	0.4	0.3	5.1
std dev	0.2	0.2	0.3	4.6

CalsR	1 hr	3 hr	24 hr	annual
min	0.6	1.0	0.7	0.5
max	8.6	7.4	8.4	11.8
average	2.5	2.8	3.0	4.1
std dev	1.1	1.1	1.2	1.0

CalsU	1 hr	3 hr	24 hr	annual
min	1.8	1.1	0.7	0.7
max	27.6	29.8	28.2	27.4
average	13.4	13.3	12.1	11.2
std dev	5.8	5.3	5.5	5.2

APPENDIX H: SPECTRUM RESULTS OF GC/MS ANALYSIS

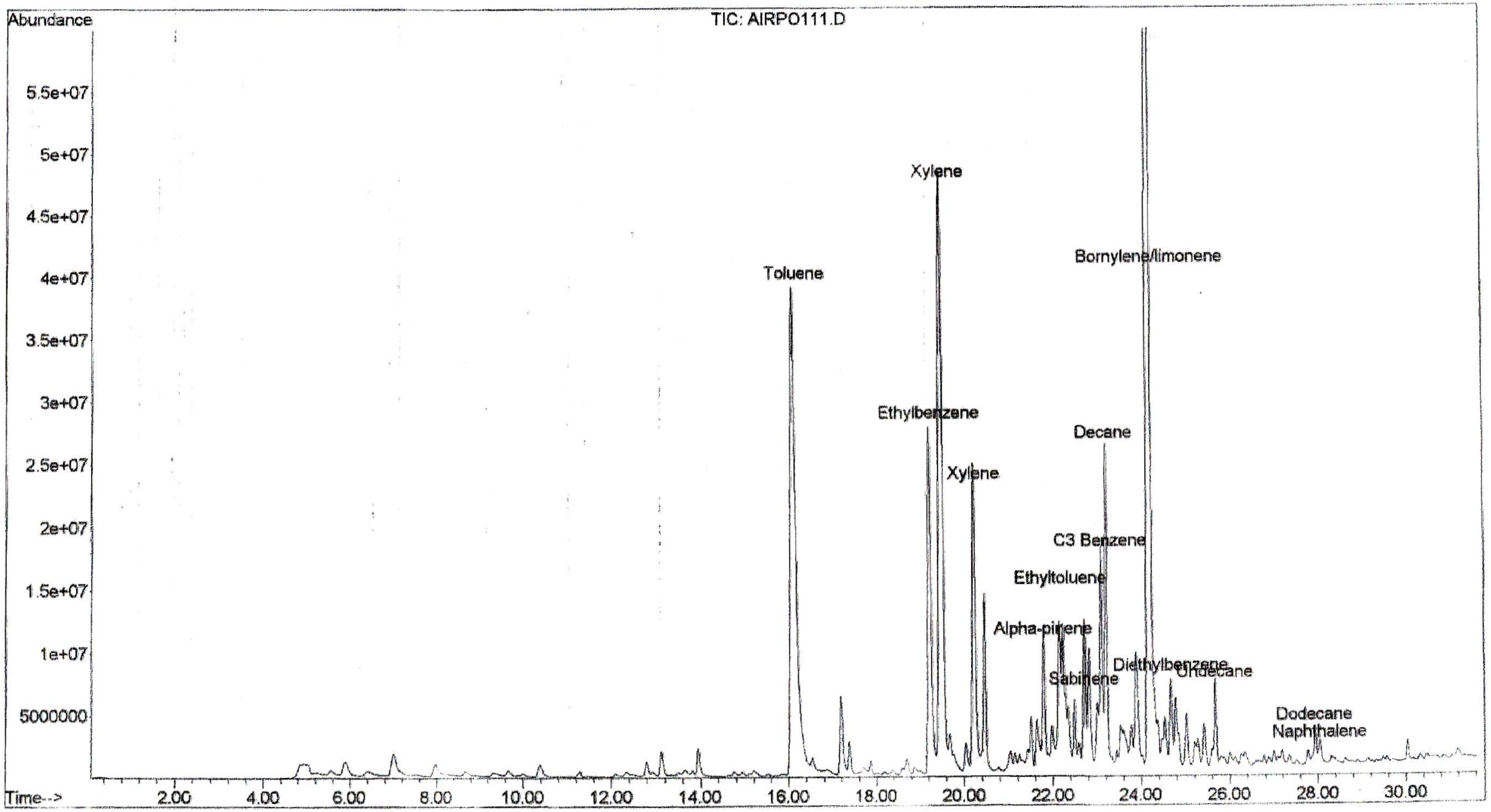


Figure 47: Full time spectrum for sample taken on 23rd August 2001 (Flow rate = 16.7 mL/min)

