CRANFIELD UNIVERSITY

UJJAINI SARKAR

Odour Nuisance from Solid Wastes: Development of a Model describing Emission, Dispersion and Reception

COLLEGE OF AERONAUTICS

Ph.D THESIS

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Supervisor: Dr. S. E. Hobbs

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

To
My Parents

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Abstract

Odours emitted from Municipal Solid Waste (MSW) landfills create nuisance in the surrounding environment. The odour comes from the mixture of volatile organic compounds present in the landfill gas, leachate and leachate treatment systems, sewage sludges and waste materials. The research objective is to develop an Odour Impact Model (OIM) to quantify the impact of odour from a landfill on the surrounding communities. The model provides a basis for site planning and odour regulations.

A suitable OIM has been developed with special emphasis on quantifying emissions from the source. A micrometeorological model has been developed based on the estimation of footprints of scalar odour concentration measurements in the atmospheric surface layer. A simple experiment has been designed based on this model. The results of this model have been compared with those from the direct emission measurement approach using a portable Lindvall Hood. Major advantages of the indirect micrometeorological approach are the simplicity of the experiment design, and its ability to cover various spatial resolutions.

The commercial software MPTER/COMPLEX-I and UK-ADMS have been used to predict the dispersion of odour around two solid waste sites. UK-ADMS uses a better representation of short-range dispersion (considering plume meandering and in-plume fluctuations) and is thus likely to be more accurate close to the source. The two models compare well at distances greater than 500 metres downwind from the source. The perception recorded in the surrounding community has been analysed with four psychophysical models to validate the impacts predicted by the suitable dispersion model. The model based on Weber-Fechner law describes the relationship between odour intensity and odour concentration (ou/m^3) very well for the less intense odour samples, while Laffort's equation expresses a better relationship with more intense odour samples.

The main strength of the integrated OIM is its ability to handle the problem of odour nuisance from solid wastes quantitatively. Amongst the major weakness was poor validation due to lack of sufficient data. Successful use of the OIM will require measurements which account for the extreme variations in surface conditions, cover type, waste composition, wasteage and subsidence.

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Nomenclature

Symbol	Name
alt	Solar-Elevation Angle
C	Concentration
CC	Cloud cover
$\overline{C'^2}$	Mean of the squared concentration fluctuations
$\overline{C}^2$	Square of the mean concentration
D_N	Normalised dimensions of the footprints
d	Julian day number of the year
dc/dz	Concentration gradient
E	The difference in position between the true sun and a fictitious sun
f	Flux of the odorous gas
$F_{\theta 0}$	Heat flux into the atmosphere
h	Boundary Layer height
H	Hour angle
I	Odour Intensity
k	Transfer co-efficient in the ammonia flux equation (2.1)
K_e	Eddy diffusivity
k_1	Coefficient of the psychophysical laws
k_2	Coefficient of the psychophysical laws
L_{MO}	Monin-Obukhov length
Q	Flow rate of the odorous gas
q	Odour flux
r	Neural response
R_v	Rate of volatilisation
s	Shape parameter of the plume
T_0	Surface temperature
$\bar{u}$	Mean advection velocity of the plume

u_*	Friction velocity
$\overline{U}$	Average wind speed
z_0	Surface roughness length
$\bar{z}$	Average height of the plume centreline above the ground the level
z_m	Height of the sensor
δ	Sun's declination
ϕ	Latitude
κ	Von Karman constant
σ_{me}	Dispersion co-efficient of meandering plume
σ_r	Plume internal dispersion coefficient
σ_v	Standard deviation of lateral wind fluctuation
σ_y	Lateral dispersion coefficient
σ_z	Vertical dispersion coefficient
Λ	Longitude

Chapter 1

1. Introduction

In this Chapter the problem of the research will be defined with the main objective along with some specific objectives and the entire methodology will be outlined.
After giving a background of the project, an overview of Municipal Solid Waste Landfills will be discussed. The next issue, which is quite important with regard to this particular research is odour from landfills, its potential sources and chemical compounds contributing towards the odour. Standard approaches for assessing the odour emissions and their impacts on the surrounding community around an odour source will be highlighted. After defining the objective of the project, methodologies will be discussed. This will follow a brief description of the particular case-study site.

1.1 Background

Odour emissions represent a big problem in the operation of a large landfill site. Large landfill sites produce large volumes of gas which are composed of odorous trace components, mostly volatile in nature. Other sources of odour at landfills include leachate and leachate treatment systems, sewage sludges and waste materials, especially those that have decomposed prior to landfilling. Problems are generally associated with the annoyance in the neighbourhood of the source and complaint rates are increasing.

This particular research is a part of an on-going research project with the International Ecotechnology Research Centre (IERC), Cranfield University on the assessment of odour impacts on the community surrounding a particular solid waste landfill site. Several complaints have been received by the local authority on the issues related to malodour from the local landfill site. The IERC has been conducting the community survey for the last five years to analyse the potential of complaints.

A number of researchers have attempted the problem of analysing the nuisance created around a potential odour source (*discussed in details in* Chapter 2). There have been various approaches towards the same kind of solution, however rarely the problem has been tackled in totality in a quantitative way, specially for cases related to malodours from huge landfill sites.

A huge MSW landfill site serves as a complex of multiple sources, each of which is very different from the other with regard to the geometry and type of emission. There are quite a number of area sources, of completely indefinite geometry, in the 'active cell' region (see Figure 1.4) of a MSW landfill site. It is often difficult to assess emissions from such kind of sources. The next aspect is how the emitted odour is dispersed. There are quite a lot of commercial software available in the market to study dispersion of pollutants. It needs to be decided which one suits cases with odour dispersion with special features like perception threshold, averaging time, fluctuations etc. The third phase of the problem can be the analysis of the perception of the dispersed odour as perceived amongst the residents in the surrounding community of the landfill site. This can be as important as the other aspects since it is the human beings living within the community, who are actually affected by the malodours.

In order to assess the impact of odorous emissions from the landfill site on surrounding community a quantitative **Odour Impact Model (OIM)** is proposed to be developed at the College of Aeronautics, Cranfield University. The main objective of this particular research will be to develop the major components of the OIM namely, assessment of odorous emissions, dispersion and reception by the surrounding community around the landfill site. Research will focus on using the OIM to quantify the impact on the surrounding communities, to provide a basis for odour regulations, to create a means for prioritising actions taken to mitigate odour impacts, and as a decision-making tool to select control options.

In the next few sections the reader is introduced to the basics of a Municipal Solid Waste (MSW) landfill, their growth in Britain, the types, and management and principles of operation.

1.2 Municipal Solid Waste (MSW) Landfills

Landfill has been defined (ISWA, 1992)[1] as

" The engineered deposit of waste onto and into land in such a way that pollution or harm to the environment is prevented and, through restoration, land provided which may be used for another purpose".

The above may define a model landfill, in reality landfills are far from ideal. As a result of landfill activities there are many causes of environmental pollution that have arisen. The key requirement of a *'sustainable'* landfill is prevention of harm to the environment. This requires effective control of waste degradation processes and effective landfill design, engineering, and management.

1.2.1 Waste Management and landfill in modern Britain

Each year Britain produces about 140 million tonnes of solid waste from a wide variety of sources, such as homes, offices and factories. Currently, 89 per cent of this is landfilled, approximately, around 6 percent recycled and the remainder burnt in incinerators or put through a range of small scale waste management techniques, for example, refuse derived fuel plants and composting facilities. Landfilling is the final disposal technique amongst the above options. Incinerators produce ashes which ultimately need to be landfilled. In a similar way, recycling facilities produce goods which will eventually need disposal.

1.2.2 The development of landfill in Britain[2]

One of the oldest forms of waste management is burying waste in the ground. However, it was not until the 20th century that the practice was considered technically and the concept of *'landfill'* was evolved.

When waste is placed in an exhausted quarry or similar (as is the case with landfill sites) it will begin to decompose. As a result of this process two main by-products are formed: *Landfill gas* and contaminated water, called *leachate*. Both of these are potential problems and require control.

Until the 1970s Britain followed the technique of *'dilute and disperse'* in landfilling. In a dilute and disperse landfill site the landfill gas and leachate produced by decomposing waste were allowed to escape to the environment. These pollutants could not travel far if the landfill site was in an area whose geology naturally restricted the escape of these by-products, such as a clay geology. However, in many cases the landfill gas and the leachate escaped freely and caused pollution and other problems like fire hazards.

Instead of dilute and disperse landfill the waste management industry turned to 'containment' or 'sanitary' landfill. Basically a barrier is placed between the waste and the environment in a containment landfill. This barrier, called a *liner*, can be composed of any material. In some cases a layer of compacted clay is used. Plastics such as a high density polyethylene, or composites made up of layers of clay and plastic may be used in certain cases. The containment 'liner' aims to prevent the uncontrolled escape of landfill gas and leachate into the environment.

Once gas and leachate are trapped within a containment landfill site efficient gas extraction systems need to be designed. These should be environment friendly. Typically this involves sinking pipework within a containment landfill and the use of pumps to remove leachate and gas. The gas and the leachate, once extracted from the landfill site, can be treated to reduce or remove their potential to affect the environment.

There are two main methods of operation with a containment landfill: *Wet* and *Dry*. In Britain wet landfill is more common whereas the other is normal in Germany and the USA.

1.2.3 Wet and dry landfills[2]

The more the landfill is wet, waste decomposes faster. As it decomposes large volumes of landfill gas and leachate will be produced over a relatively short period of time. For example, a large landfill site may produce more than 8,000 cubic metres of gas an hour.

On the other hand if the landfill is kept dry, the waste will decompose only very slowly and the production of gas and leachate would be much slower.

The advantage of the *wet landfill* site is that the waste in it will decompose to the point at which it is no longer a significant environmental risk within a reasonable period of time.

The gas and leachate management is less problematic in a *dry landfill*. However, the waste may remain an environmental risk for an extremely long period of time, since it will not decompose quickly.

The wet landfills treat the waste through a process of anaerobic decomposition while dry landfills just store the wastes. *Britain generally follows a wet landfill policy*. The liners used in containment landfills have a finite life. There is hardly any risk of pollution, if the waste within a landfill has decomposed to the point at which it is no longer a significant environmental risk before this finite life-span is reached.

1.2.4 Wet containment landfill: Its management and operation

The management of a modern wet containment landfill involves two kinds of operations. They are:

- Management of the landfill itself: gas and litter control.
- Operations associated with handling the waste itself, such as the inspection of wastes arriving at the site and wind blown litter control.

Figure 1.1 gives a regular picture of how wastes are tipped from the trucks. Figure 1.2 and Figure 1.3 give a picture of a typical MSW landfill site with various units of operation.

1.2.5 Some characteristics in the operation and management of the landfill

Waste inputs

Waste generally arrive at landfill by road. The types of waste any individual landfill may accept are usually written in the site waste management licence.

Cellular operation

Usually containment landfill sites are operated in a 'cellular' fashion. Most landfills are in used quarries dug out to serve another purpose. At any one time, only small areas of a site are 'engineered' and filled. Each of these small areas is called a 'cell'. Landfill progressively restores old quarries by operating in a cellular fashion, which could later be used for agriculture, conservation and leisure.

Figure 1.1 Lorries depositing waste at the tipping face of a MSW landfill site.

Daily cover and compaction at the tipping face

Once waste has been deposited at the working area of a landfill (the 'tipping face') it is usually made flat with a bulldozer and compacted by large machines with specialised studded steel wheels, called *compactors*. The operating area of a landfill is covered progressively through the day with a layer of earth, clay or a similar material. This cover helps minimise blown litter and odour from fresh waste. Many waste managers use heavy duty hessian, plastics and foams instead of soils and clays for daily cover.

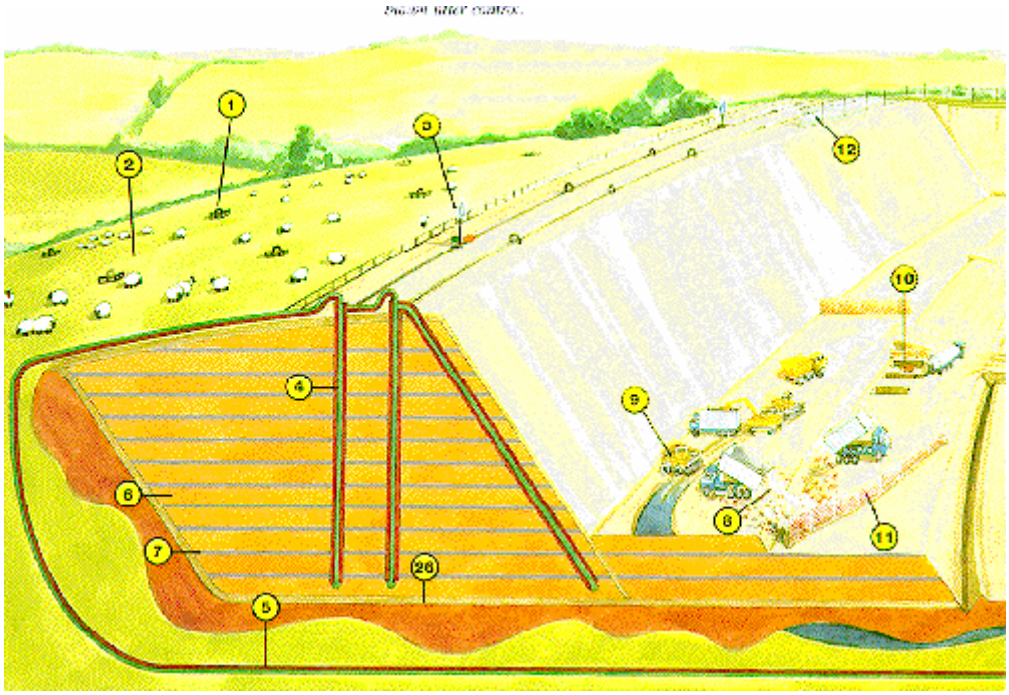


Figure 1.2[2] Various units in the management and operation of a wet containment MSW landfill site-Part (a). *Numbered units are described in Table 1.1.*

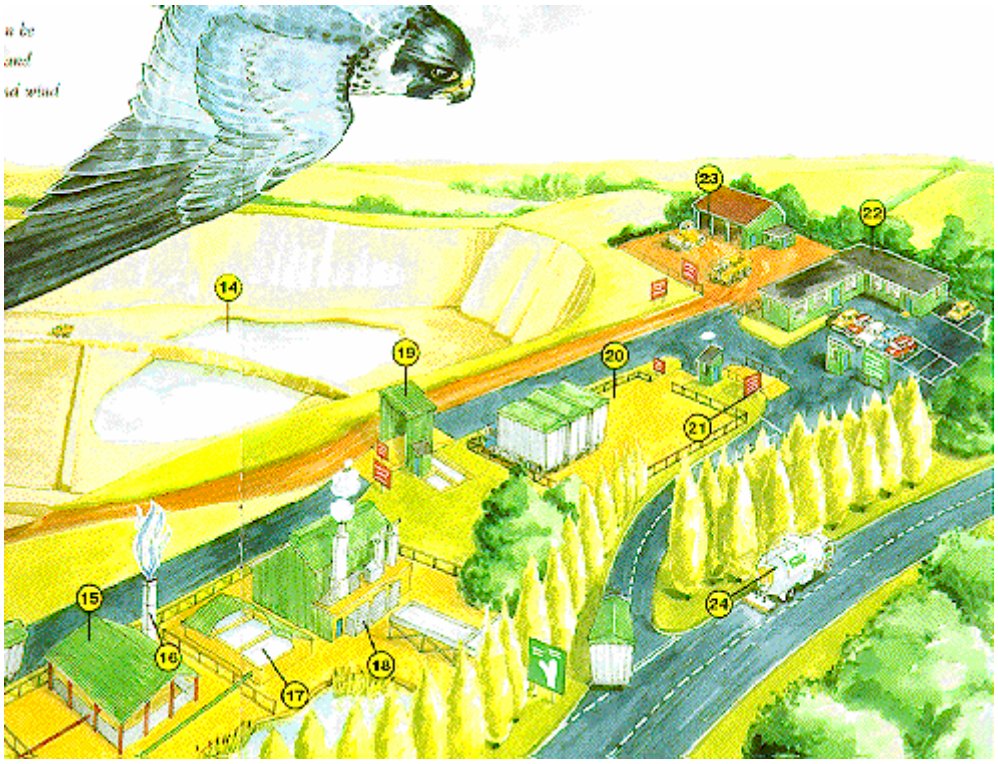


Figure 1.3[2] Various units in the management and operation of a wet containment MSW landfill site-Part (b). *Numbered units are described in Table 1.1.*

Table 1.1[2] Various units of management and operation of a wet containment landfill**.

Unit No.	Description
1	Gas and leachate extraction well heads
2	Filled land resorted to agriculture
3	Temporary flares burning gas from a recently filled area
4	Gas and leachate wells sunk deep into the waste
5	Pipes carrying gas and leachate away from the extraction wells
6	Waste disposed of in layers
7	Between each waste layer is a layer of daily cover
8	Lorry depositing waste at the tipping face
9	A compactor machine crushing the waste flat
10	Tanker trenches for liquid and sludge wastes
11	Mobile litter nets positioned to minimise wind blown litter
12	Fixed litter nets surround the active area of the site
13	The next area for filling with waste is engineered in advance
14	Lagoons collect rain water which is used on site
15	The environmental compound with pumps
16	Excess landfill gas is burnt in a high temperature flare
17	Leachate pumped out of the site is treated in a specialist plant
18	Landfill gas powered electricity generating station
19	Lorry wheel wash to minimise mud on the public road
20	Compound for inspecting and analysing wastes arriving at the site
21	A weighbridge is used to measure how much waste is being disposed of
22	Site offices
23	Workshop for machine maintenance
24	Road cleaner keeping the public highway clean
25	Trained hawks and falcons scare seagulls away from landfill sites
26	Engineered containment barrier

** *Refer Figure 1.2 and Figure 1.3.*

Landfill engineering and liners

Most of the containment landfill sites have a 'liner' designed to prevent the uncontrolled escape of gas and leachate to the environment. The materials used are usually of compacted clay, plastics or composites. Liners are engineered on the base, sides and, the top of a landfill site (called capping) after waste has been deposited. This encapsulates the waste and the gas and leachate the landfill will produce.

Gas management and electricity production

Large volumes of gas are produced from modern wet containment landfills due to the decomposition of organic wastes within the site. This could be as much as 20 per cent of the weight of waste in a landfill site that will decompose and be given off as gas. This gas needs controlling by extraction from the site and treatment to minimise its pollution and fire risk.

There are active gas extraction systems in modern landfill sites where landfill gas is 'sucked' from the site using a network of pipes linked to pumps to provide the required suction. The pipe system used can be installed as waste is being deposited, or put in place after an area of a landfill has been completed by drilling into the site.

Leachate management and treatment

Leachate can either be water which is already in the waste, rainwater which has fallen onto waste at a landfill before the containment liner (cap) has been placed over it, or water which very slowly penetrates through the top of a landfill. Leachate will contain potential pollutants since it has been in contact with waste.

Amenity protection and local issues

Landfills can be a cause of concern to local residents. The types of complaints received by the local authorities can vary from site to site. The main issues are blown litter, noise nuisance and nuisance related to the odour and dust. The methods used to reduce the amenity impact of landfills are diverse and these are briefly explained in Table 1.2.

Restoration, aftercare and environmental monitoring

Landfill sites can be restored to a variety of uses including agriculture, conservation areas and leisure uses, such as a country park. All landfill sites must have an environmental monitoring regime. These are largely based around bore-holes drilled

into the ground water and to detect if landfill gas or leachate is escaping. The function of this sampling is to ensure that the containment liner is not leaking.

Table 1.2 Possible causes and remedies of nuisance around a MSW landfill site.

Cause of the nuisance	Remedy
Seagulls scavenging on a site	Flying trained hawks and falcons to deter
Blown litter	Mobile and fixed netting
Mud trailed onto the public road by lorries using a landfill	Washes of the wheels and the vehicle
Noise nuisance	Sound walls and bunds
Odour or dust	Use of weather prediction systems to plan specific site operations for days when the wind is unlikely to carry any odour or dust to the local communities

1.3 Odour from MSW Landfills

Landfill sites that do not utilise a flaring system may experience problems with odour from emissions from vents within the waste. Other sources of odour at landfills include leachate and leachate treatment systems, sewage sludges, and waste materials, especially those that have, for whatever reason, decomposed prior to landfilling. The risk associated with odour depends on the sensitivity and location of the *'receptor'*, which includes local populations. Factors such as the prevailing wind direction, distance to the nearest sensitive target and natural topographical and hydro-geological features will therefore be important considerations at the planning stage. If these are undertaken effectively, many of the environmental problems can be reduced significantly.

1.3.1 Chemical compounds contributing towards odour

In APPENDIX-I typical landfill gas and leachate composition is given. The major components contributing towards odour from MSW landfill sites are a mixture of

halogenated compounds (chlorinated and chlorinated/ fluorinated compounds like trichlorofluoromethane, dichlorofluoromethane and dichloromethane), hydrogen sulphide, organo-sulphur compounds and some BTEX aromatics (benzene, toluene, ethylbenzene and xylene). Concentrations of halogenated trace substances, hexane and BTEX aromatic substances in samples from six MSW landfills are presented in APPENDIX-I. However, in this piece of research odour has always been considered as a mixture, as it is perceived by the people in the local community, rather than its chemical composition. Hence the methods used for analysis and quantification of odour were not the same as for detection and quantification of a chemical compound, e.g. gas chromatographic analysis etc. The objective measurement of odour will be discussed in APPENDIX-III.

1.3.2 Potential Odour Sources

The potential sources of odour within a MSW landfill site are as follows:

1. Emissions from restored surface
2. Emissions from normal operation of the site that will continue after restoration
    a) Flares
    b) Power generation plant
    c) Leachate collection, storage and treatment
3. Emissions from normal landfill operations
    a) Active landfill area
    b) Active area with temporary cover
    c) Tanker trenches
4. Incidental releases events
    a) Releases from odorous waste as it is deposited
    b) Releases from failure of tanker trench controls and procedures
    c) Releases from gas well leakage
    d) Releases from gas collection system leaks
    e) Releases caused by leachate spills
    f) Releases from cracks in the cap
    g) Releases caused by engineering work (such as removal of cap)

An emission rate needs to be estimated for each of these sources, and used to describe the subsequent scenarios or emission configurations describing the sites as work on an extension programme progresses.

1.3.3 Assessment of Odour Emissions: Standard Approaches

Assessment of odour emissions depend on the type of source. Conventional methods for estimating odour emissions from area sources include use of portable flux chambers, called Lindvall Hoods, for sampling of odorous landfill gas from the sites and analysing the gas samples by principles of *olfactometry* thereafter. The sampling techniques have been described in details in Chapter 3, *section 3.2.1*. Principles of olfactometry are described broadly in Chapter 3, *section 3.2.2* and various terms and definitions of odour are given in APPENDIX II.

1.3.4 Assessment of Odour Impacts: Standard Approaches

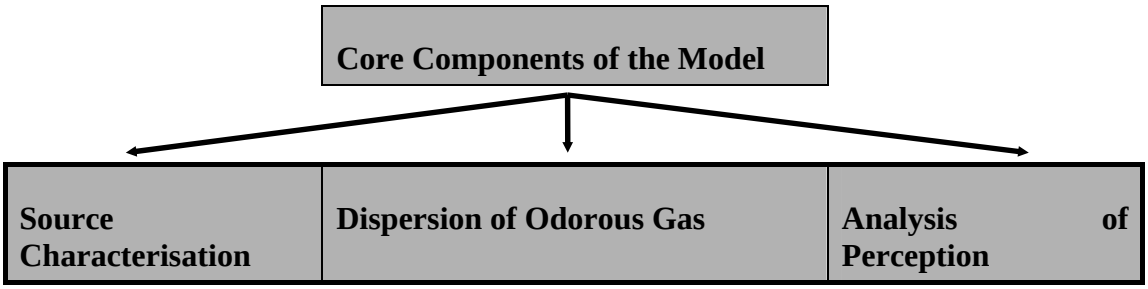
In order to assess odour impacts the standard method includes dispersion estimates with predictive models after assessing the emissions from the site. The impact definition is both *recognition threshold* (RT) and *dilution threshold* (DT) in ou/m^3. For odour concentrations to result in a nuisance, the frequency and duration of related odour events may be as important as the magnitude of a single odour event. Usually year-round monitoring programmes are scheduled with community people as the regular sniffers and dispersion estimates are validated with the events of complaints. However, the three areas: emission, dispersion and perception have always remained as separate entities and there has been no effort to put these three key factors together.

1.4 Objective of the Project

Considering the above scenario with regard to landfill odours, an overall odour impact model was planned to be developed. The idea was to improve each of the elements of the model (as described in the following section) and try to find a solution of linking each of them with other in order to assess the impact on the community around the test case MSW landfill site.

1.4.1 Principal Objective: Development of the Odour Impact Model (OIM)

Structure of an Odour Impact Model (OIM):



1.4.2 Specific Objectives

The standard methods of assessing the emissions from large MSW landfill sites involve use of portable flux chambers, called Lindvall hoods. The usual dimension of the cross-section of the hood is 1.0m x 1.5 m, though it may vary a little bit. It is very hard to conduct a huge number of experiments (involving expensive analysis with olfactometry) to cover areas as big as 166.0 hectares (Total area of our study-site). The number of experiments could be as high as 1100000 in such a case. Hence the research will focus on developing techniques of assessing emissions that would partially solve the problem of spatial resolution. Ideally, less number experiments should cover the entire study-site.

Most of the well-known commercial software, available in the market, can cope with the problems of pollutant dispersion in general. It should be the second focus of this research to try and find out the suitability of few such relevant software to suit the case of odour dispersion.

Analysis of perception has been rarely attempted by researchers, specially to study cases with MSW landfill sites, or solid wastes in general. The psycophysical aspect of odour, as it is perceived by the human receptors within the community, will be the third focus of this project.

Finally, there will be an attempt to correlate all the three elements, which will form a basis of analysing community annoyance. Hence, specific objectives of the project will be,

1. Developing a suitable OIM with special emphasis on quantifying emissions from the source with various operating, meteorological and topographic conditions.
2. Using relevant dispersion model specific to odour.
3. Analysing the perception recorded in the surrounding community to validate the impacts predicted by the dispersion model.

1.5 Methodology

The overall methodology included the following aspects:

- *Characterisation* of the odour *sources*,
- Selecting a suitable *dispersion model* incorporating necessary variations with regard to the scenario of odour, and
- *Analysing the perception* of odour with some standard models based on widely used psychophysical laws.

Each of the above modules has been validated with the test case MSW landfill site. The above modules of the OIM are discussed in the following sections.

1.5.1 Source Characterisation

1. Identification of possible sources of odour within the landfill site depending on the daily/weekly operational practice.
2. Sampling from those sources (by Lindvall Hood).
3. Testing the samples in a dynamic dilution olfactometer for odour concentrations and intensities.
4. Developing a micrometeorological model based on the concept of flux ***Footprint*** *(based on the footprint of a scalar odour concentration measured at a particular height from the ground)* to quantify the specific emission rates of odours from a specific upwind fetch.
5. Design of experiments for relevant on-site meteorological measurements.
6. On-site sampling from *above ground* that need to be quantified for odour concentration by dynamic dilution olfactometry.
7. Computing the most probable source area contributing to this emission rate.

8. Analysis of the results from Footprint method as an alternative to portable Lindvall-Hood technique.

1.5.2 Dispersion of Odorous Gas

1. Use of standard Dispersion Models of US-EPA , like **MPTER**, **COMPLEX-I**, and **ISC-ST**.
2. Application of a specialised Dispersion Model, **UK-ADMS**.
3. Comparison of various models with special reference to odour dispersion.

1.5.3 Analysis of Perception:

1. Estimating the parameters of various models (Beidler, Power-law, Laffort's and Weber-Fechner's) describing the intensity of perception and concentration of odour. This should be done by a numerical model-fitting technique.
2. Data-acquisition for testing the models.
3. Discriminating the models according to their suitability for senses of odour amongst the community.
4. Validating the results of Dispersion Models with community impact.

1.6 Case Study: MSW Landfill Site

The local County Council received a planning permission application for extending the large landfill site under consideration, located to the south west of Bedford, Bedforshire. The Council has recognised concerns about the risk of odour problems arising from the proposed extension and has requested this review of the potential for additional odour annoyance as a result of the extension of the site. In view of the above scenario, the new OIM has been tested for several cases (present and future). The landfill site under consideration is described in the following section.

1.6.1 Description of study site

The test case landfill site is located 12 km South-West of Bedford, Bedfordshire. The site is located in a former clay pit, and lies approximately 54-65 m above Ordnance

datum (AOD) [3,4]. The clay has been excavated since about 1950 to depths of 8 to 15 m. The site has been operated as a landfill since 1985. Until 1989/1990 the filling rate was relatively modest, at approximately 300,000 tonnes/year. Then the filling rate increased sharply to more than 2 million tonnes/year, with a relatively large proportion of liquid waste.

The community closest to the site is Cranfield, located approximately 1 km NW of the landfill site and some isolated farm residences are located as close as 250 m (Country Kennels, Wood End Marston and North Common Farm).

The landfill site currently extends over about 166 hectares of which 116 ha is the landfilling area [5]. An extension of the site is planned, by expanding the site by 33.4 ha to the NW, of which 17.6 ha would be landfilled. The existing landfill would be re-contoured, by surcharging the partly restored stages 1,2 and 3 and by restoring some of the current stages. This extension would extend landfilling activity on the site by an estimated 4 to 5 years.

Some characteristics of the site are:

- The landfill has a depth of up to approximately 40 metres, with the original site level, before excavation of clay, at approximately 54-65 m AOD. The excavation of clay on the site left a pit with a variable floor level at about 30 m AOD.
- The pre-settlement heights on the site will be up to 88 m AOD. After settlement the maximum height will be 75 m AOD.
- There is a filling edge, where wastes are being received and processed. A procedure for putting temporary cover in place on the filling edge is in place.
- The landfill has a system for landfill gas extraction and a system to incinerate or process the extracted landfill gas (flare or gas treatment to remove sulphides followed by use for energy generation).

Major operational characteristics:

- Currently the site can take up to 700 vehicle loads of waste/day.
- The site receives a wide range of controlled wastes of domestic, commercial and industrial origin,

  4:30AM to 6:00PM weekdays

  5:00AM to 1:00PM on Saturdays and from

6:00AM to 1:00PM on Sundays and Bank Holidays

This configuration would imply that four major sources of odours can be identified:

- The transfer and filling edge
- The gas extraction and disposal/treatment unit
- The collection, storage and treatment of leachate
- The residual fugitive emissions from the covered landfill surface

These sources would be considered while building the emission inventory of the site.

1.7 Structure of the thesis

In Chapter 2, various literatures relating the specific objective of the research would be reviewed. Chapter 3 will focus on various aspects of the sampling and measurement techniques specifically suitable for odorous gases and the computation of the odour flux ($ou/m^2.s$) and odour strength (ou/s) for different kinds of source emissions. Special emphasis will be given in the development of an innovative method, based on a micrometeorological model for estimating odour fluxes from a Municipal Solid Waste (MSW) landfill site.

Chapter 4 will outline and discuss the use of atmospheric dispersion modelling to quantify the extent of transport and dispersion of odour with two special cases, namely, an urban waste transfer depot and a MSW landfill site.

In Chapter 5 we will make an attempt to relate odour concentrations predicted by the physical models to the perceived nuisance within the surrounding community of a potential odour source, which depends on the human response. The development of methods will include:

- Measurement of odour concentration and intensity
- Model selection and parameter estimation techniques
- Evaluation of the models with statistical analysis

The results will be discussed afterwards with the nine samples taken from various locations within the MSW landfill site.

Chapter 6 attempts to correlate the predictions of the atmospheric dispersion modelling with the community odour survey records to analyse the potential of the test case MSW landfill site to have an impact in the surrounding community. Specifically an effort will

be given to correlate the results of Chapters 3, 4 and 5 and analyse the overall scenario of the odour impact within the surrounding community of the MSW landfill site.

In the concluding chapter, Chapter 7, a brief summary of the complete work will be given, highlighting the main and the specific conclusions and some useful recommendation for future work.

There are seven appendices attached herewith, to supplement the chapters.

Figure 1.4 A Municipal Solid Waste (MSW) Landfill site: Plan showing present and proposed borehole locations[1]. *Scale 1:5000*.

[1] Photocopied from Drawing No. SM/BG/97/123 of Shanks & McEwan (Southern Waste Services) Ltd, dated 22nd August, 1997. CCPY No: 3.

Chapter 2

2. Review of Literature

In this chapter work done by various other researchers on odour impact assessments will be reviewed. Odour, as generated from MSW landfills would be the primary focus of this chapter. Different types of the overall assessment methods would be discussed with individual view of:

- Sampling and measurement techniques from broad area sources of indefinite geometry
- Flux generated and the contributing source area
- Transmission of odour to various receptors as a mixture
- Analysis of perception with regard to the surrounding community.

2.1 Assessment of Odour: Background topics

Odorants released into the atmosphere disperse and sometimes react in the atmosphere and produce odours in the ambient air that are perceived by people in communities.

In this chapter we will review the present state of the art of various sampling and measurement methods, as applicable at the source, ways of handling the transmission of odour through the atmosphere and lastly analysis of the nuisance part of odour reflecting human perception. In each case the main emphasis will be given to cases related to a broad area source like an MSW landfill site.

2.1.1 Measurement of odour: Fundamentals

Odour is a sensation perceived by the human. A two-step process takes place, leading to an odour sensation.

The first step is the reception of the odorant in the human nose. This process is a physiological one, yet to be understood completely. The second step comprises of interpretation of the signal as it is transferred from nose to brain. This step is also only partially understood. Figure 2.1 gives an overview of these two steps and possibilities of measurement in various situations.

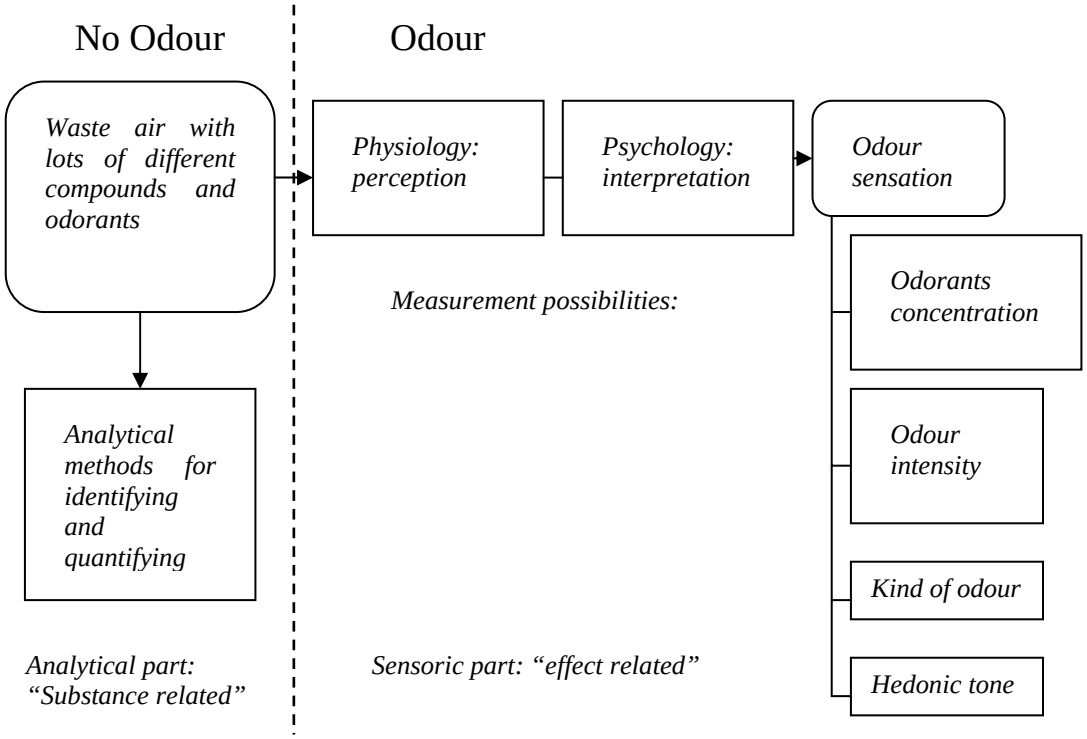


Figure 2.1 Analytical and sensoric measurement possibilities[6].

The *analytical methods* for identifying and quantifying the specific odorants contained in an odorous air sample may give component-specific values, but cannot predict any human sensation in terms of intensity or concentration. On the other *hand "sensoric" measurements* are effect-related.

From APPENDIX-I (Composition and characteristics of the landfill gas and leachate) it is clear that *key* volatile organic compounds (VOCs) responsible for a particular odour

event are so difficult to identify in MSW landfills, specially in connection to the odour impact studies within the surrounding community, that the analytical measurements are inappropriate. The other option is sensoric measurement.

Odour has got special attributes like intensity, detectability, character, and hedonic tone (pleasantness and unpleasantness). The annoyance may be related to a combined effect of all these properties. When a sample of odorous gas is progressively diluted, the concentration of odorants decreases, and the intensity of the gaseous sample becomes so low with any further dilution that detection or recognition of the odour is very difficult. This is known as the *detection threshold* (*see* APPENDIX-II). The pleasantness or unpleasantness of an odorous sample is given by its *hedonic tone* (*see* APPENDIX-II). A pleasant odour may be considered objectionable sometimes by the population exposed to it when the emission is industrial.

The objective method of measuring odour, as perceived by human beings, is by *olfactometry*. The evolution of odour measurement by various techniques of olfactometry is discussed in detail in Chapter 3 *(section 3.2.2)*, 4 *(section 4.3.1)* and in APPENDIX-III (Olfactometry).

The report by Berglund *et al.* [7] provides guidance for conducting olfactometric measurements (e.g. detection thresholds) and odour measurements (psychometric scaling methods) with the aid of human observers. Both types of measurement require an olfactometer for controlling and/or generating the stimulus with a constant exposure capacity.

2.1.2 Atmospheric Boundary Layer: Fundamentals

The part of the atmosphere which is directly influenced by the earth's surface is called the Atmospheric Boundary Layer (ABL). It is generally turbulent. The generation/dissipation of turbulence is governed by

- Shear production
- Buoyancy effects
- Viscous dissipation

The flow and turbulence structure in the ABL is the main factor influencing dispersion of material over short ranges (~ 30.0 kms). The turbulence draws its energy from wind

shear due to warming of the air near the ground. Cooling partially suppresses any turbulence induced by the wind shear. The ABL grows during the day in response to surface heating and can be as high as 2.5 kms.

The surface-layer schemes assume that over a certain range of meteorological conditions the boundary layer has a similar structure. Pasquill and Gifford defined a parameter based on these assumptions. This parameter corresponds to each of the atmospheric conditions, ranging from A for a very unstable boundary layer to G for an extremely stable one. These are well known as Pasquill-Gifford (P-G) [47] stability classes. When P-G classes are used in dispersion modelling it is implied that mean flow and turbulence are independent of the boundary layer height. However, in reality the mean flow and turbulence vary extremely with the boundary layer height *(h)*. Thus the state of the boundary layer cannot be specified accurately by any one parameter based on surface measurements only. It has been found that a parameter, called the *Monin-Obukhov length* (L_{MO}) is quite useful to characterise the atmospheric stability. This is derived from some of the measured surface data and the boundary layer height (*see* APPENDIX V). We know the vertical distribution of turbulence for each value of (h/L_{MO}) and the same is used in calculating the dispersion (*see* APPENDIX-V).