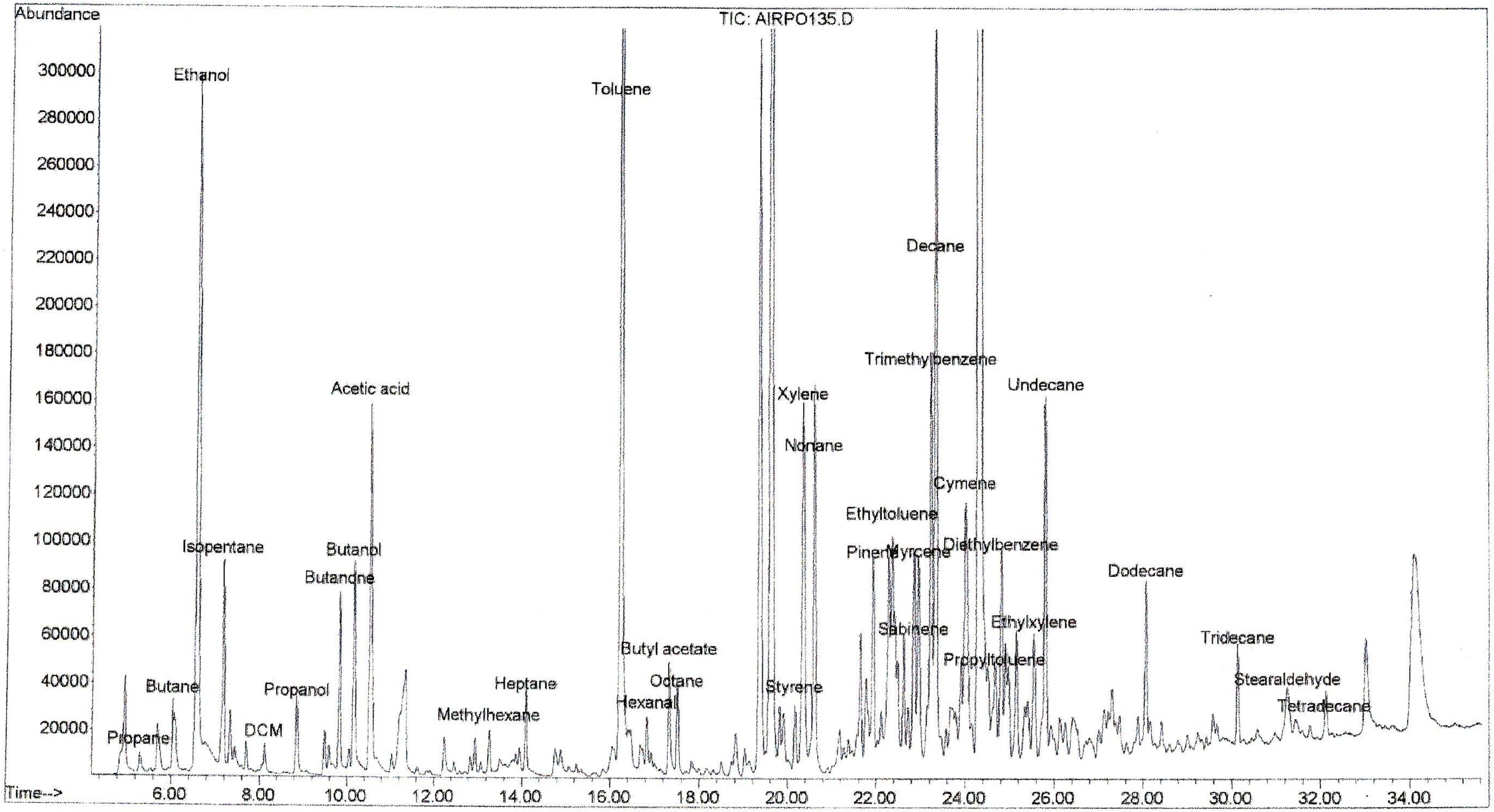


Figure 48: Partial time spectrum for sample taken on 30th October 2001 (Flow rate = 66.7 mL/min)