2.1.3 Factors affecting dispersion of pollutants in the ABL

There are three major factors that affect the atmospheric motions and the temperature distribution.

- The *'surface roughness'* and changes in terrain elevation: Any surface protrusions ranging from grass to sharp three-dimensional hills can obstruct the airflow. A roughness length, z_0, characterises the effect of these obstructions on the flow above them. Similarly for tall structures the height, *H*, and the length, *L* of the structure are important.
- Wind at the top of the boundary layer, known as the geostrophic wind speed (U_g): The air flow above the boundary layer has no effect of surface roughness. Shear stress gradients are zero here. The two gradients of U_g, temporal and horizontal,

lead to the convergence/divergence of the horizontal flow. This in turn affects the upward/downward motion above the boundary layer.

- The heat flux $(F_{\theta 0})$ into the atmosphere: This is determined by the net short wave solar radiations, longwave radiations released by the earth's surface, the absorption and release of latent heat by water vapour near the surface and the heat either absorbed or released from the surface. The temporal and spatial variations of $F_{\theta 0}$ determine the changes in the structure of the boundary layer.

2.2 Odour emission rates: Measurement techniques

An emission from a point source can be determined by measuring the flow rate and analysing the concentration. Odour emissions from other sources can be approached in the same way. Problems do arise in the case of passive area sources of typically indefinite geometry and with a spatially inhomogeneous surface like a Municipal Solid Waste (MSW) landfill, an activated sludge basin, agricultural fields etc., because the mass emission rate is difficult to determine. There are direct and indirect methods available to solve such problems. One standard direct method is the use of Lindvall hoods [8]. Frechen [6] gives a list of specific emission values for landfilling of municipal solid wastes, given in Table 2.1.

The Warren Spring laboratory conducted an odour survey on an unnamed waste water treatment site [9]. The odour samples were taken with a 200 mm funnel at a position of 20-30 mm above the surface and tested by olfactometry. The idea was to reduce the sampling velocity at the point of sampling. The uptake velocity of chemical compounds was assumed to be no more than 1-2 mm/s for sampling of the aeration tanks of the activated sludge process and trickling filters.

Prokop [10] used the Illinois Institute of Technology's Dynamic Triangular Olfactometer. He used a Styrofoam box for sampling, which served as a hood to capture the odorous compounds from a waste water treatment plant. The odour potential was calculated as the product of the odour concentration measured within the above box and the surface escape rate from the water surface.

Table 2.1 Specific emission rates from municipal waste landfill site area sources[6].

Part of landfill	Specific emission rate in ou/m^2.h	
	Lower value	**Upper value**
Active depositing area	4,000	30,000
Surface, slight daily cover	2,000	6,000
Surface, covered, not recultivated	600	2,500

*** No averages are given here, as it was mentioned already that Frechen [6] recommends a measurement programme in any individual case wherever possible. The values given in this table should serve as orientation, and future measurement programmes show whether they have to be corrected.*

In 1982, the US-EPA [11,12] developed an isolation chamber to measure the VOC (Volatile Organic Compound) emissions from a surface area. A compressed carrier gas cylinder was used. The mixing characteristics of the chemicals and the carrier gas are the critical design parameters. Several geometric configurations are reported for different applications including VOC emission rates [12], odour emission rates [13-14], and landfill gas emission rates [15]. However, the selection of the sweep air rate was not satisfactory. It was found that the increasing sweep air rate did not alter the chemical concentration inside the isolation chamber. The design was also not quite suitable for aerated liquid surface [16]. All these factors restricted the use of the equipment any further.

An alternative approach was to use a wind tunnel system to collect odour emissions from the areal sources. In the early 1970's Lindvall [8] introduced an odour emission hood used in the comparison study of odour strengths from different sources. Later, Lockyer [16-17] designed a wind tunnel system to measure ammonia losses from pastures. Both systems have successfully applied on solid surfaces.

The particular portable hood that was used for all case studies in our research, is basically a Lindvall hood. The principle of the odour sampling system is that controlled air, filtered by activated carbon through a series of devices, forms a homogeneous mixture of odorous gas over a defined surface and carries the odour emission out of the hood. A proportion of the mixture is sucked into a Tedlar bag via Teflon tubing. This is achieved by evacuating the rigid drum surrounding the bag to draw odorous air into the

bag. The specific odour emission rate at a certain velocity is calculated from the odour concentration, the flow rate and the contact area. Details of this are given in *section 3.2.1* of Chapter 3.

Jiang and Kaye [18,19] used these portable hoods for collecting odorous samples from the areal sources within a waste water treatment plant in Australia. Bode [20] describes the use of Lindvall hoods for odour and ammonia emissions from manure storage. However, he uses *odour panel* (*see* APPENDIX III) technique for odour measurement and not dynamic dilution olfactometry.

Homans [21] discusses the development of some techniques for assessing odour nuisance of manure. The experience gained comprises not only lab-scale techniques but also investigations carried out after spreading manure on agricultural land. Homans has studied the effect of wind velocity on specific emission rates using different experimental equipment such as the washing-bottle, the tube equipment with a ventilator, the little hood system and the big hood system. However all the systems were tested within a range of wind velocities 0.01 m/s to 2 m/s. It is quite likely to have higher wind speeds in the practical situations.

Micrometeorological methods and a system of small wind tunnels were used in the measurement of odour and ammonia emission following the application of pig slurries to land by Pain and Misselbrook [22]. The micrometeorological method as outlined by Pain and Klarenbeek [23] uses the theory described by Denmead [24] in which the flux of gas from the soil surface of a circular plot is estimated from the vertically integrated product of wind speed and concentration divided by the radius of the plot or the fetch. Ammonia concentrations and wind speeds were measured at 6 heights at the centre of each plot. Odour concentrations were measured at just one pre-determined height, termed $\mathbf{Z_{inst}}$, from which the surface flux could be deduced. These methods were used to compare odour and ammonia emissions following slurry application by three different machines. A system of small wind tunnels was used in experiments to investigate the effect on odour and ammonia emission of diluting slurry. Samples of air leaving each tunnel were collected for odour concentration measurement. The concentration of ammonia in the air entering and leaving each tunnel was measured using absorption flasks. Emission of odour and ammonia was calculated as the product

of the mean concentration measurement and the volume of air drawn through the tunnel for a given period.

Ammonia concentration in air was determined by absorption in acid and odour concentration by dynamic dilution olfactometry. For untreated slurries, close correlation was established between the rate of odour and ammonia emission both during and following application. Similar results were obtained for total odour and ammonia emission following application. No such relationship were established for slurries treated aerobically, anaerobically or acidified prior to application.

Total emission during spreading was calculated by multiplying the ammonia or odour concentration by the volume of air passing through the frame fitted to the front of a Land Rover. The volume of air passing through the frame was determined as:

Air volume (m^3) = (travel speed [m s^{-1}] + wind speed [m s^{-1}]) x cross-sectional area of frame (m^2) x spreading time (s)

A model has been presented by Chardon *et al.* [25] which describes the transfer of ammonia from arable land to the atmosphere after surface application or incorporation of animal manure. The model can be used to study the interaction of the chemical, physical and environmental factors influencing volatilisation losses and their combined influence on NH_3 volatilisation under field conditions.

The following flux[1] equation is applicable:

$$R_v = k \cdot (C_S - C_a) \qquad \textbf{-(2.1)}$$

where k is a transfer coefficient, C_s is the surface ammonia NH_3(g) concentration and C_a is the atmospheric ammonia NH_3(g) background concentration. The rate of volatilisation R_v can be calculated at any moment after application, provided k, C_s and C_a are known.

It has been recognised for many years that gaseous transfer is an important pathway in the terrestrial Nitrogen cycle. In recent times direct field measurements have been made of the exchanges of nitrogenous gases between soils, plants and the atmosphere. Three methods that are important for the evaluation:

- Diffusion theory to calculate gas transport in the soil profile

[1] Flux = quantity per unit area per unit time

- Enclosure methods in which the flux density of the gas at the soil or water surface is calculated from changes in gas concentration in an enclosure placed over the surface.
- Micrometeorological techniques in which the vertical flux density of the gas is measured in the free air above the surface.

Since ambient odours are complex mixtures of various odorants, many of which are impossible to measure analytically, the techniques mentioned above are not very useful for cases related to odours generated from municipal solid wastes.

Another category of emissions, other than fugitive emissions from passive area sources, is a throughput related emission [6] like emissions from a ventilated building emitting odorous air from stored wastes. Standard methods of assessing emissions from a ventilated building are applicable for these cases. The method is described in APPENDIX-IV. Hartung [26] gives tentative calculations of gaseous emissions from pig houses by way of the exhaust air. The amount of 20 trace gases which are emitted by way of the exhaust air from piggeries is calculated based on the known concentrations of these gases in the air of pig barns and on an average ventilation rate of 150 m^3 / h.

2.2.1 Odour emissions from landfills: Measurements by direct methods

A landfill gas is composed of many volatile organic compounds that contribute towards the odour (*see* APPENDIX-I). It is difficult to identify a key component that will represent the odour, which is perceived only as a mixture.

It is difficult to quantify odour emissions from a large area source of typically indefinite geometry and with a spatially inhomogeneous surface like a Municipal Solid Waste (MSW) landfill.

Direct measurement of odour with enclosure method (with Lindvall hoods) is quite common [6]. However, they have their own disadvantages like,

- The surface under the enclosure is in an artificial atmosphere, that cannot replicate the natural atmosphere.
- Spatial resolution that the enclosure can cover is restricted by its cross-sectional area. Usually portable hoods can have a face area as high as approximately (2.0 m x

2.0 m). It is very hard to conduct a huge number of experiments (involving expensive analysis with olfactometry) to cover areas as big as 166.0 hectares (Total area of our study-site).

2.2.2 Odour Flux and the Contributing Source Area: Indirect method

Indirect measurement techniques measure gas/odour concentration above the ground. These measurements are then related mathematically and statistically to the point of origin of the gas., to give estimates of the flux.

The following indirect measurement techniques are know to date:

- Micro-meteorological methods
- Tracer techniques
- Long-path techniques
- Combined reversed modelling and odour detection campaigns

Micro-meteorological methods

Two general micro-meteorological methods have been applied for the measurement of trace substances at uniform surfaces; the **gradient method** and **the eddy correlation method**.

The gradient method requires the variation of concentration with height, and the variations in wind speed, air temperature and (optionally) water vapour concentration to be measured. The method is analogous to Fick's law for the molecular diffusion of gases:

$$f = -K_e \cdot (dc/dz) \qquad \textbf{-(2.2)}$$

where,

f	flux of the odorous gas (ou/m^2.s)
K_e	Eddy diffusivity ($m^2.s^{-1}$)
dc/dz	Concentration gradient (ou m^{-4})

The eddy diffusivity is obtained from the measurement of profiles of wind speed and temperature with height. The empirical relationships for the same have been previously established in field experiments by Dyer and Hicks [27].

The concentration at each height is subject to short-term fluctuations due to eddies rising from the surface carrying relatively enriched air being replaced by those from above containing depleted air. Thus, the gradient at each height must be measured over a relatively long time period compared with the frequency of the eddies. According to Bellingham et al. [28], an averaging time of 10-60 minutes is sufficient. The averaging time cannot be too long as atmospheric conditions may change rapidly, significantly altering the height of the boundary layer.

In contrast, eddy correlation methods only require measurements at one height but care must be taken to ensure that this height is well within the internal boundary layer. Flux is obtained by calculating the correlation between concentration and the vertical component of wind velocity. The method is absolute as it does not require the use of empirical relationships, unlike the gradient method, but the instruments must be fast enough to respond to the eddies transporting methane from the surface. Typical required response times are 0.1-1.0 second over a sampling duration of 30-60 minutes for a layer of 1-10 metres.

In principle, this method is not influenced by instrument noise, provided it does not correlate with the short-term variations from the mean that occur in the vertical component of the wind velocity. The odour sensor is required to detect concentration changes of the order of 1 ou/m^3 if it is to be used to measure fluxes typical of UK MSW landfill sites.

This method has been applied by Fan *et al.* [29] to measure the fluxes of the green house gases from sub-arctic tundra using a laser based infra-red method to measure the methane concentration.

Experiments carried out using both micrometeorological methods and chamber techniques at a Tennessee based landfill [30] have shown that the eddy correlation and gradient techniques give comparable results to those obtained using Lindvall hoods. However, for the gradient technique, a wind speed greater than 1.0 ms^{-1} is required and accuracy is limited to 20-30% [31]. However, micrometeorological methods are preferred over the Lindvall hood technique for areas more than 2000 m^2 [31]. The main reason is the spatial resolution of the micro-meteorological technique, which is better suited to large areas than the restricted covered area in the case of the hood method.

Since the profile technique works best where we have an identifying key component in the sample gas, this method is not quite applicable when odour is considered as an unknown mixture of compounds. The eddy-correlation technique requires quite a fast response odour sensor, which is not readily available in the market. Both the gradient method and the eddy correlation technique can give a flux magnitude but not the contributing source area or location. Also these techniques cannot satisfy the problems of surface-atmosphere interaction over spatially inhomogeneous surfaces.

Wilson *et al.* [32] proposed a method of estimating the rate of gaseous mass transfer from a *disc-shaped* surface source plot to the atmosphere using the predictions of a trajectory-simulation model of turbulent dispersion. It was shown that the rate of gaseous mass transfer from a small (radius $R \leq 50.0$ m) *disc-shaped* source plot to the atmosphere may be calculated from measurements of mean cup wind speed $\bar{s}$ and mean concentration $\bar{c}$ at a single height $\mathbf{Z_{inst}}$, where Z_{inst} is a function of roughness length z_0 and source radius *R*. This was an inexpensive and simple alternative to the use of a large (~300 m fetch) plot and eddy-correlation or profile measurements to determine the source strength.

Smith and Hancock [33] employed the Gaussian dispersion model of Smith [34] to calculate a non-dimensional concentration $\psi(z)$ at selected receptor locations downwind of an odour source. The emission rate *E* is given by:

$$E = \frac{C(z) \cdot u(z)}{\psi(z)} \qquad \textbf{-(2.3)}$$

where *C(z)* and *u(z)* are the simultaneous measurements of concentration and wind speed respectively, taken at height *z* at the downwind location over the same averaging time *t* for which $\psi(z)$ is calculated. This method has been tested for kerwee feedlot, sandalwood feedlot and a ring of manure.

An alternative method proposed by Smith [35] employs the Lagrangian particle trajectory simulation of Wilson *et al.* [32] for the vertical dispersion and a Gaussian lateral dispersion.

The fact that Wilson's approach is restricted to a disc-shaped plot of radius $R \leq 50.0$ m, is not quite suitable for huge MSW landfills of area ~166.0 ha. In Smith's algorithm, there is a doubt about the effect of surface roughness being included in $\psi(z)$. His

modified one [34] employs Wilson's approach, hence it is restricted by the same argument. Both Wilson's and Smith's models are based on a pre-determined source area and give no clear idea about the extent of that area.

If we stick to the principles of dynamic dilution olfactometry as the method for objective measurement of odour, at the same time utilise the micrometeorology based methods, we have to design a slightly different model that would give us the flux as well as the contributing source area.

Tracer techniques

Tracer techniques use concurrent measurements of the concentration of the gas of interest and that of a tracer released at a known rate. The concentration ratio of these two gases is then related to the ratio of their fluxes. A technique applied in a limited way to landfills has been the use of sulphur hexafluoride (SF_6) tracer (Lamb *et al.* [36], McManus *et al.* [37]). A SF_6 tracer is released near a landfill or other methane generating source under certain conditions. Concentrations of both methane and the SF_6 are the measured at numerous locations downwind of the release plume using vehicle mounted instrumentation [37]. This technique has not been tested on odour as a mixture with *olfactometric analysis*. It is presumed that this technique can work only if there is a bulk emission of a gas a not trace releases like odour. Published results compare reasonably well with those obtained from the micrometeorological methods discussed in the previous section, but the method requires that the methane and tracer gas be emitted in an identical manner [37], which is quite unlikely to happen with a trace element like odour. On top of that, the entire technique, with all the instrumentation, looks to be quite expensive.

Long-path techniques

These techniques can be applied over considerable distances in the range of 1.0 km, and provide gas specific concentrations representative of the ambient atmosphere over the path [38]. An infra-red beam is reflected back (using mirrors) across a given transect to, for example, a Fourier-Transform Infra-Red (FTIR) spectrometer, where spectral analysis determines the infra-red absorbence of individual gases. For a given area source of methane, this method produces a series of path-based concentrations for the air above the source. These are often combined with a suitable dispersion model to

calculate the overall emission. This method has hardly been applied to a landfill trace gas release and looks as expensive as the tracer technique.

Combined reversed modelling and odour detection campaigns

Mensink et al. [39] measured odour emissions coming from a landfill by using a reversed modelling technique in combination with a series of odour detection campaigns. During the campaigns an odour detection team traced the boundaries of the odour pollution area and at the same time the meteorological data needed for the atmospheric dispersion model IFDM were collected at the landfill site. Two different methods, namely the *plume edging* method and the *plume screening* method, were used to compare the modelled odour distributions with the experimentally obtained data. In the plume edging, it is assumed that the odour threshold is situated at the edge of the plume, right between the locations where odour was detected (x) and locations where no odour was detected (o). In the second method modelled odour concentrations were directly mapped on the odour detection data. The methods produced comparable results for the different campaigns, allowing an evolution of the impact of the odour limiting measures currently applied to the landfill. This approach looks quite innovative in a sense, however gives only one source strength (ou/s) for the entire landfill site. However, considering the variability and the distribution of various sources within the landfill site (as discussed in Chapter 1) this method cannot be appreciated in the context of the present research.

With a view of the applicability of all these available techniques for the emission of an odorous gas from a broad area source, the following micro-meteorological model has been proposed to be developed within the scope of this research project.

2.2.3 Footprint Methodology: A new approach

In the case of turbulent transport, the determination of a surface source area is quite complex. The temporally averaged “field of view” or the “footprint” of a temperature, humidity or a mass concentration sensor is determined not primarily by geometry, but rather by the turbulent diffusion characteristics of the atmosphere between the sensor and the surface. The footprint is constantly changing both its size and position, depending on wind direction and speed and qualities of the flow.

The problem of the “view factor” and the source area of a scalar that is subject to turbulent diffusion was addressed by Pasquill [40], and more recently by Schmid and Oke [41,42] and Schmid [43]. In this work, K-theory is used to describe the diffusion of a passive scalar in the surface layer. The source weight function of a scalar concentration is found by applying Robert’s solution to the advection-diffusion equation, as described in Gryning et al. [44]. This model has been verified against measured mass concentration data, as reported in the APPENDIX of Schmid and Oke [41]. This model has been tested for evapotranspiration measurement of crops and for estimating regionally representative heat flux over patchy terrain [41,42].

The footprint can be described (see Chapter 3 and APPENDIX VI) as the upwind source area [43] (with relative weighting given to each area element) which contributes to a downwind measurement data point in the boundary layer. The measured difference in the scalar concentration *(local concentration-background concentration)* is the integral of the contributions from all upwind surface emissions.

A *new micrometeorological model* has been designed with an integrated approach of quantifying odour emissions and identifying the magnitude and location of the source area. This model is based on the estimation of footprints of scalar concentration measurements of odour in the atmospheric surface layer. Model parameters depend on the location of the odour sensor and standard surface layer scaling factors, which include mean height and shape of the emerging plume, Monin-Obukhov length etc.

2.3 Dispersion Modelling: Application to odour

In the last 50 years, different models of atmospheric dispersion have been developed. There are very preliminary basic models, e.g. box model where we assume a uniform concentration in each box. Next category of models assume a concentration distribution. These are practical models, based on a Gaussian plume concept, which are used for the regulatory purposes. Particle models calculate trajectories of large number of particles. Lastly we have the highly sophisticated range of mesoscale models based on solution of diffusion equations with computational fluid dynamics (CFD) techniques.