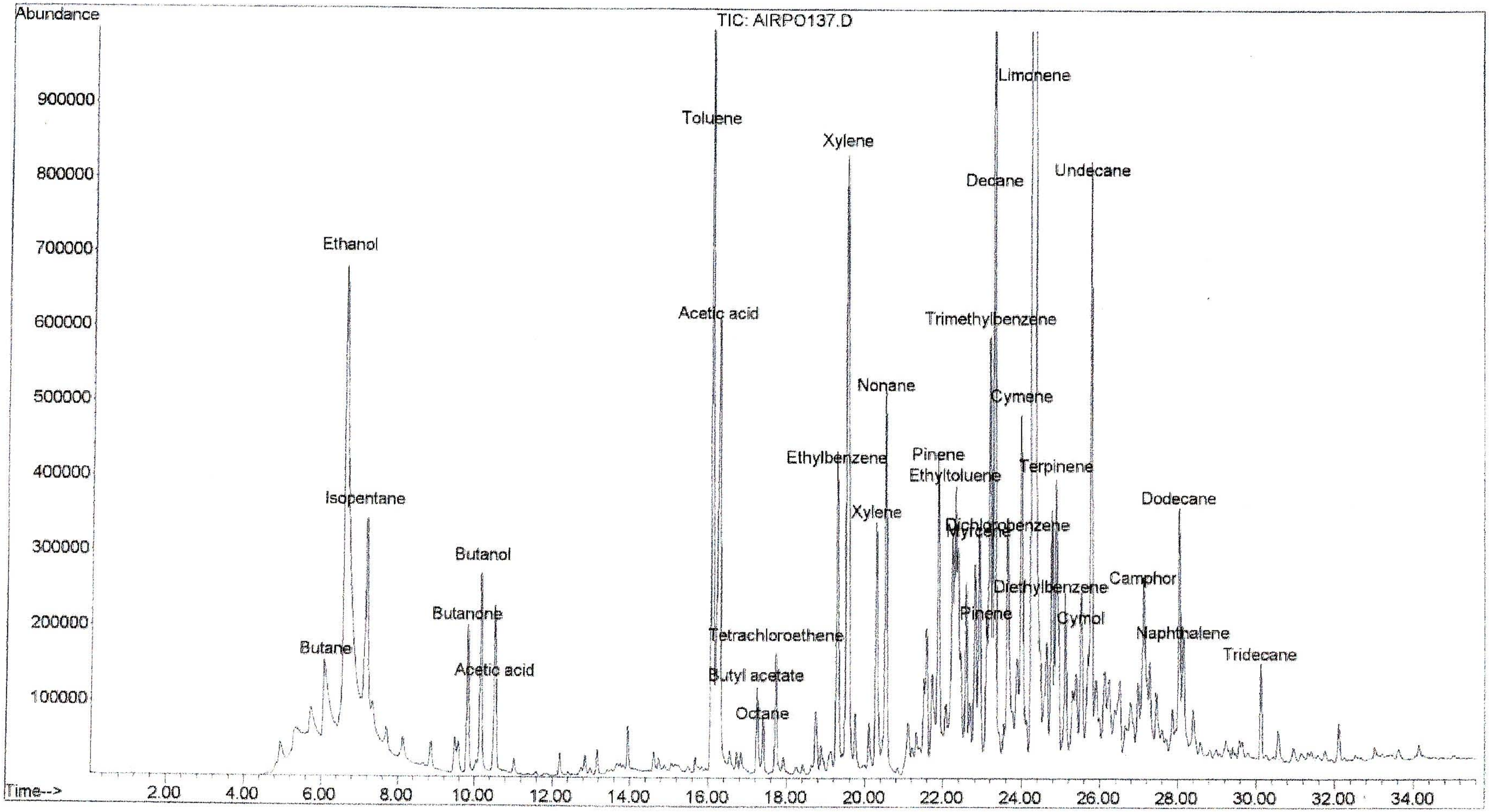


Figure 49: Full time spectrum for sample taken on 2nd November 2001 (Flow rate = 16.7 mL/min)

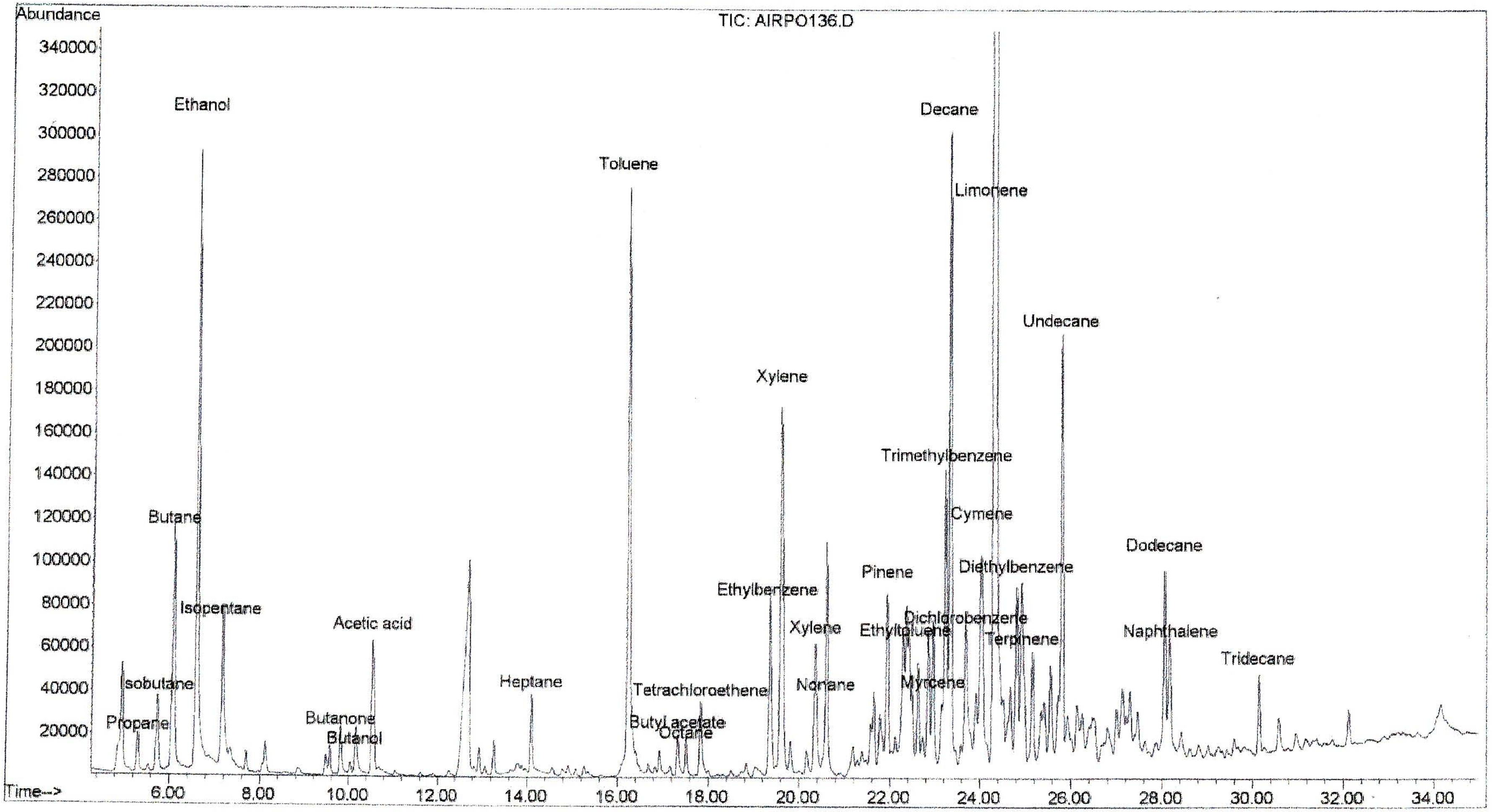


Figure 50: Partial time spectrum for sample taken on 2nd November 2001 (Flow rate = 66.7 mL/min)

APPENDIX J: CODE FOR COMPONENTS OF *OMS*

APPENDIX J.1: BATCH FILE

```
del "D:\Masters\OMS\Weatherdata\ADMSWeatherCalm.met"
‘Deletes the ADMSweathercalm.met’ file from the previous run

del "D:\Masters\OMS\ADMS™\omsirec.dat"
‘Deletes the file ‘omsirec’ from the previous run so that
‘that new ‘omsirec.gst’ can be renamed

Start "" /wait "D:\Masters\OMS\VisualBasic\Weather.exe"
‘Weather processing program is executed

Start "" /wait
"D:\Masters\OMS\VisualBasic\FillingLocationInput.exe"
 ‘ The filling location is updated in the ADMS™ input file

If exist "D:\Masters\OMS\Weatherdata\ADMSWeatherCalm.met"
goto end
‘Check to see if the conditions are calm, and if so exit the
‘batch file

Start "" /wait "D:\Program Files\Dispersion
Models\ADMS™\ADMS3h.exe" "D:\Masters\OMS\ADMS™\omsirec.apl"
/e2
‘ADMS™ is run

rename "D:\Masters\OMS\ADMS™\omsirec.gst" "omsirec.dat"
‘The file ‘omsirec.gst’ is renamed omsirec.dat as an
‘application on the computer already uses a file with the
‘.gst extension

Start "" /wait "D:\Masters\OMS\VisualBasic\ExcelSubst.exe"
‘ADMS™ output is processed to create a contour plot of
‘concentration

Start "" /wait
"D:\Masters\OMS\VisualBasic\Excelsubstirec.exe"
‘A second program is executed to determine whether any
‘complaints are likely
```