It is quite critical to judge their suitability towards the analysis of odour dispersion relative to other quantities dispersed in the atmosphere. Odour dispersion is a short-range problem. Therefore models should cope with relatively short length and time scales. There are also a few points to be noted with regard to the perception of odour.

- Each person has a specific perception threshold for each odorous compound.
- A small increase in gas concentration may lead to a rapid increase in the perceived intensity
- Adaptation (*see* APPENDIX-II) may occur at high odour concentration

The human noseresponds quickly to changes in odour- within a fraction of a second. Adaptation affects the longer timescales. Figure 2.2 illustrates the variation of the perceived intensity as a function of time.

Mainly for these characteristics of the human nose, concentration fluctuation is quite important in odour dispersion analysis.

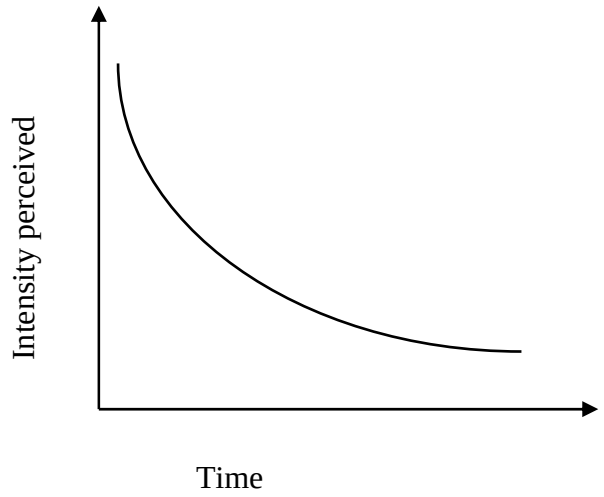


Figure 2.2 Perceived odour intensity versus time.

There are few aspects of the atmospheric turbulence, like the scales of turbulence, ensemble average and concentration fluctuations, which are quite important in the context of our research.

Scales of turbulence

Turbulence has a range of time scales varying from fractions of seconds up to tens of minutes and a range of length scales associated with those time scales. The

characteristic time and length scales vary according to the local meteorology and topography. In a convective, unstable atmosphere, the eddies can be large and go upto hundreds of metres across, while in a stable atmosphere the turbulent motions are small. For an application to dispersion modelling, 1 hour period is taken as the time scale over which meteorology remains more or less constant. However, turbulent time scales are much less than 1 hour.

Ensemble average

The ensemble average is the average value of many values taken from, either, one very long period during which meteorological conditions were the same or, from a large number of shorter records during which meteorological conditions were the same. In general, it is the ensemble average associated with a particular meteorological condition that is predicted by an atmospheric dispersion model. For the same meteorological conditions one measured hourly average will be close to the measured hourly ensemble average, since turbulent time scales are generally less than one hour, variability in the measured values remaining less. The shorter the averaging time, the greater the difference between the ensemble average and one measured value.

Concentration fluctuations

Concentrations fluctuations are due to the variations in measured concentrations of material which occur due to the turbulent fluctuations of the flow field. The time scales when concentration fluctuations are important also depend on the meteorology and topography. This will also depend on the distance downwind from the source and the crosswind distance from the plume centreline.

There are also variations in concentration due to unsteady external conditions, like the change in mean wind direction, other than fluctuations due to turbulence. The slow change in the mean wind direction is called meandering. Meandering of the mean wind direction contributes to flow field turbulence and concentration fluctuations but in general it has a longer time scale than the short scale boundary layer turbulence.

Now, if we give due consideration towards the above aspects of the atmospheric turbulence we will find that the following are responsible for the fluctuations in odour concentration.

- The horizontal and vertical movement of the plume near the source are mainly due to the large eddies produced by the thermal turbulence induced by the heat flux coming from the ground which has been already warmed by the sun. This phenomenon is called meandering, which is the first thing responsible for the concentration fluctuation.

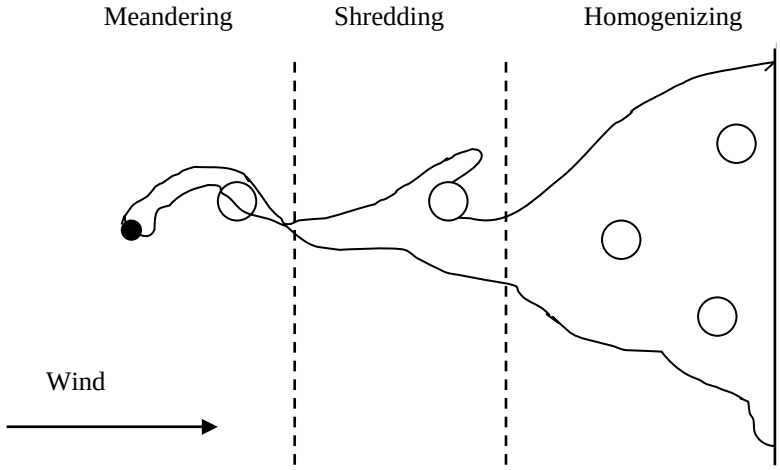


Figure 2.3 Eddies acting on the plume to bring in puffs of clean air.

- The second zone (see Figure 2.3) starts when smaller eddies, generated mainly due the surface roughness, shred the plume to bring in puffs of clean air within. At this point the concentration fluctuates both due to meandering and due to the in-plume turbulence. Smaller eddies are common in a stable and towards neutral atmosphere. Experiments by Mole et al. [45] show that the frequency of concentration fluctuations is always higher in the unstable and neutral atmosphere than a stable one.
- The third and the final zone (see Figure 2.3) is where the eddies and the advective wind both are responsible to homogenise the plume and the fluctuations of concentration slowly decay and tend to match a Gaussian distribution.

Concentration fluctuations vary depending on meteorological conditions and distance from the source. In an odour event, peaks of odour concentration could be much higher than the perception threshold, even though the average concentration is lower (see Figure 4.2). Myles *et al*. [46] have reported peaks of odour concentration about three

fold over the average value. It is thus very important to consider concentration fluctuations in odour modelling.

We can visualise the essential characteristics of a suitable dispersion model for odour-impact study as follows:

- One that estimates the peaks of odour concentration caused by fluctuations characterised by short length scales and times.
- One that considers the effect of eddies on the plume: meandering, shredding and homogenising.
- One that considers the evolution of fluctuations with the distance from the source.
- One that is able to estimate phenomena of the order of few seconds (peaks of concentrations) while working with hourly meteorological input data.

The Gaussian model represents certainly the most widely used simple dispersion model. The maximum average concentration is predicted along the plume centreline. The equation representing a Gaussian concentration is given by Equation 2.4. In this model, the concentration profile follows a Gaussian distribution with respect to the lateral and vertical distribution.

$$C(x,y,z)=\frac{Q}{2\pi\overline{U}\sigma_y\sigma_z}exp\left\{-\frac{y^2}{(2\sigma_y)}\right\}\cdot\left[exp\left\{-\frac{(z-H)^2}{(2\sigma_z)}\right\}+exp\left\{-\frac{(z+H)^2}{(2\sigma_z)}\right\}\right] \qquad \textbf{-(2.4)}$$

where,

C = Concentration (ou/m^3)

Q = Flow rate (ou/s)

$\overline{U}$ = Average wind speed (m/s)

σ_y = Lateral dispersion coefficient

σ_z = Vertical dispersion coefficient

x,y,z = Position from the point source at *(0,0,H)* (m)

H = Effective height of the stack (m)

Because of its popularity and efficiency to predict average concentrations for average meteorological inputs over periods of 10 to 60 minutes it is extremely convenient to use

this model for the dispersion of odours. Clearly, the Gaussian model is inaccurate to predict the odour dispersion for short distances form the point source because the dispersion coefficients, σ_y and σ_z, are evaluated for time scales of 10 to 60 minutes. Average concentrations are predicted for the same time scale, while the peaks are neglected.

In order to correct this discrepancy of the Gaussian model many researchers attempt to use the peak-to-mean ratios as a correction factor while obtaining the peak concentrations. The variations of *peak-to-mean* ratio with distance, averaging time, atmospheric stability, stack height, terrain, building effects etc. have been studied by various researchers. This will be discussed in Chapter 4, *section 4.2.4*.

Using the relationship proposed by Turner [47] the peak to mean ratio of concentration can be expressed as:

$$C_l / C_s = \left(t_s / t_l \right)^p \qquad \textbf{-(2.5)}$$

where,

$C_l =$ concentration estimate for sampling time t_l.

$C_s =$ concentration estimate for shorter sampling time t_s.

p, as a function of stability classes [47] are given in Table 4.1.

The simplicity of this technique is very attractive to take into account peaks of concentration. However, the use of right averaging time for odours is not obvious and its choice can lead to large differences in results. The effect of averaging time in predicting odour concentrations, using peak-to-mean ratios will be discussed with graphs in Chapter 4 and Chapter 6. Another major disadvantage of this approach is that this ratio completely neglects the evolution of concentration fluctuations as a function of the distance from the source. Odour concentration is highly underestimated near the source and far from the source it is overestimated.

Now, most of the regulatory software developed by the US-EPA have been developed based on the use of peak-to-mean ratios, for example ISCST (Industrial Source Complex-*Short Term*). So are the cases with the non-regulatory software like MPTER,

COMPLEX-I etc, developed also by the US-EPA. These are all very popular models, because of their simplistic approach, use of easily available meteorological data and their adaptability to tackle most of the features of atmospheric dispersion. This issue will be discussed in Chapter 4, *section 4.4.1*. All of these models, thus have the same nature of discrepancies arising from the negligence of concentration fluctuations. We have developed our own version of COMPLEX-I with additional features of the effect of peak-to-mean ratio, frequency analysis and finding maximum concentrations at specific grid locations. However in-plume concentration fluctuations could not be taken care of. This version has been adapted to the Ordnance Survey [3] tile data in the format of their Digitised Terrain Model (DTM).

Högström [48] has developed a method for predicting odour frequencies from a point source on the basis of a fluctuating-plume dispersion model. It is used to give estimates of odour frequencies around a point when the odour threshold of the material emitted is determined by sensory methods. He verified his model using trained observers who made a large number of instantaneous (yes/no) observations in a variety of locations around a sulfate pulp factory. The results are tabulated in Table 2.2.

Table 2.2[46] Results of Högström's experiment with validations of observations from trained panelists and model predictions.

Distance downwind (km)	% frequency of detected odour	% frequency of predicted odour
2.0	10.8	8.9
5.0	9.8	5.6
10.0	8.5	3.1
20.0	5.1	1.6

It was concluded that with increasing distance downwind of the source, the validation was getting worse. Högström also conducted other experiments to verify the model with different sensory measurements. The model consistently over-predicted the number of occurrences of odour detection by 30%, possibly because of adaptation of the observers towards the same type of odour. However, this did give an idea of the

reliability that can be obtained from later day odour models. Unfortunately, with Högström's model it is impossible to quantify the odour concentration. It is only possible to know whether odour was detected, but not its concentration. This information is quite insufficient for an integrated odour-impact study.

Clarenburg [49] performed a study of the perception of odorous air pollution with a population in the Netherlands in 1973. He developed a mathematical model for the perception of odour by the population living in the vicinity of a chemical industry in order to describe it quantitatively. He started with the basic Gaussian plume model and developed a penalisation function based on the percentage of the population that would perceive an odour, assuming a log-normal distribution function for such perception. The main problem was to predict the number of complaints, i.e., how many people would perceive odour as a function of the population distribution around the complex.

TRC (The Research Corporation of New England) developed a puff model that predicts the number of occurrences of specified odour dilution ratios (to detection threshold) during a specified period. This model was presented by Murray et al. [50] at the annual meeting of the Air Pollution Control Association in Houston, Texas, in June 1978. The verification data was limited for the test cases. No measurements were made of the frequency of occurrence of odours exceeding the threshold at these points in order to test that part of the model.

We find that there is a fundamental need for a verification programme of the puff model. More work needs to be done on the actual frequency of occurrence and to determine why Högström's model apparently under-predicted at greater distances downwind. Clarenburg's model was based on odour complaints to begin with and offers a slightly different set of data, because he was trying to develop a penalisation function, rather than a control function, to eliminate odour complaints.

It can be concluded that dispersion models are useful tools for predicting the impact of odorous emission on community odour levels and in developing solutions to odour complaints. However, they must be used with great care and consistency.

The first model that *considers concentration fluctuations in relation to plume meandering* explicitly was developed by **Gifford** [51]. His approach considers an instantaneous plume with a Gaussian shape that meanders within Gaussian boundaries, as given in Figure 2.4.

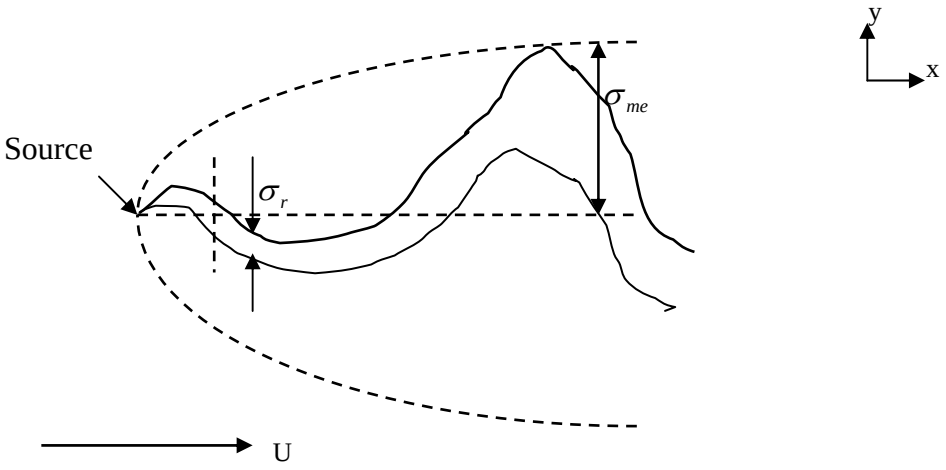


Figure 2.4 Schematic diagram showing the plume meandering by Gifford [51].

Assumptions of Gifford's plume meandering model are:

- Instantaneous plume is Gaussian.
- Instantaneous plume width changes only width distance and not with time.
- Centre of instantaneous plume has a random position drawn from a Gaussian distribution.

It is to be noted that Gifford's model ignores "in-plume" fluctuations, which in practise can give rise to as much variability as the meandering. The width of the meandering zone is a function of the meteorological conditions and the plume diameter. By integrating the concentration and the square of the concentration distributions of the plume probability distribution between the meandering limits, Equations 2.6 and 2.7 are obtained.

$$\overline{C}(y,z) = \frac{Q}{2\pi U\left(\sigma_r^2 + \sigma_{me}^2\right)} \cdot exp\left[-\frac{y^2 + z^2}{2\left(\sigma_r^2 + \sigma_{me}^2\right)}\right] \qquad \textbf{-(2.6)}$$

$$\bar{C}^2(y,z) = \frac{Q^2}{(2\pi U)^2 \cdot \sigma_r^2\left(\sigma_r^2 + 2\sigma_{me}^2\right)} \cdot exp\left[-\frac{y^2 + z^2}{\left(\sigma_r^2 + \sigma_{me}^2\right)}\right] \qquad \textbf{-(2.7)}$$

$$\overline{C'^2} = \overline{C^2} - \overline{C}^2 \qquad \textbf{-(2.8)}$$

where,

$\overline{C'^2}$ = Mean of the square concentration fluctuations

$\overline{C^2}$ = Square of the mean concentration

Q = Flow rate (ou/s)

U = Average wind speed (m/s)

σ_r = Plume internal dispersion coefficient (m)

σ_{me} = Dispersion coefficient of the meandering plume (m)

This is the expression for typical peaks of concentration. The Gifford's meandering plume model is especially efficient to provide estimation of fluctuations near the source. As the plume homogenises with the Gaussian plume due to the eddies working on them at further distances downwind, the fluctuation is small and a standard Gaussian plume model can cope with the situation for distances far away from the source. This effect is quite prominent with single sources, like the case of a waste transfer depot where we had a single odour emitting source. With multiple sources (a mixture of point, line and/or area) it may be difficult to visualise this effect. However, we find that a combination of the Gifford's meandering model and standard Gaussian plume model is probably a better solution for odour dispersion analysis. We find that another commercial software, called the UK-ADMS (United Kingdom Atmospheric Dispersion Modelling System) [52], utilises this particular feature along with a better treatment of fluctuations within the software. UK-ADMS calculates the probability distribution of concentration for averaging times less than 1 hour. The UK-ADMS model for fluctuations will be discussed in *section 4.3.3* of Chapter 4. The model is based on "two-particle dispersion" concept, which has got much in common with Gifford's meandering plume model. In order to complete the model, UK-ADMS calculates the following:

- The probability distribution of concentration in terms of $\overline{C}^2$ and $\overline{C'^2}$.
- Effect of time averaging

For calculating the probability distribution a "clipped-normal" distribution is adopted assuming:

$$\left.\begin{aligned} Prob\{concentration \le \hat{C}\} &= \phi(\hat{C},\mu,\sigma) \quad \text{for } \hat{C} \ge 0 \\ &= 0 \qquad\qquad \text{for } \hat{C} < 0 \end{aligned}\right\} \text{ for some } \mu \text{ and } \sigma . \qquad \textbf{-(2.9)}$$

where $\phi(\hat{C},\mu,\sigma)$ is the cumulative probability curve for a normal (or Gaussian) random variable with mean μ, standard deviation σ.

Considering various approaches towards dispersion modelling of odour, UK-ADMS seem to be a better option, specially when receptors are close (within 500.0 meters downwind) to the source. However, the performance of modified COMPLEX-I [53] and UK-ADMS (version 1.5) are both satisfactory for receptors beyond 500.0 metres downwind of the source. We used UK-ADMS (version 1.5), which is a single source model, for the case of the waste transfer depot quite extensively. However, for the MSW landfill site, modified COMPLEX-I has been used more for the case studies, except for few cases. Since the community odour monitors were all beyond 500.0 metres downwind, this choice was quite satisfactory. It is a pity that we did not have access to the later versions (version 2.0 and version 3.0), which could not be included within the budget of the project.

2.4 Assessment of Odour Impacts: Standard Approaches

The standard methods of assessing odour impacts include:

- Matching standard method
- Community survey by the population panel

Matching standard method

Amoore and O'Neill [54] conducted experiments with squeeze-bottles of odour samples, which are used on-site for comparison with ambient odours. A selection of a standard odour series, with several calibrated odour intensity levels, serves as an aid for evaluation of odours involved in complaints. If one (or more) of the standards is considered representative of the ambient odour, then an intensity scale is provided, consisting of squeeze bottles representing 7 odour levels. The evaluator sniffs them, in

ascending order of strength, and selects the closest match with the overall intensity of the ambient odour. Evaluations are done in real time; or may be used to evoke a remembered odour type and level from previous experience. Professionals are assisted with their ability to identify the major odour types and intensity levels. Various lines of reasoning are presented that support a recommendation that an unpleasant odour level of 5 times average detection threshold be used as a level of odour annoyance for regulatory purposes.

Community survey by the population panel

Panels are chosen from residents usually living around large scale and/complex sources. They are asked to assess the odour intensity in the ambient air at their residence at a specific time every week/day. The results might have a very interesting trend taking into account the annoyance of perceived odours but cannot distinguish between them sharply and in a quantitative manner. In situations dealing with large, complex sources, the results can indicate a general trend in the annoyance but are not suitable to provide a useful regulatory tool.

Hangartner [55] gives a classification scheme for odour emission threshold values *(Odour Annoyance Index)* based on experience. A scheme for odour annoyance is also given, based on the survey technique.

Perrin and Jezequel [56] used population panels for assessing odour annoyance experienced by the local population on the east bank of the Etang de Berre in the south-east of France. A survey was done with the members of the local population where they had to complete a questionnaire over a one-year period regarding the positive odour events they experienced in certain occasions. The survey results were used to calculate the *odour annoyance index* for each sector and for various meteorological conditions, and to plot odour annoyance compass cards. MacKenzie and Mann [57] used *odour annoyance index* based surveys for assessing community annoyance due to sewage treatment plants in Sydney, Australia.

A community odour survey was designed by the *IERC*, Cranfield University in order to assess nuisance impacts particularly from the local MSW landfill site. In this survey community monitors regularly reported the following parameters (at more or less the same time of the day). The selection of the monitors and the design of the monitor's report are explained in [58].

- Name of the monitor:
- Address of the monitor:
- Date of the report:
- Location:
- Activity (at the time of the report):
- Time:
- Length:
- Cloud Cover:
- Source:
- Description:
- Certainty: In the scale of 1-3
- Odour event: Yes/No
- Origin: Landfill/Brick work/Agricultural/local
- Unpleasantness: In the scale of 1-7
- Intensity: In the scale of 1-7
- Comments:

Although a public survey can confirm that spontaneous complaints are truly indicative of a community odour problem, it does not provide any quantification of the magnitude of the impact of the alleged odour source on the residents. A fast and simple method was presented first by Poustchi *et al.* [59] to analyse an odour impact on a community. The introduction of the concepts of percent probability of complaint (PPC), predicted degree of annoyance (PDA), degree of offensiveness (DO), potential level of source annoyance (PLSA), and potential odour impact (POI) provides a basis for quantifying the severity of an odour problem at the source or at the downwind community. However, the above concepts could not be validated by the authors for odour problems resulting from the landfill operations due to the lack of proper emission data. Poustchi's method measures samples from the source and needs a dispersion technique to find out the dilution at the receptor to find out POI. *This method [70] completely avoids the actual reports/complaints of the people within the community*.

Instead, we propose a different method that will analyse the actual perception of odour within the community.

2.4.1 Analysis of Odour Perception: Its utility in assessing community annoyance

It is necessary to establish the relationship between the intensity of an odour and the odour concentration. The standards and regulations based on odour concentration could be correlated using this relationship. The relationship is far more important when used in conjunction with dispersion modelling, in terms of comparing the resultant odour concentrations at the receptors (locations of potential complainants), as obtained from the dispersion analysis, with those obtained by reducing the intensity scales of the odour complaints to odour concentration levels.

Thus, one of the objectives of the research was to develop a model of odour intensity and odour concentration by using data collected from various sensitive areas of the Municipal Solid Waste landfill site.

It was observed that one type of mathematical function could not describe the growth of intensity for all types of odours or odour mixtures. **S.S.Stevens** [60,61] proposed that the growth of sensation ψ on all prothetic continua is a power function of stimulus magnitude ϕ, i.e., $\psi = k\varphi^{\beta}$. Weber-Fechner's law stated that the magnitude of sensation is linearly related to the logarithm of stimulus magnitude. ***Fechner's logarithmic law*** did not find much support from category scaling in various sense modalities. Misselbrook *et al*. [62] derived a relationship between concentration and intensity of odours from pig slurry and broiler houses. Their data fitted into Fechner's law quite well.

Beidler [63] proposed a relation for the growth of neurophysiological responses from taste receptors and from the chorda tympani nerve of various species. Beidler's equation, as applied to taste, is

$$r = \frac{RK\phi}{1 + K\phi} \qquad \textbf{-(2.10)}$$

where ϕ is concentration, r is the neural response, K is the equilibrium constant and R is a constant that reflects the maximum neural response from a particular type of olfactory receptor.

Laffort [64] suggested that Beidler's fundamental taste equation may be modified to describe psychophysical functions for odour intensity obtained by direct interval and direct ratio scaling. These models will be discussed in detail in Chapter 5.

It is to be noted that these models are for the analysis of perception and not annoyance. A major character of odour, the *hedonic tone* (defined in ANNEX-I), has been completely neglected in these models assuming a landfill odour can never be pleasant. *There are many more psychological factors related to the perception of odour, which have been found beyond the scope of this study and have been carefully avoided*. An odour sample may be quite annoying to somebody, while not to the other person. This may be due to the reason that the first person has been used to the odour since the potential source of that odour may be very near to his/her residence and he/she considers it as a part of his/her daily life. It is just the opposite case for the second person.

2.5 The Odour Impact Model (OIM): Present research

In the present context we have developed an odour impact model (OIM) that considers:

1. Indirect micrometeorological measurement technique (based on the concept of footprint of scalar odour concentration) as the method for assessing emissions from the solid waste landfill site and the contributing source area.
2. UK-ADMS as the most suitable model for short-range odour dispersion and COMPLEX-I or UK-ADMS for distances beyond 500.0 metres.
3. It was proposed to test all of the four psychophysical models (described in the previous section) with the intensity-concentration data of several odorous samples from the MSW landfill site. A parameter estimation technique was proposed to be used, based on the Levenberg-Marquardt [65] minimisation of χ^2, to obtain the respective co-efficients of each model. The selected model will be used with the results predicted by the dispersion model to analyse the reports of the community monitors. Specifically, an attempt will be made to match/correlate the intensity scales predicted by the model with those reported by the community monitors.

Thus the new odour impact model (OIM), with its individual components, will solve the nuisance analysis partially.

In the next Chapter, various emission assessment techniques including the new micrometeorological model, based on the concept of footprint, will be discussed elaborately.

Chapter 3

3. Assessment of Emissions

This Chapter focuses on various aspects of the sampling and measurement techniques specifically suitable for odorous gases and the computation of the odour flux (ou/m^2.s) and odour strength (ou/s) for different kinds of source emissions. Two different cases have been dealt with separately. The first one is for samples from a solid waste transfer depot, which is basically a temporary junction house for the wastes, where the odorous gas is more or less confined to one particular ventilated building. The second case involves sampling from a Municipal Solid Waste (MSW) landfill site, which is a huge open area of totally indefinite geometry having various types of source within it and most of them are open to the atmosphere.

This Chapter will focus on the development of an innovative method for estimating odour fluxes from a Municipal Solid Waste (MSW) landfill site. A micrometeorological model has been developed based on the estimation of footprints of scalar odour concentration measurements in the atmospheric surface layer. The model is based on an analytical solution of the Eulerian advection-diffusion equation for vertical diffusion; model parameters include the location of the odour sensor and standard surface layer scaling factors.

Lindvall Hoods are commonly used for measuring odour fluxes from ground based fugitive sources. However these cannot replicate the real atmospheric conditions. Common micrometeorological techniques for determining fluxes, such as vertical gradient measurements or eddy correlation methods, yield a flux magnitude but give

little information about the source location. On the other hand the flux footprint describes the expansion and contraction of the required fetch under varying stabilities. Preliminary results from the model seem to be in good agreement with those from Lindvall hood measurements.

3.1 Introduction

Issues related to odour complaints from a local community around industrial sites dealing with solid wastes are difficult to deal with. One of the efficient methods involve use of atmospheric dispersion models, particularly in conjunction with knowledge of site operations.

All sophisticated dispersion models need reasonably accurate emission data. It is difficult to quantify emissions from a large area source of typically indefinite geometry and with a spatially inhomogeneous surface like a Municipal Solid Waste (MSW) landfill. One standard method is the use of Lindvall hoods. These hoods are mechanically operated with a rated induced-draft fan and as such cannot replicate the real world atmosphere. The results are not very reliable due to leakage along the piping and at fittings, especially when these hoods are used over a relatively rough surface like the daily operational area of a MSW landfill site.

On the other hand, commonly used micrometeorological techniques like the gradient method or the eddy correlation technique can give a flux magnitude but do not in themselves predict the contributing source area or location. Also these techniques cannot satisfy the problems of surface-atmosphere interaction over spatially inhomogeneous surfaces. The fundamental difficulty at the base of all such problems is that the well-known homogeneous surface-layer relationships used to describe turbulent exchange of heat, mass, and momentum fail in the regions of inhomogeneity. The spatial resolution of observations relating turbulent diffusion of atmospheric pollutants constantly changes in size and position, depending on wind direction and speed and on the characteristics of the flow.

A number of studies have been done in the past that address these problems and try to find a relationship between the spatial distribution of surface sources and a measured signal at a height in the surface layer [41,66-68]. These studies focus on a common

problem, but lead to different models of solution that cannot be interchangeably applied.

The footprint can be described as the upwind source area [43,66,67] (with a relative weighting given to each area element) which contributes to a downwind measurement data point in the boundary layer. The measured scalar concentration is the integral of the contributions from all upwind surface emissions. The uncertainty in the magnitude and area of this contribution is a problem for experimental design, and the interpretation of atmospheric observations. Knowledge of the upwind extent of the effective source fetch is necessary to ensure that sensors are placed correctly with respect to the upwind area of interest. The new micrometeorological model has been designed with an integrated approach of quantifying odour emissions and identifying the magnitude and location of the source area. This model is based on the estimation of footprints of scalar concentration measurements of odour in the atmospheric surface layer. The expressions for vertical diffusion are derived from the Eulerian advection-diffusion equation. Parameters of the model depend on the location of the odour sensor and standard surface layer scaling factors, and include mean height and shape of the emerging plume, Monin-Obukhov length etc, which can be computed with standard numerical tools.

The next few sections WILL describe sampling and measurements of odorous gases from a waste transfer building, the Lindvall hood approach and the new micrometeorological model for calculating the odour flux from a large area source, and an experiment for testing the new model. The final sections present the experiment results and discuss the relative merits of the two methods.

3.2 Odour: Sampling and Measurement

Odour assessment requires collection of representative samples, measurement and detection of specific odorous compounds, and interpretation of results. These activities need to support the ultimate goal of minimising odour annoyance in communities. Throughout this project odour has been considered as it has been sensed by human beings, *i.e. the result of a mixture of compounds*, mostly volatile in nature, and *not due to a particular compound in the mixture*.

3.2.1 Sampling Strategy

Proper collection of an odorous air sample is of prime importance in attaining an accurate analysis of the odour, both qualitatively and quantitatively. In the following two sections the specific sampling strategies for samples from a waste transfer depot and that from a landfill site are explained.

Case 1: Waste Transfer Depot

It was evident that odour emissions occur from sources both internal and external to the transfer building on site. Emissions from the site but external to the building were mostly the refuse vehicles, wash-down area and oil-trap. Within the transfer building (refer Figure 3.1) freshly tipped refuse and materials for recycling were the main sources of odour.

For the purposes of sampling the most significant odour source was used. From early site inspections by Cranfield and SRI staff it was agreed that the transfer building was the main source of odour. Whilst emissions from the building were the strongest it was noted that the building could also provide information about the background odour from vehicles. These could be inferred by taking measurements whilst loading operations were ceased and would be likely to provide an indication similar to that of sampling odours from vehicles.

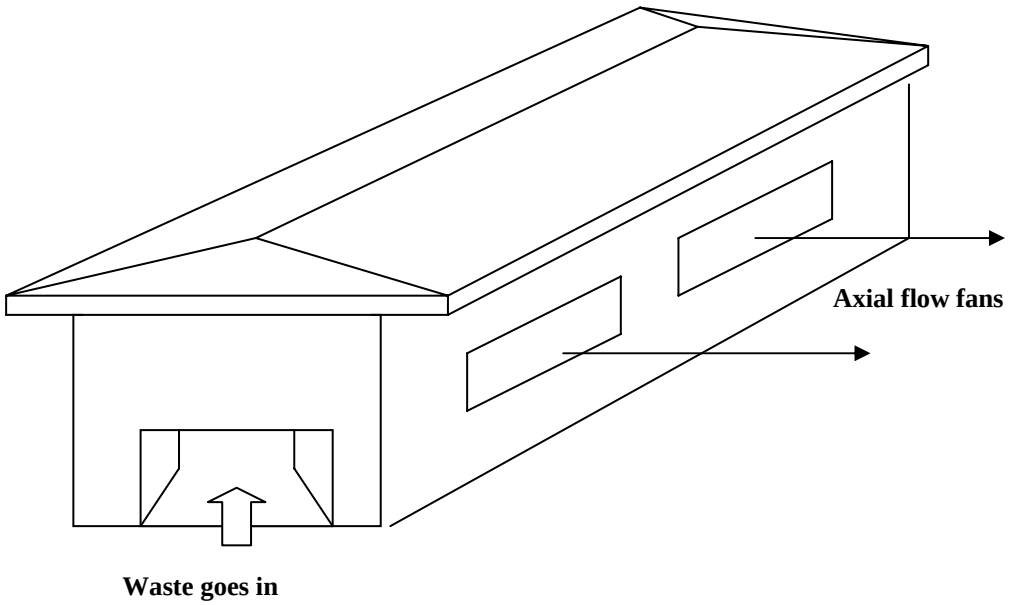


Figure 3.1 A waste transfer depot, where we get throughput related specific emissions.

The quantification of odour emissions is dependent upon achieving effective air sampling from the source. Sampling from static surfaces such as those on vehicles is often unreliable as it is dependent upon airflow over the surface at the time of measurement. Therefore it was decided that measurements should be taken from fan outlets within the building. This sampling location was proposed to be the best for a reasonably representative sample of emissions from the building. It was expected that the sample would be considerably higher than samples diluted by air from nearby open doors, but not as strong as less representative samples taken from within the waste itself. Should the odour strength have proved to be low from the building then further samples would have been taken from vehicles elsewhere on the site. Thus the transfer building was used as an indicator of potential emissions for internal and external sources. To assess any potential operational changes an understanding of the difference in emission between periods of vehicles operating and remaining static was decided to be important. Six samples were taken and the resulting odour strength analysed for threshold and intensity.

The samples were collected in Teflon sample bags, through a Teflon FEP sample probe with stainless steel fittings positioned within 25 cm of the north easterly exhaust fan. These materials were used to avoid contamination of the sample. Three replicate samples were taken during the two periods. The first period was one of lowest activity between 8:30 and 9:30 am and the second period was of high activity between 11:30 and 12:00 noon. Details of activities are shown in Table 3.1. Samples were transported to Silsoe for analysis the same day.

Sampling Details

The six samples taken from the site are summarised in Table 3.1. Sampling times were determined by the need to assess odour concentrations in the building when activity was at a minimum and then to compare this with routine activity. For all samples Table 3.1 shows the temperature of 16°C. Table 3.2 shows the difference in odour strength between samples 1-3 where operations in the transfer building were largely static and 4-6 where the CAT vehicle was moving and loading refuse.

Table 3.1 Sampling times and conditions.

Sample	Time	Activity temp = 16.5°C, wind = NE
1	08:40-08:48	Garden waste tipped at 08:43
2	08:58-09:06	Small truck tipped at 08:55 and 09:08
3	09:15-09:22	CAT started at 09:12, soil tipped at 09:15
4	11:03-11:11	CAT active and loads of refuse tipped on floor, load complete 11:08
5	11:20-11:28	CAT working until 11:29, load complete
6	11:39-11:49	CAT restarted 11:37 working through sampling

Table 3.2 Odour concentrations and 95% confidence limits for samples taken on 19th Sept. 1995.

Sept. 19th sample		ou/m^3		
	Odour Threshold		95% confidence limits*	
		mean	high	low
1	50%=	123	139	108
2	50%=	132	184	95
3	50%=	57	65	51
4	50%=	1695	1895	1516
5	50%=	969	1320	711
6	50%=	1409	1571	1264

** Assumed Normal distribution*

Calculation of Source Strength

The mean odour concentration of the sample (ou/m^3) is then multiplied by a volumetric flow rate to give the odour strength in ou/sec. In this study a fixed ventilation rate is used for each set of computations which has been calculated on the basis of the minimum extraction required to prevent a positive air pressure inside the building

resulting in leakage of odour. The calculations allow for the average effects of natural wind forces in order to overcome the possibility of a pressure differential between the inside and outside of the building. The extraction rate for the worst scenario is 131.2 m^3/sec when both the doors of the building are open. Details of calculation for ventilation exhaust rates, following the procedure in Valentine et al [69], are given in APPENDIX-IV (Ventilation exhaust rates to prevent air escape from the waste transfer building).

Case 2: MSW Landfill Site

Odour samples from three gas well locations and at a representative area within the active filling site were taken by **SRI** in duplicate on three days. These samples were assessed individually by dynamic olfactometry and on one sample from each location an assessment of odour offensiveness and intensity was also carried out at **SRI**.

Collecting samples from the gas wells

The samples were collected, through a Teflon FEP sample probe with stainless steel fittings, from the permanent gas sampling valves on each of the gas wells in Nalophan NA sample bags. Theses materials are particularly used to avoid contamination of the sample, as specified in the CEN draft standard [70]. Two replicate samples at each position were taken each time.

Collecting samples from the tipping area

- By Cover Sheet Method

The compacted freshly tipped surface is covered with a sheet of Nalophan NA bag material, supported to make a low ‘tent’, as given in Figure 3.2. The atmosphere is usually left for a period of 10 minutes to enable the gases trapped to reach an equilibrium concentration. Duplicate samples were collected using the standard method of filling the odour bags [70].

- By Lindvall Hoods

The particular MSW landfill site has a gas collection pipe network installed which ensures that the whole mass of capped landfill is under negative pressure, and therefore it is unlikely that there is a vertical outward flux of gas from the freshly filled compacted waste. A more suitable method was required than the cover sheet method.

SRI provided a Lindvall Hood, of surface area 1.5 m^2, as given in Figure 3.5. In this method a controlled flow of air is passed over the surface and samples of inlet and exhaust air are collected. Figure 3.3 shows a close view of a Lindvall Hood.

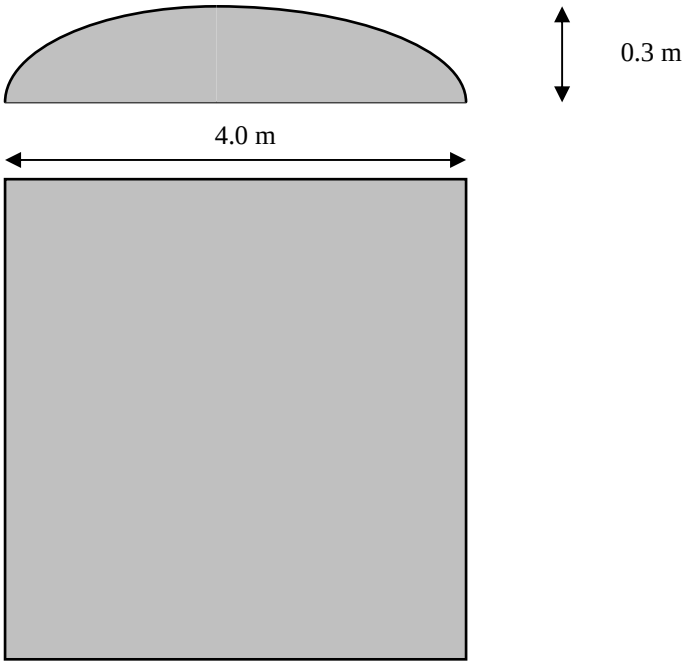


Figure 3.2 Dimensions of Cover Sheet.

Collecting samples from the tipping area

The principles of operation and computation of the flux (ou/m^2.s) and the source strength (ou/s) would be explained broadly in *section 3.3*.

Samples collected by various methods are then sent to **SRI** for the olfactometry tests. These will be explained in the next section.

3.2.2 Measurement of odour concentration: Olfactometry

This is an objective method of expressing the strength or concentration of an odour. The method used determines how many times a sample must be diluted with odour-free air to be just detectable by 50 percent of the panel. The number of required dilutions defines the odour concentration in Odour Units per cubic metre (**ou/m^3**). These test are

carried out in laboratory conditions with trained and selected panellists. The odour concentration in ou/m^3 can be used together with atmospheric dispersion modelling to predict community impacts.