APPENDIX J.2: WEATHER DATA PROCESSING CODE

```
'Placing "Option Explicit" at the top of the code means that
'all variable have to be declared. Assists in editing code
'as an error message is brought up if a variable is not
'declared or spelt incorrectly, etc.

Option Explicit

'Declare all variables

Dim LastLineNum As Integer
Dim intLineCounter As Integer
Dim strThisLine As String
Dim RecLen As Long
Dim LastLineLen As Long
Dim ADMWeatherLen As Long
Dim Weather As WeatherInfo
Dim LastLine As WeatherInfo
Dim LastLinea As String
Dim LastLineNuma As Integer
Dim WeatherDataLen As Long
Dim ADMSWeatherLen As Long
Dim ADMSWeather As WeatherInfo
Dim ADMSWeatherNum As Integer
Dim ADMSWeatherNum2 As Integer
Dim ADMSWeatherCalm As Integer
Dim FileNum As Integer
Dim Individuals As Variant
Dim DDNumbers As Variant
Dim TNumbers As Variant
Dim DateTime As String
Dim DayDate As String
Dim Time As String
Dim WindSpeed As String
Dim StanDev As String
Dim WindDirection As String
Dim WindDirecSURFER As Single
Dim RelHum As String
Dim SolRad As String
Dim TempC As String
Dim Rain As String
Dim DDWithoutOps As String
Dim TWithoutOps As String

Sub Main()

'File containing weather data is opened and the last line
'copied to a temporary location, "strThisLine"

FileNum = FreeFile
```

```
Open "C:\Program Files\OMS\Weatherdata\WeatherData.dat" For_
Input As FileNum
    intLineCounter = 0
        While Not EOF(FileNum)
            intLineCounter = intLineCounter + 1
            Line Input #FileNum, strThisLine
        Wend
Close FileNum

'File containing one line of data from previous time step
'needs to be cleared.

Kill "C:\Program Files\OMS\Weatherdata\LastLine.dat"

'Current weather conditions can be pasted to a new file.

LastLineNum = FreeFile
Open  "C:\Program  Files\OMS\Weatherdata\LastLine.dat"  For
Binary_ As LastLineNum
    LastLineLen = 1
        Put #LastLineNum, LastLineLen, strThisLine
Close LastLineNum

'Another file then needs to be set-up with the correct
'headers and in the correct format for use in ADMS™

ADMSWeatherNum = FreeFile
Open "C:\Program Files\OMS\Weatherdata\ADMSWeather.met" For_
Output As ADMSWeatherNum
Print #ADMSWeatherNum, "VARIABLES:"
Print #ADMSWeatherNum, "8"
Print #ADMSWeatherNum, "U"
Print #ADMSWeatherNum, "PHI"
Print #ADMSWeatherNum, "SIGMA THETA (DEGREES)"
Print #ADMSWeatherNum, "TEMPERATURE (C)"
Print #ADMSWeatherNum, "RELATIVE HUMIDITY (PERCENT)"
Print #ADMSWeatherNum, "INCOMING SOLAR RADIATION"
Print #ADMSWeatherNum, "P"
Print #ADMSWeatherNum, "SENSIBLE HEAT FLUX"
Print #ADMSWeatherNum,
Print #ADMSWeatherNum, "DATA:"
Close ADMSWeatherNum

'The weather station records information that is of no use
'here, therefore the useful information is extracted. This
'is done using the SPLIT command, as each parameter is
'separated by a comma.

LastLineNuma = FreeFile
Open  "C:\Program  Files\OMS\Weatherdata\LastLine.dat"  For
Input_ As LastLineNuma
    Line Input #LastLineNuma, LastLinea
    Individuals = Split(LastLinea, ",")
Close LastLineNum
```

```
'The date and time need to be further processed into the
'correct format. The date is recorded as DD/MM/YY and the
'time as HH:MM. ADMS™ does not require the date or time, but
'both will be used for making the header of the plot and for
'the file name. Cannot have operators (/ and :) therefore, a
'six digit number and a four digit number are created for
'the date and time respectively. The TRIM function is used
'to remove any characters before or after the parameter.

ADMSWeatherNum2 = FreeFile
Open "C:\Program Files\OMS\Weatherdata\ADMSWeather.met" For_
Binary As ADMSWeatherNum2

    DayDate = Trim(Individuals(0))
    DDNumbers = Split(DayDate, "/")
    DDWithoutOps     =     DDNumbers(2)     +     DDNumbers(0)     +
DDNumbers(1)
    Time = Trim(Individuals(1))
    TNumbers = Split(Time, ":")
    TWithoutOps = TNumbers(0) + TNumbers(1)

'Files containing the date and time are then written out.

Dim CurrentDateWOOpsNum As Integer
CurrentDateWOOpsNum = FreeFile
Open  "C:\Program  Files\OMS\Weatherdata\DateWOOps.dat"  For
Output_ As CurrentDateWOOpsNum
Print #CurrentDateWOOpsNum, DDWithoutOps
Close CurrentDateWOOpsNum

Dim CurrentTimeWOOpsNum As Integer
CurrentTimeWOOpsNum = FreeFile
Open  "C:\Program  Files\OMS\Weatherdata\TimeWOOps.dat"  For
Output_ As CurrentTimeWOOpsNum
Print #CurrentTimeWOOpsNum, TWithoutOps
Close CurrentTimeWOOpsNum

'Files containing the date and time with operators are also
'written out to use in the heading of the plot.

Dim CurrentDateNum As Integer
CurrentDateNum = FreeFile
Open "C:\Program Files\OMS\Weatherdata\Date.dat" For Output
As_ CurrentDateNum
Print #CurrentDateNum, DayDate
Close CurrentDateNum

Dim CurrentTimeNum As Integer
CurrentTimeNum = FreeFile
Open "C:\Program Files\OMS\Weatherdata\Time.dat" For Output
As_ CurrentTimeNum
Print #CurrentTimeNum, Time
Close CurrentTimeNum

'A file for the wind speed is written out to call later to
'place the wind speed as text on the plot.
```

```
    WindSpeed = Trim(Individuals(2))

Dim CurrentWSNum As Integer
CurrentWSNum = FreeFile
Open "C:\Program Files\OMS\Weatherdata\Windspeed.dat" For
Output_ As CurrentWSNum
Print #CurrentWSNum, WindSpeed
Close CurrentWSNum

'Two wind directions are calculated. One file written out
'containing the wind direction for use on the plot. ADMS™
'automatically assumes that North is directly up as a
'terrain file is plotted. This is no the case here.
'Therefore the wind 'has to be rotated 180 degrees for use
'in ADMS™.

    If Trim(Individuals(3)) < 180 Then
        WindDirection = Trim(Individuals(3)) + 180
        Else: WindDirection = Trim(Individuals(3)) - 180
    End If

    WindDirecSURFER = 180 - Trim(Individuals(3))

Dim CurrentWDNum As Integer
CurrentWDNum = FreeFile
Open "C:\Program Files\OMS\Weatherdata\WindDirection.dat"
For_ Output As CurrentWDNum
Print #CurrentWDNum, WindDirecSURFER
Close CurrentWDNum

'Five other parameters measured directly by the weather
'station, Standard deviation, Temperature, Relative
'Humidity, Solar Radiation and Rainfall, are used by ADMS™
'as well.

StanDev = Trim(Individuals(4))
TempC = Trim(Individuals(5))
RelHum = Trim(Individuals(6))
SolRad = Trim(Individuals(8))
Rain = Trim(Individuals(10))

'This sub section of the program calculates the Sensible
'Heat Flux in units of Watts/m^2. The calculations are
'based on the paper written by: Holtslag & Van Ulden (1983)
'entitled 'A simple scheme for Daytime Estimates of the
'surface fluxes'

Dim NetRadiation As Single
Dim NetRadStr As String
Dim albedo As Single
Dim Incomlongrad As Single
Dim Ougolongrad As Single
Dim Incomsolrad As Single
Dim TempK As Single
Dim constant1 As Single
```

```
Dim constant2 As Single
Dim constant3 As Single
Dim cover As Single
Dim StefBoltz As Single
Dim RainSingle As Integer
Dim ADMSWeatherNum3 As Integer

albedo = 0.23   'Grass covered surface
Incomsolrad = SolRad

'Incoming Solar Radiation is affected by cloud cover, a
'quantity that we don't measure. If raining, assume cloud
'cover = 1, otherwise, assume that skies are always 20%
'covered. Cloud cover value alters SHF by approx 15% from 0
'to 100%

RainSingle = Rain
If RainSingle > 0 Then
    ccover = 1
    Else: ccover = 0.2
End If

TempK = TempC + 273
constant1 = 5.31 * 10 ^ (-13)
constant2 = 60
constant3 = 0.12
StefBoltz = 5.67 * 10 ^ (-8)

'First, the net radiation is calculated from the incoming
'and outgoing radiation.

NetRadiation = (((1 - albedo) * Incomsolrad) + (constant1 *_
(TempK ^ 6)) - (StefBoltz * (TempK ^ 4)) + (constant2 *_
ccover))_/ (1 + constant3)

Dim alpha As Integer
Dim beta As Integer
Dim Soilheatflux As Single
Dim constant4 As Single
Dim gammas As Single
Dim gsRatio As String
Dim SensHeatFlux As Single
Dim SHF As String

constant4 = 0.1 ' grass covered surface in the Netherlands
Soilheatflux = constant4 * NetRadiation

alpha = 1
beta = 20

'This equation was derived by adding a tread line to values
'plotted in excel

gammas = (0.0013 * (TempC ^ 2)) - (0.0802 * TempC) + 1.4965
```

```
'The variable gammas is a single and a 'String' variable is
'needed to write this number to file

gsRatio = gammas

'The Sensible Heat Flux can now be calculated.

SensHeatFlux = (((1 - alpha) + (gammas)) / (1 + gammas) *_
(NetRadiation - Soilheatflux)) - beta
SHF = SensHeatFlux

'The parameters can now be written to the ADMS™ weather
file. 'ADMS™ does not run if the conditions are calm (i.e.
wind speed '< 0.75 m/s). If conditions are calm, then a file
a separate file is written out stating that conditions are
'calm. If the wind speed is > 0.75 m/s, then the parameters
'are written to the ADMS™ weather file.

If WindSpeed < 0.75 Then

ADMSWeatherCalm = FreeFile
Open "C:\Program files\OMS\Weatherdata\ADMSWeathercalm.met"
For_ Binary As ADMSWeatherCalm
Put #ADMSWeatherCalm, , "The wind speed = " + WindSpeed + "
m/s, therefore calm conditions exist and ADMS™ will not run
for this time step"

Else

Put #ADMSWeatherNum2, 151, WindSpeed + "," + WindDirection +
"," + StanDev + "," + TempC + "," + RelHum + "," + SolRad +
"," + Rain + "," + SHF
Close ADMSWeatherNum2
End If

End Sub
```