In this study odour concentration was measured using an "Olfactomat" dynamic dilution olfactometer (Project Research Co., Amsterdam). The protocols described in the CEN (Comite Europeen de Normalisation) draft standard [70] were followed for the olfactometry tests. The sample was presented to an odour panel using the forced-choice method. Six dilutions of each sample, differing from each other by a factor of 2, were presented to the panellists three times. Dilutions were made using odour-free air

Figure 3.3 Lindvall-Hood, in use at the MSW Landfill Site. *Date: 18th August, 1998.*

supplied by a compressor fitted with carbon filters and an air dryer. The olfactometer has two sniffing ports, one containing the diluted sample air and the other odour-free air. For each presentation, panellists indicated via a keyboard which port delivered the odorous air. In order to put greater confidence on the panellists' responses, they were also asked to indicate whether their choice was a "guess" (as it would have to be if the

odour presented was below their personal threshold level), or whether they had an "inkling" that their choice was correct (when the odour was close to the threshold level) or whether they were "certain" their choice was correct. Only when the correct port is chosen and the panellist is certain that their choice was correct is it taken as a TRUE response and at least two consecutive TRUE responses must be obtained for each panellist to determine an individual threshold estimate (ITE). The mean threshold value for each sample is calculated from the geometric mean of the ITE's of all panel members using the Dravniek's [71] method. The odour concentration determined by this method has units of odour units per m^3 of air (ou/m^3).

In the case of the *waste trasfer depot*, the geometric mean of odour concentration for the emitted air during the time of low activity was 97 ou/m^3 and rose to 1323 ou/m^3 when waste was being tipped and loaded into the bulk lorries.

In case of the MSW landfill site, the results of the olfactometry tests for the odour concentration and intensity are presented in Table 5.2 of Chapter 5.

Dynamic Dilution Olfactometer: Principles of Operation

Dynamic olfactometry is a technique where a stream of sample air is continuously mixed with a stream of odour free air before being presented to a panel of people through some type of sniffing port. The principles of operation are explained in APPENDIX-IV.

3.2.3 Odour Intensity Measurement

The assessment of odour intensity indicates the effect of differing odour dilutions on the likely smell sensation for an individual. Different types of odour require differing dilutions to gain an equivalent reduction in their impact or sensation. Intensity tests give an indication of the level of dilution required to change odour strengths. Measurements of intensity are determined by the "sniffing" panel using a subjective scale (usually 0-6) from *no odour* to *extremely strong.* Depending upon odour type and selection of the panel high confidence levels can be achieved from these qualitative judgements.

For all the human senses, including the sense of smell, the relationship between the magnitude of a sensation and the intensity of stimulus can be assessed. The form of these relationships depends on the scaling method used. *Category estimation* derived

from Fechner's Law when related to the sense of smell, states that equal ratios of odour concentrations lead to equal differences between perceived intensities, (e.g. points on a category scale), thus perceived intensity (I) is a linear function of the logarithm of odour concentration (C) :

$$I = k_1(\log_{10} C) + k_2 \qquad \textbf{-(3.1)}$$

where k_1 and k_2 are constants for a particular set of panellists and an experimental set-up.

Odour intensity was measured using this category estimation technique. Following the determination of odour concentration, a range of suprathreshold dilutions were presented in random order. The panellists were required to indicate their perception of intensity at each dilution according to the following scale.

0	No odour	4	Strong odour
1	Very faint odour	5	Very strong
2	Faint odour	6	Extremely strong odour
3	Distinct odour		

Case 1: Waste Trasfer Depot

Intensity scores were obtained from each panellist for each of 12 dilution presentations with the average score for each presentation plotted against $\log_{10}$ concentration. Linear regression was performed on intensity *vs.* $\log_{10}$ concentration and the line of best fit plotted on the graph.

The relationship between odour intensity and logarithm of odour concentration for one of the odour samples taken, Figure 3.1, shows that at an odour concentration of between 10 and 4 ou/m^3 the emitted odour intensity reduces from a *distinct* odour to a *faint* odour. This is often regarded as the point at which odours will not be a nuisance. The emission sample was judged to need dilution by approximately 330 times to reach a level where the odour would be perceived as *faint.*

Intensity scores for the samples taken from the MSW landfill site will be used for analysing the perception (Chapter 5) and hence all the intensity-concentration plots are presented in Chapter 5.

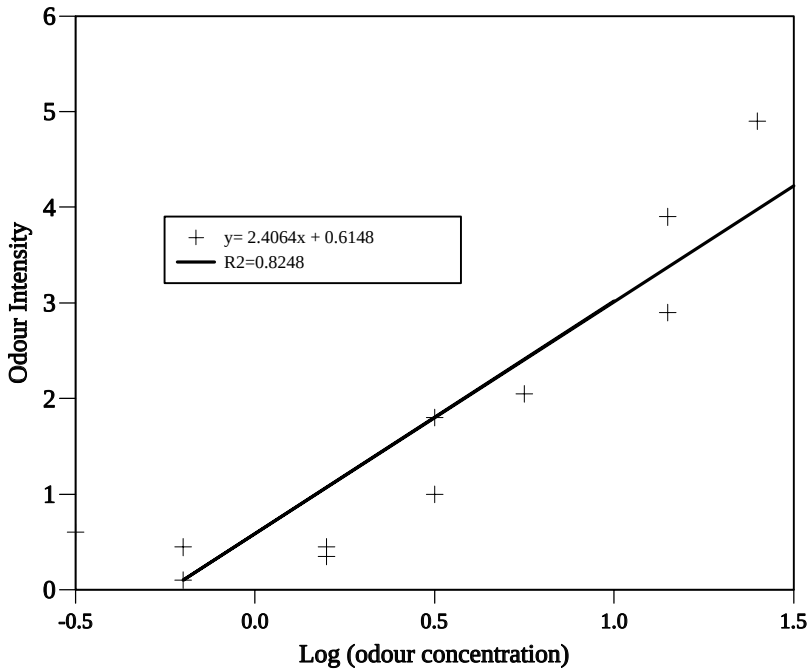


Figure 3.4 Relationship between intensity and concentration for odours.

Case 2: MSW Landfill Site

The results of the odour intensity measurements for *the Municipal Solid Waste(MSW) Landfill Site* are presented in section 5.5 of Chapter 5. In the next section the emission calculation methods would be discussed. The methodologies of the conventional Lindvall hood and the new footprint-based techniques are described.

3.3 Emission Assessment: Direct Method

In the following section, the direct emission measurement technique with portable Lindvall Hoods will be discussed.

3.3.1 Lindvall Hood Approach

Lindvall hoods (as given in Figure 3.5) are portable flux chambers with an induced-draft fan-hose connection. There is an on-line adsorption chamber in the inlet line with activated charcoal filter pads for adsorbing any odour from the inlet gas. The inlet to the fan can be throttled to control the airflow rate. Air passes from the filter into a plenum chamber and is diffused homogeneously across the width. The air travels the length of the hood over the surface and out of the exit. There

are two connection points for the sampling ports, one each on the inlet and outlet pipes

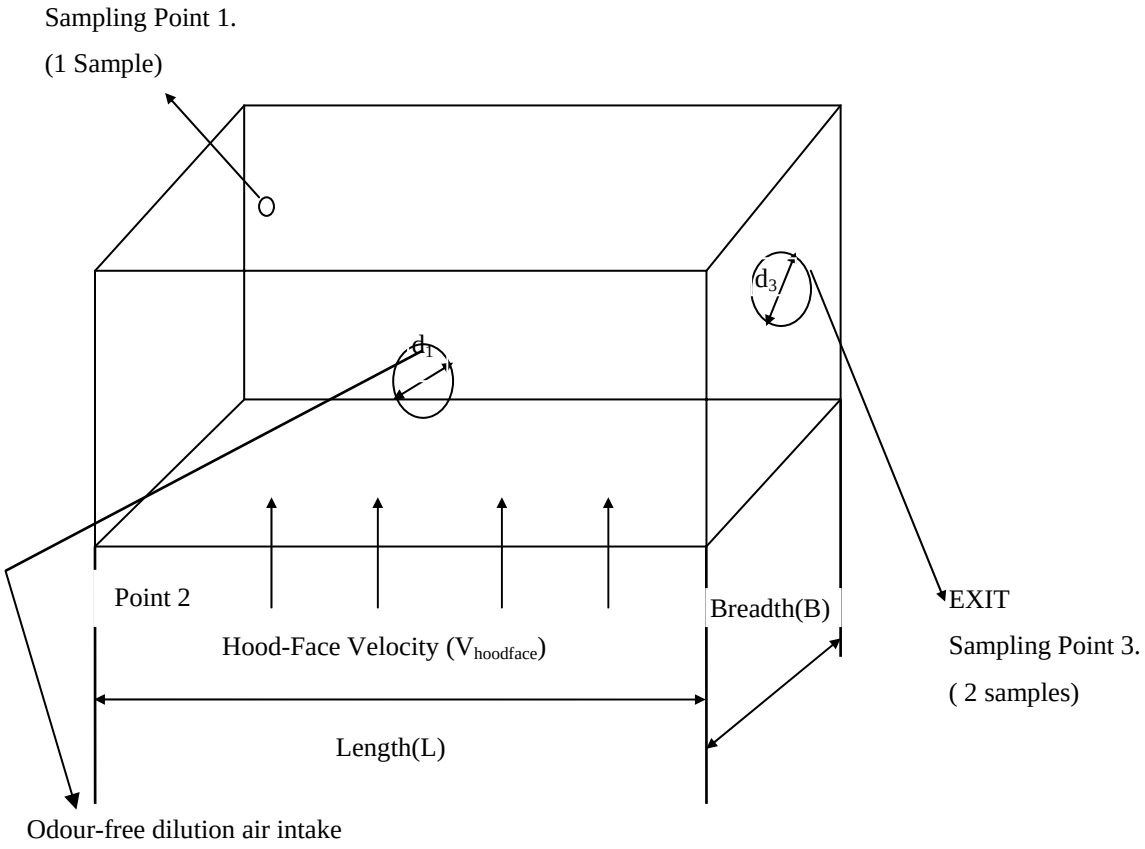


Figure 3.5 Sketch of Lindvall Hood showing various sampling points.

respectively. Sampling ports are connected to the Tedlar bags. Each bag takes about 15-25 minutes to be filled and the samples are taken for the Olfactometry tests [70] for odour concentration.

- Assume that inlet pumping maintains a slightly positive pressure in the hood so that no unfiltered odorous air is drawn into the chamber. In equilibrium, the odour added per unit time is equal to odour removed per unit time. Thus, with the following assumption the source emission rate (q, ou/m^2 .s) can be measured.
- It is also assumed that there is good mixing within the hood volume and therefore from whichever point air is extracted from the hood would have the same odour concentration. Referring to Figure 3.5,

1. Point 1: Odour-free dilution air intake.
2. Point 2: Odorous air intake through the hood face.

3. Point 3: Hood exit point.

We can write:

New odour added per unit time in the hood = $q \cdot A_2$ **-(3.2)**

In equilibrium,

Change in odour content per unit time = (volume flow rate) x (change in odour concentration)= 0, where volume flow rate is the total exhaust flow rate at the input.

Odour removed per unit time = $V_1 A_1 (C_3 - C_1)$ **-(3.3)**

Hence, $q = \frac{V_1 A_1}{A_2} \cdot (C_3 - C_1)$ **-(3.4)**

where

C_i = Odour concentration (ou/m^3)

V_i = Velocity of the fluid (m/s)

A_i = Cross-Area of the flow (m^2)

3.4 Emission Assessment: Indirect Method

New Micrometeorological Model

This model is based on the analytical solution of the Eulerian advection-diffusion equation for a line source and then extrapolated to the case of an area source for cases of shorter downwind distances as compared to the infinite crosswind stretch. The assumptions, as explained in the next section, match with the actual conditions during the experimentation at the landfill site. The approach includes calculation of a factor $\int K \cdot dx$ (as explained in the next section) with standard surface layer scaling parameters and meteorological data and measurement of odour concentration at a certain height. Then the source areas are computed with the SAM-2 [43] model. Ultimately the odour fluxes, in ou/m^2.s are multiplied with the source areas in m^2 to give the odour emission rates in ou/s, which are used in the dispersion models for future predictions of odour dispersion.

3.4.1 Computation of the Odour Flux

The concentration distribution, $C(x, y, z_m)$, downwind of a unit surface point source of a passively diffusing scalar can be described as [72]:

$$C(x, y, z_m) = Q_p \cdot \frac{D_y(x, y).D_z(x, z_m)}{U} \qquad \textbf{-(3.5)}$$

where

Q_p = source strength of the unit surface point source (ou/ s)

D_y = crosswind concentration distribution functions

D_z = vertical concentration distribution function

U = effective speed of plume advection at the mean height of the plume, $\bar{z}$.

z_m = sensor height from the ground (defined to be at x=y=0)

Depending on **standard surface layer scaling parameters** and based on an analytical solution of the Eulerian advection-diffusion equation for vertical diffusion [44,73], we have:

$$D_z(x, z) = \frac{A}{\bar{z}(x)} \cdot \exp\left\{-\left(\frac{B.z}{\bar{z}}\right)^s\right\} \qquad \textbf{-(3.6)}$$

where

A = $s.\ \Gamma(2/s) / \Gamma^2(1/s)$

B = $\Gamma(2/s) / \Gamma(1/s)$ are functions of the shape parameter (s, see APPENDIX-V) and s is determined by the growth of the vertical spread with distance.

Γ = gamma function

$\bar{z}$ = mean height of the plume.

Diffusion in the lateral direction is commonly assumed to be Gaussian, so that $D_y(x,y)$ can be written [44]:

$$D_y(x, y) = \frac{1}{\sqrt{2\pi} \cdot \sigma_y} \cdot \exp\left\{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right\} \qquad \textbf{-(3.7)}$$

Here σ_y is the standard deviation of the lateral spread and can be related to the plume travel time, *x/U*, and the standard deviation of lateral wind fluctuation, σ_v as $\sigma_y \cong \sigma_v.x/U$.

Hence Equation (**3.5**) can be written as:

$$C(x,y,z) = \frac{Q_p}{U} \cdot \left[\frac{A}{\bar{z}(x)} \cdot \exp\left\{ -\left(\frac{B.z}{\bar{z}} \right)^s \right\} \right] \cdot \left[\frac{1}{\sqrt{2\pi} \cdot \sigma_y} \cdot \exp\left\{ -\frac{1}{2}\left(\frac{y}{\sigma_y} \right)^2 \right\} \right] \qquad \textbf{-(3.8)}$$

In case of a line source of infinite crosswind extent, releasing Q_l units of material in unit time from unit length of the line, the equation defining $C(x,z)$ is exactly the same as that defining $\int_{-\infty}^{\infty} C(x,y,z) \cdot dy$, i.e. the *crosswind integrated concentration* or the *CIC* from a point source releasing Q_p , units of material in unit time. Hence we can write,

$$\int_{-\infty}^{\infty} C(x,y,z) \cdot dy = C(x,z) \qquad \textbf{-(3.9)}$$

Now, assuming the crosswind and vertical distributions to be independent of *z* and *y* respectively, from equations (3.8) and (3.9) we get,

$$C(x,z) = \frac{Q_l}{U} \cdot \left[\frac{A}{\bar{z}(x)} \cdot \exp\left\{ -\left(\frac{B.z}{\bar{z}} \right)^s \right\} \right] \qquad \textbf{-(3.10)}$$

Now, the expressions for *U* and *s* are given in APPENDIX-V and they are computed with a numerical scheme and they are solved iteratively using *Newton-Raphson* algorithm.

In the next section the concentration distribution for a line source would be extended to an area source model under certain physical assumptions.

Area Source Odour Flux (q)

Let us consider first the case of emissions from an area at a uniform rate of q per unit area at ground level and, as in Figure 3.6, consider a crosswind element of downwind extent δx. This constitutes an elementary crosswind line source of strength $Q_l = q \cdot \delta x$ per unit length.

The basic assumption for the following derivation is:

At downwind distances, which are not large compared with the crosswind extent of the element in either direction the effect of the elementary line source may be taken for many practical situations as approximating that from an idealised line source of infinite crosswind extent.

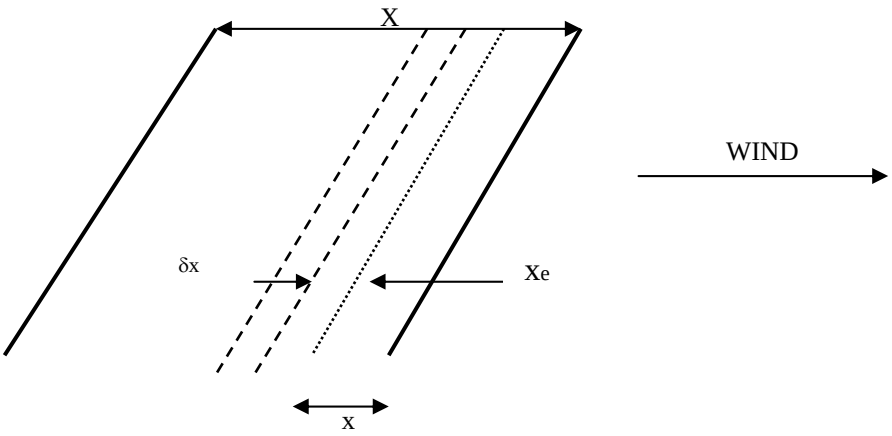


Figure 3.6 Representation of an area source

From Equation (3.10) we can write:

$$C(x, z_m) = K^{'}.Q_l \qquad \textbf{-(3.11)}$$

where

$$K^{'}U = \left[\frac{A}{\bar{z}(x)} \cdot \exp\left\{ -\left(\frac{B.z}{\bar{z}} \right)^{s} \right\} \right] \qquad \textbf{-(3.12)}$$

where $K^{'}$ depends primarily on the wind speed and the magnitude of the vertical spread (at a given distance downwind) but also on the shape of the vertical distribution. Referring to Figure 3.6 again, the contribution δC on the downwind boundary of the

area source from an element distance *x* upwind is $K^{'}q\delta x$. Thus the total concentration at ground level on the downwind boundary, from all sources within a distance X upwind is:

$$C(x, z_m) = q\int_0^X K^{'} \cdot dx$$

or

$$q = C(x, z_m) \Big/ \int_0^X K^{'} \cdot dx \qquad \textbf{-(3.13)}$$

Equation 3.13 is solved for q numerically. The meteorological data were obtained from the experiments carried on the site and the concentration of the odour samples were obtained from the results based on olfactometry (carried out at the **Silsoe Research Institute**, **SRI**, Bedford, UK).

In APPENDIX-V computation of the following factors, contributing towards the vertical spread of the plume and hence the calculation of *q*, will be explained:

- The mean height of the plume $\bar{z}$
- The shape parameter *s*
- The mean advection velocity of the plume $\bar{u}$
- The Monin-Obhukov length *L*.

3.4.2 Computation of the source areas

A *source area of a signal (difference between the measured and the background(measured) concentration) of level P* is defined [43] as the smallest area (Ω_P) bounded by a source weight-function isopleth $f(x, y, z_m) = f_P$ such that *P* is the fraction of the total integrated source weight function, φ_{tot}, contained in Ω_P:

$$P = \frac{\varphi_P}{\varphi_{tot}} = \iint_{\Omega_P} C(x, y, z_m) \cdot dx \cdot dy \Big/ \int_{-\infty}^{\infty}\int_{0}^{\infty} C(x, y, z_m) \cdot dx \cdot dy \qquad \textbf{-(3.14)}$$

where φ_P is the integral of the source weight function over Ω_P ,e.g. 90% source area is the smallest area accounting for 90% of the detected signal. C is the signal at x and sensor height z_m, due to the source element $dx \cdot dy$. Source areas have been computed using the SAM-2 [11] model. In

Figure 3.7 x_{mc} is the maximum source location (upwind distance of the surface element with the maximum influence on a given sensor), a_c is the near end, e_c, the far end, d_c the maximum lateral half-width of the source area. The size of the area bounded by the isopleth is denoted as A_c. Various dimensions for the 50% influence source areas have been computed and the results are given in Table 3.5. The expressions for characteristic dimensions are:

$$D_N = \alpha_1 \cdot (z_m / z_0)^{\alpha_2} \cdot \exp\{\alpha_3 \cdot (z_m / L)^{\alpha_4}\} \cdot (\sigma_v / u_*)\alpha_5 \qquad \text{L>0} \qquad \textbf{-(3.15)}$$

$$D_N = \alpha_1 \cdot (z_m / z_0)^{\alpha_2} \cdot \{1 - \alpha_3 \cdot (z_m / L)\}^{\alpha_4} \cdot (\sigma_v / u_*)\alpha_5 \qquad \text{L<0} \qquad \textbf{-(3.16)}$$

where the normalised dimensions *(D_N)* are given as functions of α_i (i=1,5) in Table 3.3 for stable stratification (equation 3.15) and in Table 3.4 for unstable stratification (equation 3.16). Source weight functions and source areas are described in APPENDIX-VI.