APPENDIX J.3: USER INTERFACE: NEW FILLING LOCATION

```
Option Explicit

Dim ComPrompt

Sub RunSURFER()

' Open MS-Dos command prompt.
' Specifying 3 as the second argument opens the application
' in normal size and gives it the focus

ComPrompt = Shell("C:\SURFER6\Gsmac32.exe", 3)

'Keystrokes are then passed, to open the file
'"FillingLocationSURFERBisasar"

SendKeys "^o", True
SendKeys "FillingLocationSURFERBisas", True
SendKeys "~", True
SendKeys "{F5}", True

End Sub

'If the "YES" command button is clicked, i.e. to go ahead
and 'change the filling location, then the routine RunSURFER
'above is run.

Private Sub cmdChange_Click()
    RunSURFER
    End
End Sub

'If the user has erroneously opened the application, hitting
'the '"EXIT" button will close the application.

Private Sub cmdExit_Click()
    End
End Sub
```

APPENDIX J.4: UPDATING *ADMS*™ INPUT FILE: NEW FILLING LOCATION

```
Option Explicit

Dim FillLocNum As Integer
Dim OmsNum As Integer
Dim Individuals As Variant
Dim co-ordinates As String
Dim x As String
Dim xloc As String
Dim y As String
Dim yloc As String

Sub Main()

‘Open the ASCII file containing the co-ordinates of the
‘filling location. The split command is used to separate the
‘two co-ordinates. The co-ordinates are the divided by 1000
‘put them in kilometers and not metres.

FillLocNum = FreeFile
Open                                    "D:\Masters\OMS\Plot
Archive\CurrentFillingLocation.dat" For Input As FillLocNum
    Line Input #FillLocNum, co-ordinates
    Individuals = Split(co-ordinates, ",")
    x = Trim(Individuals(0)) / 1000
    y = Trim(Individuals(1)) / 1000

Close FillLocNum

‘The co-ordinates are then written to the ADMS™ input file.

OmsNum = FreeFile
Open "D:\Masters\OMS\ADMS™\OMS.apl" For Binary As OmsNum
    Put #OmsNum, 14280, x
    Put #OmsNum, 14325, y
Close OmsNum

End Sub
```

APPENDIX J.5: PROCESSING OF *ADMS*™ OUPUT: GRID RECEPTORS

```
Option Explicit

Sub Main()

Dim FileName, OutputFile As String
Dim DataArray(1 To 962, 1 To 8)
Dim Temp, Temp2
Dim r, q, w, X, a As Integer

'ADMS™ output file "omsirec.dat" is opened.

FileName = "C:\Program Files\OMS\ADMS™\omsirec.dat"

Open FileName For Input As #1

'The 8 columns and 962 rows of data are copied to a
'temporary array.

For r = 1 To 962
For q = 1 To 8
Input #1, Temp
DataArray(r, q) = Temp

Next q
Next r

Close #1

'Only the data that is required for plotting the graphic in
'SURFER™ is used. Line 1 in the original file contained
'headers which are not necessary. Column five contains the x
'co-ordinate, column six contains the y co-ordinate. The
'values in both of these columns need to be transformed onto
'the Lo31 grid.

For w = 2 To 962
DataArray(w, 5) = Round((-1 * Val(DataArray(w, 5))) - 924,
0)
DataArray(w, 6) = Round((-1 * Val(DataArray(w, 6))) -
3298804, 0)

'Column eight contains the concentration data. The log of
'zero cannot be performed, therefore wherever the
'concentration equals zero, it is replaced by a number small
'enough that it can be logged but would not change the
'properties of the plot.

If DataArray(w, 8) <= 0 Then
DataArray(w, 8) = 3E-28
Else
DataArray(w, 8) = DataArray(w, 8)
End If
```

```
DataArray(w, 8) = Round(Log10(1 / DataArray(w, 8)), 2)

Next w

'The three columns of data (x, y, log[dilution]) are then
'written to a new file for use in SURFER™.

OutputFile = "C:\Program Files\OMS\ADMS™\OmsfiltLo31.dat"

Open OutputFile For Output As #2

For a = 2 To 962
Temp2    =    Format(DataArray(a,    5))    +    Chr(32)    +
Format(DataArray(a, 6)) + Chr(32) + Format(DataArray(a, 8))
Print #2, Temp2
Next a
Close #2

End Sub

Static Function Log10(X)
   Log10 = Log(X) / Log(10#)
End Function
```