SAM-2

The form of the relationship between the modelled source area dimensions and the input variables was evaluated by Smith [43] by a large number of SAM-2 runs in a sensitivity test for the wide range of input values that can be expected in the atmospheric surface layer. If the source area dimensions described in Figure 3.7 are scaled by z_0 (z_0^2 in the case of the area, A_{r_c}), the sensitivity test shows clearly that all dimensions are dependent on the non-dimensional variables z_m / z_0 (indicating the measurement height above the roughness elements) and z_m / L (indicating the strength of buoyancy at the reference height). The crosswind dimension, d_c, and the area,

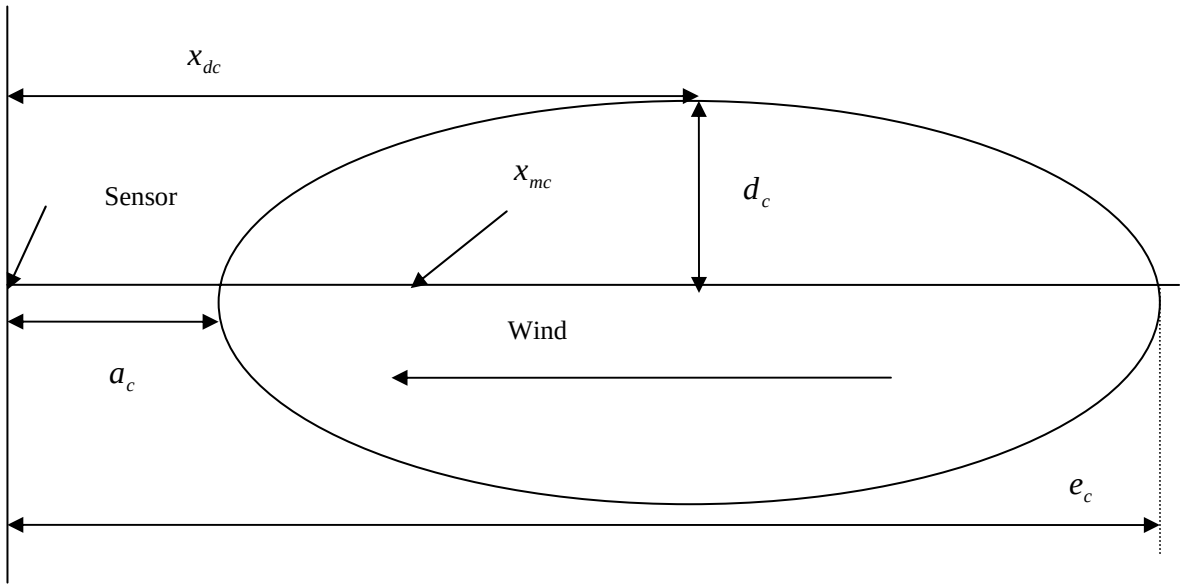


Figure 3.7 Characteristic dimensions of the source area . x_{mc} is the maximum source location (upwind distance of the surface element with the maximum influence on a given sensor), a_c is the near end, e_c , the far end, d_c the maximum lateral half-width of the source area. The size of the area bounded by the isopleth is denoted as A_{r_c} .

A_{r_c} , are also dependent on σ_v / u^* , the strength of lateral wind fluctuations. The resulting normalised dimensions are given in equations 3.15 and 3.16 for the scalar concentration-source area with $P = 0.5$ (i.e. the 50% influence source area).

If *K*-theory is used , the core of any model for the source weight function or the source area is formed by the scalar concentration distribution *C(x,y,z)*. Depending on the choice of the functional form of the concentration distribution, and of the shape of the wind-profile, $\bar{u}(z)$, analytical solutions for the source areas of scalars and scalar fluxes, respectively, may be possible. The present study employs a surface-layer dispersion model presented by Gryning et al. [44], which cannot be solved analytically (*see* APPENDIX V). This model has the advantage of including thermal stratification and a realistic wind profile. This dispersion model is the same as that used for the scalar source area model (SAM) by Schmid and Oke [1], but is extended to include stable stratification here. *In this case instead of using a separate surface layer dispersion model, the particular dispersion model used in the commercial software that will be*

used later on for dispersion analysis can be utilised for the purpose of finding out the footprint size and dimensions also. The determination of $C(x,y,z)$ is strongly dependent on:

- The reference height z_m
- The Monin-Obukhov Length, L
- The surface roughness length, z_0
- The friction velocity, u_*
- The standard deviation of lateral wind speed fluctuations, σ_v.

Steps to compute the source areas for several values of P can be summarised as follows and η is equivalent to the source weight distribution and stands for C in case of scalar concentration.

1. The maximum value of the distribution function and its location, $\eta_{\max}$ and x_m is determined by a numerical search.
2. A number of η-values are defined as fractions of $\eta_{\max}$: η_i, for i= 1,.....,n.
3. The isopleths corresponding to η_i are determined by root-finders and the source weight functions are integrated incrementally between each two successive isopleths to give the P-levels, P_i, corresponding to each isopleth level η_i. The pairs (P_i, η_i) are considered as samples of a continuous function $\eta = \eta(P)$.

The isopleth values corresponding to round decadal-fraction values of P are determined by cubic spline interpolation of the function $\eta = \eta(P)$. The characteristic dimensions of these isopleths are then determined by numerical search methods. Apart from the upwind distance of the maximum source location (x_m), which is computed in step 1, and is independent of P, these dimensions are (see Figure 3.7): the upwind distance to the near end of the isopleth (a) and to the far end of the isopleth (e), and the maximum lateral half-width of the isopleth (d). In addition, the size of the area bounded by the isopleth is determined (A_r).

3.5 Experimental Methods

Field measurements were conducted during August 1998 at the Municipal Solid Waste (MSW) landfill site at Brogborough, Bedfordshire, UK. The terrain was approximately

flat and at an average elevation of about 0.5 m from the local ground level. Solid wastes 0.15 m to 0.3 m high are the dominant elements in the tipping area and 0.1 m to 0.2 m high is the dominant vegetation in the partly restored/restored areas. The sensor (the sampling tube) was placed along the prevailing wind direction. One 2.5 m high mast was located downwind along the prevailing wind direction with an approximate upwind fetch of 45.0 m. The idea of placing the tower in approximately the right position with respect to the shape and the size of the source area according to the prevailing meteorological conditions (some source areas were calculated before the actual experiment with various possible wind directions and speed and were ready to use as an initial guess) was to encompass a reasonably correct source area contributing towards the sensor having an odour-less background behind the edge of the footprint. Figure 3.8 shows a distant view of the portable meteorological mast with odour sampling arrangements. The tower was equipped with two sets of anemometers (cup and vane type) one at a height of 0.8 meter and the other at 2.25 meters from the ground, two temperature sensors and two humidity sensors (one at the ground and the other at 2.25-meters height). An odour sampling tube was positioned at 1.5 m from the ground level. This tube was connected to the Tedlar bags and odour concentration was measured later by a dynamic dilution olfactometer using ternary forced-choice technique (*see* APPENDIX III] at Silsoe Research Institute. Another sample was taken at the end of the upwind fetch to quantify the background odour. The meteorological data collected were later processed with specific calibrations of respective sensors. A short meteorological pre-processor was designed to obtain the Monin-Obhukov length, as explained in APPENDIX-V, *section* V.4.

3.6 Results and Discussion

In the following sections results showing the calculated source strengths with various methods will be presented individually for the waste transfer depot and the MSW landfill site. Results of the new micrometeorological model will be compared with the standard Lindvall Hood technique, for the specific case of the landfill site.

Figure 3.8 A distant view of the portable meteorological mast in use at the MSW Landfill Site with two sets of cup and vane anemometers, two sets of temperature and humidity sensors and a connection for the odour sampling. *Date: 18th August, 1998.*

3.6.1 Case 1: Waste Transfer Depot

Calculation of Source Strength

This has been clearly discussed in section 3.2.1 and APPENDIX IV.

3.6.2 Case 2: MSW Landfill Site

Table 3.5 gives the average characteristic dimensions of the upwind fetch and the corresponding source area during the sampling period, based on a 50% passive scalar Source Area Model (*SAM-2*) parameterisation. Table 3.6 shows the odour fluxes (ou/m^2.s) with respect to real time meteorological data. The odour fluxes have been computed from Equation (3.13) with an average odour concentration of 250.0 ou/m^3 as measured at 1.5 meters from the local ground level. The flux is the ratio of concentration measured at 1.5 meters and the factor $\int K' \cdot dx$. It was not possible to use a fast response odour sensor (like a portable electronic nose) within the scope of the

experiment to have varying concentrations measured with the same time-interval as the meteorological data and as such we could only use an average concentration. However the factor $\int K' \cdot dx$ varies continuously depending on the Monin-Obukhov length. The apparent footprint area varied from 550.0 m^2 to 1057.0 m^2 during the sampling period with higher areas corresponding to higher values (more negative) of the Monin-Obukhov length and thus a more unstable atmosphere. Table 3.7 gives the odour fluxes from fresh tipped wastes measured by the Lindvall hood based on both inlet and outlet air volumes.

Preliminary results from the model seem to be in good agreement with those from Lindvall hood measurements. Typical results show an average odour flux of 25.91 ($ou/m^2.s$) from freshly tipped waste for an upwind fetch of 45.0 m and with the sensor at a height of 1.5 m from the ground. The hood results have a geometric mean of 29.35 ($ou/m^2.s$) based on the inlet air volume and a shade air temperature of 22.5 ° C.

It is necessary to measure emissions for each contributing land surface category to come to a definitive set of emission data. A more rigorous validation experiment was not possible with the resources available, although these initial results are encouraging.

Table 3.3[43] Parameter values for the 50% passive scalar source area model (SAM-2), stable stratification.

Normalised (D_N)	Dimensions	Reference Equations	α_1	α_2	α_3	α_4	α_5
a_c/z_0		22a	0.773	1.24	0.957	1.25	0
e_c/z_0		22a	30.4	1.23	2.60	0.452	0
d_c/z_0		22a	4.31	1.07	1.69	0.397	1
x_{dc}/z_0		22a	15.7	1.25	2.49	0.449	0
x_{mc}/z_0		22a	4.30	1.28	1.74	0.688	0
A_{r_c}/z_0^2		22a	$0.203.10^3$	2.28	4.38	0.408	1

Table 3.4[43] Parameter values for the 50% passive scalar source area model (SAM-2), unstable stratification.

Normalised Dimensions (D_N)	Reference Equations	α_1	α_2	α_3	α_4	α_5
a_c/z_0	22a	0.853	1.23	0.441	1	0
e_c/z_0	22b	40.4	1.22	15.5	-0.548	0
d_c/z_0	22b	5.73	1.05	16.8	-0.458	1
x_{dc}/z_0	22b	21.3	1.23	16.9	-0.517	0
x_{mc}/z_0	22b	5.37	1.25	5.96	-0.472	0
A_{r_c}/z_0^2	22b	$0.405.10^3$	2.25	16.0	-1.03	1

Table 3.5 Average dimensions (*refer* Figure 3.7) of source areas computed during the sampling time with the routine meteorological data of *August 18,1998*. Z_m =1.5 meters, Z_0 =0.05 meters. Experiment started at 14:22 (BST). Results are averaged for 2 minutes.

L	Z_m/L	a_c *(m)*	e_c *(m)*	x_{dc} *(m)*	x_{mc} *(m)*	d_c *(m)*	A_{r_c} *(m^2)*
-83.75	-0.018	1.18	42.5	23.0	7.19	10.50	733.4
-38.99	-0.038	1.17	42.8	23.1	7.21	10.65	748.4
-40.11	-0.037	1.17	33.2	18.0	6.39	10.20	550.4
-15.39	0.097	1.14	37.5	20.3	6.79	10.69	654.8
-22.98	-0.065	1.16	40.6	21.9	7.04	11.06	734.7
-31.32	-0.048	1.17	46.4	25.0	7.45	11.37	868.3
-63.72	-0.024	1.18	47.5	25.7	7.52	11.50	900.0
-75.71	-0.020	1.18	46.5	25.1	7.46	11.62	889.2
-64.67	-0.023	1.18	50.3	27.2	7.69	11.57	961.5
-132.3	-0.011	1.19	43.3	23.4	7.25	11.84	842.7
-42.75	-0.035	1.17	50.7	27.4	7.70	11.59	970.5
-144.1	-0.010	1.19	52.8	28.6	7.82	11.46	1001.2
-303.6	-0.005	1.19	64.2	35.0	8.31	9.89	1057.2

Table 3.6 Computation of odour flux and odour emission rates from the micrometeorological parameters and characteristic dimensions of the upwind fetch (x_{dc}=45.0 m). Z_m=1.5 meters, Z_0=0.05 meters. Experiment started at 14:22 (BST). Results are averaged for 2 minutes.

Time (BST)	L	$\bar{z}$ (m)	s (m)	$\bar{u}$ (m)	$\int K' \cdot dx$ Eqn. 3.12	q ($ou/m^2.s$)	A_{r_c} (m^2)	q_{avg} ($ou/m^2.s$)
14:22	-83.75	3.66	1.16	0.67	11.38	21.97	733.39	25.91
14:24	-38.99	3.98	1.03	0.66	11.06	22.61	748.44	
14:26	-40.11	3.96	1.04	0.77	7.40	33.78	550.44	
14:28	-15.39	5.04	0.86	0.55	10.27	24.35	654.75	
14:30	-22.98	4.44	0.93	0.66	9.95	25.12	734.68	
14:32	-31.32	4.14	0.99	0.77	10.13	24.67	868.35	
14:34	-63.72	3.74	1.12	1.10	7.65	32.68	899.97	
14:36	-75.71	3.69	1.14	1.10	7.53	33.20	889.21	
14:38	-64.67	3.74	1.12	0.99	8.99	27.80	961.54	
14:40	-132.3	3.56	1.21	1.24	6.36	39.30	842.72	
14:42	-42.75	3.93	1.05	0.67	13.17	18.99	970.49	
14:44	-144.1	3.54	1.22	0.78	12.29	20.35	1001.24	
14:46	-303.6	3.46	1.27	0.57	20.81	12.01	1057.16	

Table 3.7 Lindvall hood results[74] from Landfill surface odour measurements on 18th August,1998.

Time (BST)	Hood Air Temp. (°C)	Surface Temp. (°C)	Inlet volume flow rate (m^3/s)	Outlet volume flowrate (m^3/s)	Sample No.	Odour Concentration (ou/m^3)	Emission rate based on inlet air volume ($ou/m^2.s$)
13:25	31.0	31.2	0.027	0.018	1	2958	53.12
13:40	30.6	30.1	0.027	0.012	2	1552	27.87
13:55	30.7	30.7	0.027	0.016	3	1318	23.67
14:10	35.2	34.0	0.027	0.010	4	1979	35.54
14:25	36.2	34.5	0.027	0.014	5	974	17.49
						Geometric Mean:	**29.35**

3.7 Conclusion

This Chapter describes two approaches to measuring emission rates of odour from a municipal solid waste landfill site containing area sources of fugitive emissions. The first one is a direct emission measurement approach- the enclosure approach using an emission isolation flux chamber (the Lindvall hood). The second approach is based on an indirect method of emission rate measurements based on micrometeorological modelling that uses simple meteorological measurements, suitable odour sampling methods, and analysis of the odour samples based on principles of olfactometry. The emission rate data can be useful for the design of emission control and remediation strategies as well as for predictive modelling for population exposure assessments.

The overall accuracy and precision of Lindvall hood measurements will depend on the biases and variability associated with the emission source, the sampling method and the analytical methods for analysing the odour samples. On the other hand the suitability of the micrometeorological method depends on the proper selection of the area source where dispersion assumptions for the model are valid. The major advantage of this method over the hood is that the surface under consideration is in the natural influence of the atmosphere. Secondly the micrometeorological method can be applied at various spatial resolutions for experiments within the surface layer, depending on the choice of the sensor height for a particular type of surface under certain bounds. Depending on the choice of the sensor height the footprint area contributing to a certain odour concentration can be reduced or enlarged under varied meteorological conditions and effectively a huge area of certain homogeneity could be covered within the scope of one experiment. Successful field use of both methods will require measurements which account for the extreme variability in surface conditions, cover type, waste composition, waste age, and subsidence which is expected at full scale landfills. It is important to determine the magnitude and distribution of such variability and the impact on gas emissions in order to design an accurate emission monitoring programme which provides a coherent picture of emissions from the entire landfill surface.

Chapter 4

4. Dispersion Modelling

In this Chapter various aspects of dispersion modelling will be discussed with specific emphasis on odour dispersion.

4.1 Introduction

Odour complaints are common in urban communities where residential neighbourhoods are located near industrial areas. Most of the time it may be difficult to identify the sources of the odours since there may be many facilities located close to one another. In these cases, it is important to have an appropriate method of determining whether a plant's emissions are, in fact, creating odours in the surrounding community. The focus of this chapter is to outline and discuss one such method, which uses **atmospheric dispersion modelling** and knowledge of site operations to quantify the potential odour strength causing an impact on the community. Two types of solid waste sources were used. Firstly, an experiment at an urban waste transfer depot was used as a data source for part of the overall study in order to assess the extent of nuisance arising from the site. For the second part of the case study, a Municipal Solid Waste (MSW) landfill site was used as a source of odour. An assessment of odour emissions from the most significant odour source was made to determine the likelihood of complaints. The methods of emission assessment were very different for the two types of source mentioned. These methods have been explained in details in Chapter 3.

The first method of assessment was used to calculate odour strength from the waste transfer building. In addition, an intensity test was used to assess the number of times the odour would need to be diluted to achieve a reasonable expectation of no complaints from the site operations. Within the building the odour strength is high enough to necessitate its containment or reduction by extraction and filtration to avoid complaints. It is also evident that this level of containment cannot be achieved during normal operations with the existing building design. Calculations show that if normal operations are maintained the volume of air required to extract and dilute the air from the building is impractical. The study was designed to understand to what extent fluctuations in the level of site emissions might reduce the effect of odour reaching the neighbourhood. The ventilation exhaust rates from the building were calculated on the basis of basic natural ventilation physics (see Appendix-IV).

The second method assessed the odour strengths from various potential sources within the MSW landfill site. Lindvall hoods have been primarily used for the area sources of the tipping sites. An indirect fetch method, based on the footprint methodology, has been used for a small number of area sources, mainly representing the freshly tipped wastes. These techniques have been covered in Chapter 3 (*see section 3.3*).

Quantifying emissions from both the sites was an important step to identify both the current levels of annoyance as well as potential future levels that may occur including the effects of any mitigating measures. Olfactometry tests and emission assessments were carried out by **Silsoe Research Institute (SRI)** with sampling undertaken by **ADAS (the Agricultural Development and Advisory Service)**. In order to predict the extent of dispersion from the above two sources various dispersion models have been used. The study also attempted to compare the performance of the models for application to odour dispersal. The test cases are briefly outlined in the following paragraph and detailed in *section 4.6* of this chapter and Chapter 6.

Case 1: Waste Transfer Depot

The two models **UK-ADMS (version 1.5)** [52] and **US-EPA's MPTER** (A **M**ultiple **P**oint Gaussian Dispersion Algorithm with Optional **TER**rain Adjustment) [53] were used to characterise the extent of dispersion of the odorous air from the waste transfer building. These models have been extensively used to study various cases with different meteorological conditions. The hourly mean odour concentrations have been

predicted by both the models under various conditions and cases have been compared (see Chapter 6- section *6.1.2*).