APPENDIX J.6: PROCESSING OF *ADMS*™ OUPUT: EXCEEDANCES

```
Option Explicit

Sub Main()

Dim FileName, OutputFile As String
Dim DataArray(1 To 14, 1 To 9)
Dim Temp, Temp2
Dim r, q, w, X, a As Integer
Dim Temp4 As String

‘“Omsirec.pst” contains predicted concentration at specific
‘receptors. The same procedure is followed as above in
‘Appendix K.3, but an ‘extra column is added for the address
‘of the specific ‘receptors.

FileName = "C:\Program Files\OMS\ADMS™\omsirec.pst"

Open FileName For Input As #1

For r = 1 To 14
For q = 1 To 4
Input #1, Temp
DataArray(r, q) = Temp

Next q

'Column 5 contains addresses, which are space-delimited
‘strings, and need to be opened separately as not to confuse
‘the ordering of the columns.

Input #1, Temp4
DataArray(r, 5) = Temp4

For q = 6 To 9
Input #1, Temp
DataArray(r, q) = Temp

Next q

Next r

Close #1

For w = 2 To 14
DataArray(w, 6) = Round((-1 * Val(DataArray(w, 6))) - 924,
0)
DataArray(w, 7) = Round((-1 * Val(DataArray(w, 7))) -
3298804, 0)

If DataArray(w, 9) = 0 Then
DataArray(w, 9) = 3E-28
```

```
Else
DataArray(w, 9) = DataArray(w, 9)
End If

DataArray(w, 9) = Round(Log10(1 / DataArray(w, 9)), 2)
DataArray(w, 5) = DataArray(w, 5)

Next w

OutputFile = "C:\Program Files\OMS\ADMS™\OmsirecLo31.dat"

Open OutputFile For Output As #2

For a = 2 To 14
Temp2    =    Format(DataArray(a,    6))    +    Chr(32)    +
Format(DataArray(a, 7)) + Chr(32) + Format(DataArray(a, 9))
+ Chr(32) + Chr(34) + Format(DataArray(a, 5)) + Chr(34)
Print #2, Temp2
Next a
Close #2

'"Signal" calls the subroutine described below.

Signal

End Sub


Sub Signal()

'This sub routine is used to check whether the dilution at
'any of the specified receptors is less than the threshold
'(i.e. complaint is likely).

Dim InputFileName, IrecOutputFile As String
Dim DataArray2(1 To 13, 1 To 4)
Dim Temp1, Temp3
Dim c, d, e As Integer

InputFileName = "C:\Program Files\OMS\ADMS™\omsirecLo31.dat"

Open InputFileName For Input As #3

For c = 1 To 13
For d = 1 To 4
Input #3, Temp1
DataArray2(c, d) = Temp1

Next d
Next c

Close #3

IrecOutputFile="C:\ProgramFiles\OMS\ADMS™\OmsirecLo31sig.dat
"
```

```
Open IrecOutputFile For Output As #4

For e = 1 To 12

'The threshold dilution is 5.192, so each value of predicted
'dilution is compared with the threshold and if less than
'the threshold, then that line of data (x, y, address and
'dilution value) is written to a new file (OmsirecLo31sig).
'Id the threshold has not been exceeded on any particular
'line, than the line of data is ignored.

If DataArray2(e, 3) < 5.192 Then
Temp3    =    Format(DataArray2(e,    1))    +    Chr(44)    +
Format(DataArray2(e,    2))    +    Chr(44)    +    Chr(34)    +
Format(DataArray2(e, 4) + Chr(34))
Print #4, Temp3
Else
Temp3 = ""
End If

Next e

End Sub
Static Function Log10(X)
   Log10 = Log(X) / Log(10#)
End Function
```

APPENDIX J.7: *SURFER™* SCRIPT TO PLOT FINAL GRAPHIC

```
Option Explicit

Dim Srf As Object
Dim DayDate As String
Dim Time As String
Dim WindSpeed As String
Dim WinddirecSURFER As String
Dim DateWOOps As String
Dim TimeWOOps As String
Dim exceedances As String

‘OPEN SURFER™ AND A NEW PLOT WORKSHEET

‘Open SURFER™ as an application

SET Srf = CreateObject("SURFER™.App")

‘Close all open windows

Srf.FileClose()

‘Open to plot document

Srf.FileNew(0)

‘GRID DATA

‘Grid the data file, using Kriging on a 50m x 50m grid
‘spacing.

Srf.GridData("C:\ProgramFiles\OMS\ADMS™\OmsFiltLo31.dat",xSi
ze=50,ySize=50,GridMethod=1,OutGrid="C:\ProgramFiles\OMS\ADM
S™\OmsFiltLo31.grd",OutFmt=1)

‘PLOT

‘The file containing specific locations of exceedances is
‘opened.

OPEN "C:\Program Files\OMS\ADMS™\OmsirecLo31sig.dat" FOR
Input AS #1

‘If the file is empty (the threshold was not exceeded at any
‘specific locations), then the subroutine “noexceedances is
‘run. If the file is not empty and the threshold was
‘exceeded at specific receptors, the subroutine “exceedances
‘is run.

IF EOF(1)=-1 THEN

GOSUB noexceedances
```

```
end
ELSE GOSUB exceedances:
end
ENDIF

noexceedances:

‘Open existing .dxf file as the base map.

Srf.MapLoadBaseMap("C:\ProgramFiles\OMS\TerrainData\Guyedite
d.dxf",ID="Terrain")

‘Create a filled contour map from the grid file created
‘above from the “OmsFiltLo31” file.

Srf.MapContour("C:\ProgramFiles\OMS\ADMS™\OmsFiltLo31.grd",6
7,LevelFile="C:\ProgramFiles\OMS\ADMS™\Contcol.lvl",LabType=
0,LabnDig=0,SmoothAmount=1,iLabBeg=1,iLabFreq=5,ID="Concentr
ation",ScaleID="ConcScale")

Srf.Select("Terrain")
Srf.Select("Concentration")
Srf.MapOverlayMaps()

‘Edit Colour Scale

Srf.EditColorScale(ScaleID="ConcScale",LabFace="Concentratio
n (ppb)",LabFontSize=16,LabFontStyle=1,LabType=0,LabnDig=1)

‘Edit the left hand axis

Srf.Select("Terrain:Left Axis")
Srf.MapEditAxis("LeftAxis","Distance(m)",TitleOff1=0.5,Title
Off2=0,TitleAngle=0,TitleFontSize=16,TitleFontStyle=1,AxisLi
neStyle="Solid",LabOff=0.1,LabType=0,LabNDig=0,LabFontSize=1
2,MajTicType=1)

‘Edit the bottom axis

Srf.Select("Terrain:Bottom Axis")
Srf.MapEditAxis("BottomAxis","Distance(m)",TitleOff1=0.1,Tit
leOff2=0,TitleAngle=0,TitleFontSize=16,TitleFontStyle=1,Axis
LineStyle="Solid",LabOff=0.1,LabType=0,LabNDig=0,LabFontSize
=12,MajTicType=1)

‘Adding current time and date to the heading by opening the
‘files created in the weather processing

Open "C:\Program Files\OMS\Weatherdata\Date.dat" For Input
As #2
       Line Input #2, DayDate
 Close #1

Open "C:\Program Files\OMS\Weatherdata\Time.dat" For Input
As #3
       Line Input #3, Time
```

```
 Close #2

Srf.Select ("Terrain:Top Axis")
srf.MapEditAxis("Top Axis","Predicted dispersion of odour
from the working face on " + DayDate + " at " +
Time,TitleOff1=0.1,TitleOff2=0,TitleAngle=0,TitleFontSize=24
,TitleFontStyle=1)

'Insert heading text for weather conditions

Srf.DrawText(1.7, 17.5, "Weather", "Text for weather")
Srf.Select("Text for weather")
Srf.DrawTextAttributes(Size=20, Style=11)
Srf.DeSelect()

Srf.DrawText(1.5, 16.5, "conditions", "Text for conditions")
Srf.Select("Text for conditions")
Srf.DrawTextAttributes(Size=20, Style=11)
Srf.DeSelect()

'Add wind speed as text

Open "C:\Program Files\OMS\Weatherdata\Windspeed.dat" For
Input As #4
      Line Input #4, WindSpeed
 Close #1

'Add arrow showing direction of wind.

Open "C:\Program Files\OMS\Weatherdata\Winddirection.dat"
For Input As #5
 Line Input #5, WindDirecSURFER
 Close #2

Srf.DrawMarker(3,13,"winddirection arrow")
Srf.Select("winddirection arrow")
Srf.DrawSymbolAttributes("Default Symbols",Size=2,Symbol=61)
Srf.DeSelect()
Srf.Select("winddirection arrow")
Srf.ArrangeRotate(WindDirecSURFER)

Srf.DrawText(2, 12, WindSpeed + " m/s ", "Text for
windspeed")
Srf.Select("Text for windspeed")
Srf.DrawTextAttributes(Size=16, Style=1)
Srf.DeSelect()

'Insert North sign

Srf.DrawMarker(27,15,"North arrow")
Srf.Select("North arrow")
Srf.DrawSymbolAttributes("Default Symbols",Size=2,Symbol=69)
Srf.DeSelect()

'Insert text for threshold value
```

```
Srf.DrawText(23, 4.5, "Dilution Threshold", "Text for
threshold")
Srf.Select("Text for threshold")
Srf.DrawTextAttributes(Size=18, Style=1)
Srf.DeSelect()
Srf.DrawText(25, 3.8, "5.192", "Text for threshold value")
Srf.Select("Text for threshold value")
Srf.DrawTextAttributes(Size=16, Style=1,HorzAlign=1)
Srf.DeSelect()

'Insert text for colour scale

Srf.DrawText(25, 11, "Dilution", "Text for concentration")
Srf.Select("Text for concentration")
Srf.DrawTextAttributes(Size=18, Style=1)
Srf.DeSelect()
Srf.Select("Text for concentration")
Srf.ArrangeRotate(90)
Srf.DeSelect()

Srf.DrawText(26, 11, "Log scale", "Unit for concentration")
Srf.Select("Unit for concentration")
Srf.DrawTextAttributes(Size=16, Style=1)
Srf.DeSelect()
Srf.Select("Unit for concentration")
Srf.ArrangeRotate(90)

'Get name for file to save under currentdate and time

Open "C:\Program Files\OMS\Weatherdata\TimeWOOps.dat" For
Input As #6
      Line Input #6, TimeWOOps
 Close #1

Open "C:\Program Files\OMS\Weatherdata\DateWOOps.dat" For
Input As #7
 Line Input #7, DateWOOps
 Close #2

Srf.DeSelect()
Srf.ViewFitToWindow()
Srf.DocMaximize()

'The file is first saved as a SURFER™ file (.srf)

Srf.FileSaveAs("C:\ProgramFiles\OMS\Plotarchive\"+DateWOOps+
TimeWOOps+".srf", 0)

'The file is then exported as .jpeg file

Srf.FileExport("C:\ProgramFiles\OMS\Plotarchive\"+DateWOOps+
TimeWOOps+".jpg",0,0)

END

exceedances:
```

```
‘The procedure for producing the plot where the threshold
‘has been exceedances at specific receptors, is the same as
‘above except for the addition of an extra layer. Only code
‘that is different from above has been included in this
‘subroutine.

‘The file containing the names of the locations where the
‘threshold was exceeded is opened as a “post map”.

'Open postmap file of exceedance locations

Srf.MapPost("C:\ProgramFiles\OMS\ADMS™\OmsirecLo31sig.dat",L
abCol=2,SymSize=0.3,Symbol=15,SymColor="R255G255B000",LabCol
=2,LabPosType=4,FontStyle=1,FontColor="R255              G255
B000",ID="Exceedances")

‘All other files are opened as above in the “no exceedances”
sub ‘routine.

‘Key is added on the plot for possible complaint locations

Srf.DrawText(0.6,8.5,"Possible Complaint", "TFPCL1")
Srf.Select("TFPCL1")
Srf.DrawTextAttributes(Size=18,Style=11)
Srf.DeSelect()

Srf.DrawText(2,7.8,"Locations", "TFPCL2")
Srf.Select("TFPCL2")
Srf.DrawTextAttributes(Size=18,Style=11)
Srf.DeSelect()

Srf.DrawMarker(3.1,6.5,"Complaint key")
Srf.Select("Complaint key")
Srf.DrawSymbolAttributes("DefaultSymbols",Size=0.6,Symbol=15
,Color="R255 G255 B000")
Srf.DeSelect()

‘The files are then saved and exported in the same manner as
‘above.

END
```