Case 2: MSW Landfill Site

The two models **UK-ADMS (version 1.5)** -(1) and **US-EPA's – COMPLEX-I** (2) were used to validate various cases of dispersion of the odorous air from the landfill site. These models have been used to predict the following cases:

a) Several emission scenarios: Including possibilities of extending (or not) the existing landfill site in the years 1998, 2004 and 2008 considering relevant operational practice (results related to the years 2004 and 2008 are presented in *Chapter 6*).

b) Various meteorological conditions: Hourly meteorological data have been used (provided by UK-Meteorological Office) for the year 1997-1998. Test runs included:

   i. Yearly runs for various averaging periods.

   ii. Maximum odour concentrations of the hourly averages (and other averaging periods) have been plotted (see Figure 4.11, Figure 4.12 and Figure 4.13). The hourly mean odour concentrations have been predicted by both the models under various conditions and cases have been compared.

   iii. Runs to predict percentage frequencies of odour concentrations exceeding various threshold limits around the MSW landfill site.

Various receptor grids: Test runs included:

   i. Use of Ordnance Survey (OS) actual grids (generated from Digitised Terrain Model- **Land-Form PANORAMA** [3]) in and around the MSW landfill site covering a suitable area of suspected exposure.

   ii. Finding out the odour concentration levels at the real co-ordinates *(x,y,z)* of the monitor's house locations. Theses have been worked out from the OS datafiles and files provided by the Royal Mail based on postcodes (dealt with in detail in *Chapter 6*).

c) Various other options: Including,

   i. An optional terrain adjustment as a function of stability class.

   ii. Inclusion or omission of stack downwash.

   iii. Inclusion or omission of buoyancy-induced dispersion.

   iv. Input of wind profile power law exponents as functions of stability.

v. Input of peak-to-mean ratio as a function of stability classes.

All the models have been compared with each other and with the data reported by community sniffers (method would be described in details in Chapter 6). In the next few sections dispersion modeling would be described as a particular tool for handling cases with odour emissions.

4.2 Issues in Odour Modelling

Traditional dispersion modelling differs from odour dispersion modelling in a variety of ways: i.e. the characterisation of source, transport and dispersion of odorous gas mixtures, and, the representation of a receptor (the human nose). The entire method for assessment of odour should include the following considerations.

4.2.1 Odour Perception

Most odours discharged to the atmosphere consist of a complex mixture of components. Human sensory responses to the individual components of such mixtures varies considerably from compound to compound, and from person to person. For all human senses, including smell, a general approach to assessing the relationship between the magnitude of a sensation and the intensity of stimulus can be applied. A method referred to as *category estimation* can be derived from Fechner's Law (equal ratios of stimulus lead to equal differences between perceived intensity) when related to the sense of smell. Thus perceived intensity (*I*) is a linear function of the logarithm of odour concentration (*C*):

$$I = k_1(\log_{10} C) + k_2 \qquad \textbf{-(4.1)}$$

Where k_1 and k_2 are constants for a particular group of panelists within an experiment. Perceived odour intensity can decrease rapidly for continuous exposure (referred to as adaptation). The sensitivity to odour is recovered when the exposure is removed. Both these processes, adaptation and recovery, operate over short time scales and are not yet well understood. Perception of odour will be discussed broadly in *Chapter 5* (Analysis of Perception).

4.2.2 Averaging Time

The use of an appropriate averaging time is one of the primary considerations for modifying standard dispersion modelling methods for use in odour assessment.

Figure 4.1(a) is a schematic of hypothetical plume boundaries observed instantaneously, and averaged over 10 minutes and 2 hours [75]. This is in the same way a camera with different exposure times might photograph a smoke plume. An instantaneous snap shot of the smoke plume will primarily show the meander of the plume under the influence of atmospheric turbulence larger than the plume. As the exposure time increases, the photograph will capture both the meander and the internal spread of the plume.

As the distance increases far downwind, the boundary of the time-averaged plume can fluctuate around the centreline since it is heavily affected by the large-scale atmospheric turbulence. The centreline concentration for an instantaneous plume is significantly higher than that for the time-averaged plume, as in

Figure 4.1(b). The use of a finite averaging time filters out very high and very low frequency fluctuations. This variation in "*peak*" concentration with averaging, or sampling time is one of the major concerns in odour modelling where short-term peak impacts are important (see Figure 4.2).

Inoue [76] predicted that the width of a smoke cloud increased in proportion to the –1/2 power of the sampling time, *t*. Stewart et al. [77] and Cramer [78] reported a 1/5 power law relationship between sampling time and concentration at heights near the height of release for short sampling times. The power law coefficient is –1/2 for sampling times above 10 minutes and upto 5 hours [79]. For sampling times less than 10 minutes, the –1/5 power law is valid, as reported by Nonhebel [80]. Based upon these observations, for very short sampling times, concentration ratio can be estimated from:

$$C_l / C_s = \left(t_s / t_l \right)^p \qquad \textbf{-(4.2)}$$

where,

$C_l =$ concentration estimate for sampling time t_l.

$C_s =$ concentration estimate for shorter sampling time t_s.

p is a function of stability classes [81] and given in Table 4.1.

Table 4.1[47] Variation of *p* with Pasquill-Gifford (P-G) stability classes.

P-G Stability Classes	A	B	C	D	E	F
p	0.5	0.5	0.333	0.2	0.167	0.167

Standard dispersion models mostly use Gaussian Dispersion equations. These are based on data that are time-averaged, such as turbulent diffusion parameters. Since Gaussian models assume a steady-state condition, the applicable averaging times are usually 3 minutes to 1 hour. If the perception of odour impact corresponds to a much shorter time, in the order of seconds, then the time-averaged models would conceivably underestimate a shorter-term peak odour impact.

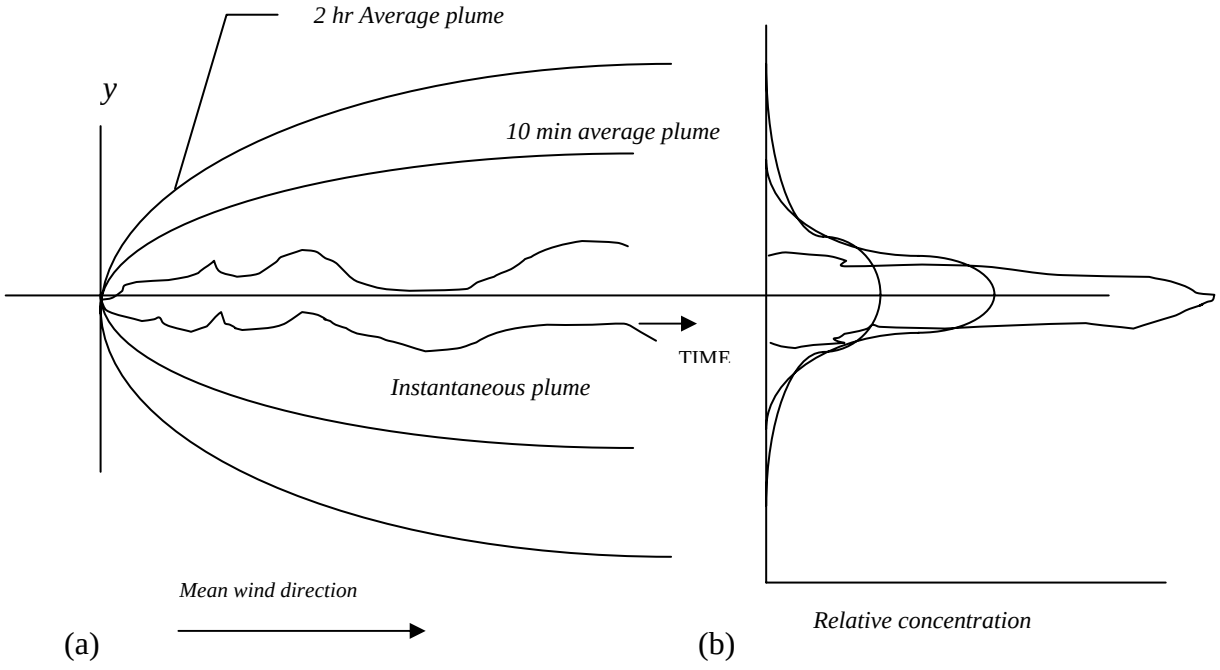


Figure 4.1[75] Smoke plume observed instantaneously and averaged over 10 minutes and 2 hours. Diagram (b) shows corresponding crosswind concentration profiles.

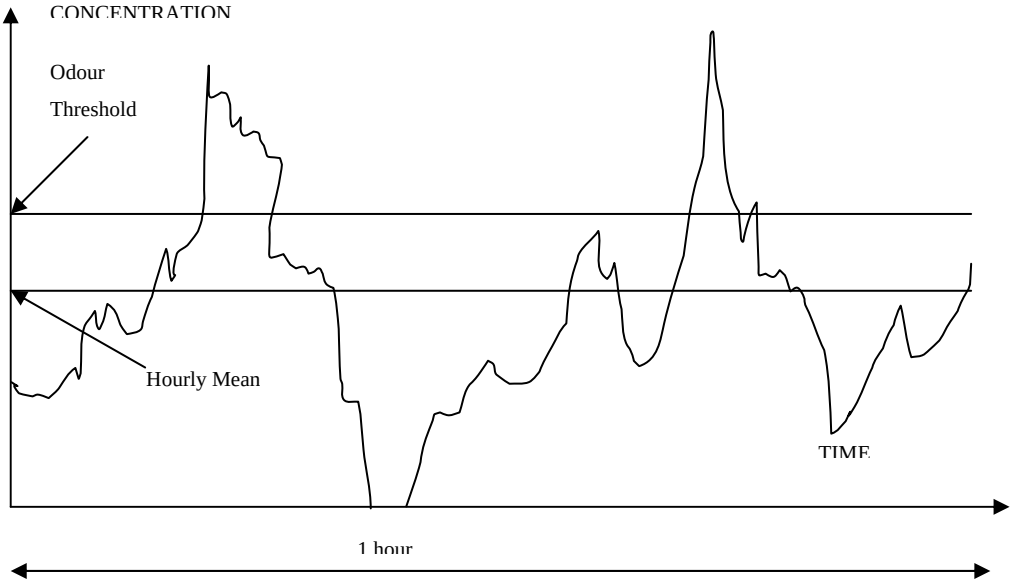


Figure 4.2 Schematic diagram showing how the odour concentration can exceed the odour threshold several times during a period when the hourly mean is much below the odour threshold.

4.2.3 Source Characteristics

Variable and constant release times are factors when characterising a source. Traditional modelling generally assumes that the emission of a pollutant is continuous and that the rate of emission does not vary over time. An instantaneous, or a short-term release, such as a puff of gas from a pressure vessel, however, can have a different mode of dispersion than a continuous release, especially in the region near the source. A better representation of these kind of releases is given by alternative models like *puff* or *stochastic models*.

An additional distinction between standard regulatory modelling and odour modelling is in the characterisation of the emissions. Air dispersion models are commonly run for specific pollutants. Many odorous emissions, on the other hand, are the result of a complex combination of compounds. A single indicator compound, with a low odour threshold and high emission rate can be used if it is truly representative of the sources

under consideration. However this could lead to a significant underestimate of the overall impact [82].

Odour emission rates (ou/s) are based upon determining a source concentration in odour units per cubic meter (ou/m^3) and multiplying this concentration by the volume flow rate (m^3/s). It is important to arrive at an emission rate that fairly represents the source. This approach requires site-specific source sampling in order to correctly characterise the odour emissions. Assessment of odour emission rates has been dealt with in detail in *Chapter 3* (*sections 3.3 and 3.4*).

4.2.4 Peak to Mean Ratio

In order to avoid the difficulty in measuring high-speed fluctuations of some meteorological variable, most concentration and turbulence field measurement data are collected over relatively long sampling times (of the order of minutes). For any fixed sampling time, the mean concentration (mean), which is assumed to remain nearly constant, can be determined. However, within this time frame there are significant short-term fluctuations of certain variables responsible for the dispersion process. In order to account for this difference, several scientists (Gifford [83], Singer [84], Hino [79], Islitzer [85], Pasquill [40]) put their effort in finding out a peak concentration (*peak*). Analysis of numerous field data have led to the estimates of a ***"peak-to-mean ratio"*** for different source/receptor configurations. This factor could be successfully used in conjunction with any of the regulatory dispersion models, where the model output (average) could be multiplied by the same to estimate a peak concentration. One main advantage of this approach is that the analysis retains the benefits of using a standard dispersion model, catered for regulatory purpose. The variations of *peak-to-mean* ratio with sampling time, distance, stack height, terrain, building effects etc. have been studied by various researchers. This has been discussed in Table 4.2.

4.3 Atmospheric Dispersion Models

Atmospheric dispersion is a result of scales of turbulence in the atmosphere, and the instantaneous concentration downwind of a source varies continuously with the turbulence in the wind. One of the characteristic features of atmospheric dispersion is

the presence of large-scale, short-term fluctuations in concentration and these have been verified by field observations. At the '*receptor*' location, there may be periods of turbulent concentration fluctuations as a result of advection and periods of intermittence, i.e. of zero concentration, when the plume meanders away from the receptor. Hence the entire dispersion phenomenon can be viewed as a combination of :

a) The plume spreading out almost instantaneously in the vertical and crosswind directions due to the turbulence created by the small eddies.
b) The plume fluctuating or *meandering* about its mean centreline position due to the large scale eddies.

A comprehensive atmospheric dispersion model should interpret both the phenomenon reasonably. An '*ideal*' dispersion model should predict the concentration downwind of any single (or multiple) source(s) reasonably correct under all possible atmospheric conditions. Most of the standard regulatory models can cope with the following situations:

- Various types of source (point, area or line).
- Effects of simple or complex terrain.
- Urban or Rural options.
- Different release types (plume, puff).
- Different meteorological conditions (stable, unstable and neutral).

Figure 4.3 describes the elements of a mathematical model for relating pollutant emissions to ambient air quality. In Table 4.3 various types of dispersion models (based on type of release) are presented briefly.

Table 4.2 Table showing variations of Peak to Mean Ratio with various factors.

Factors	Variation of Peak to Mean Ratio	Remarks	Reference
Distance downwind	*Decreases with increasing distance downwind*	*Plume disperses more with increasing distance as a result of the atmospheric turbulence, thus smoothing out the peak concentrations until the peak concentration approximates the mean concentration.*	*[83]*
Stack Height	*Increases as the difference in height between the source and the receptor increases*	*For sources and receptors at approximately the same height, however the peak to mean ratio ranges from 1 to 5.*	*[83]*
Terrain	*Terrain smoothes out the short term peaks.*	*Depending on the location of the receptor with respect to the source.*	*[80,84,86,87]*
Building effects	*Peak concentration in the wake of a building does not exceed the mean concentration by more than a factor of 2 more than 10% of the time at any reasonable distance downwind of a building.*	*Related to the cumulative probability distribution function of concentration.*	*[88,89]*

Gaussian Plume models [47,81] are the most widely used model for plume dispersion. They fit well in the real world atmospheric conditions. Time-averaged Gaussian outputs can be adapted to short-term peak events like odour perception through the use of a peak to mean ratio. Assumptions of Gaussian plume models are:

- A continuous release.
- Stead-state conditions
- Lateral and vertical concentration profiles follow normal distribution.
- Commercial software based on this model have been widely applied with several field tests and modified according to the custom needs.
- Limited by the longer time averaging periods (10 minutes to 1 hour).

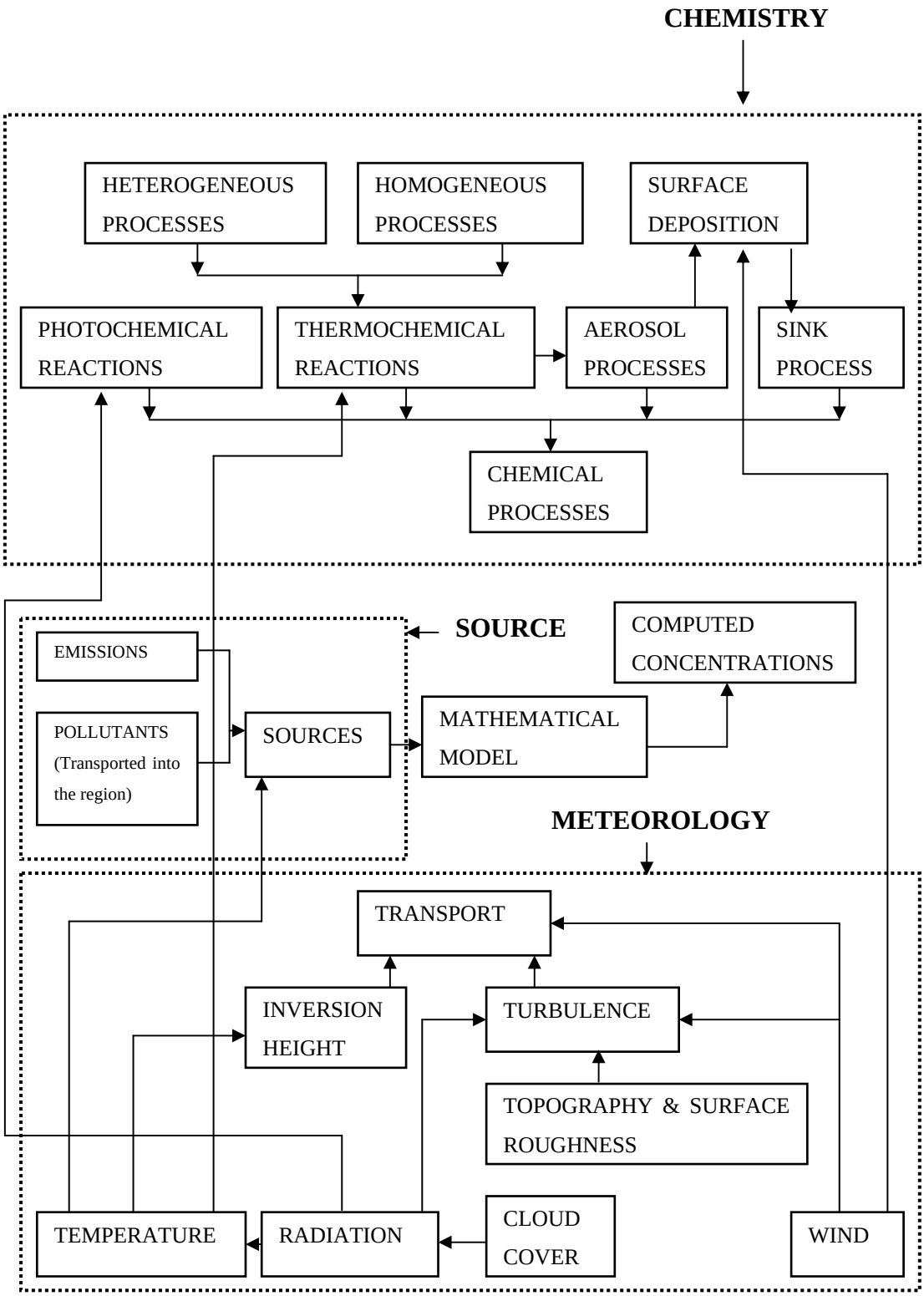

CHEMISTRY
HETEROGENEOUS PROCESSES
HOMOGENEOUS PROCESSES
SURFACE DEPOSITION
PHOTOCHEMICAL REACTIONS
THERMOCHEMICAL REACTIONS
AEROSOL PROCESSES
SINK PROCESS
CHEMICAL PROCESSES
SOURCE
COMPUTED CONCENTRATIONS
EMISSIONS
POLLUTANTS (Transported into the region)
SOURCES
MATHEMATICAL MODEL
METEOROLOGY
TRANSPORT
INVERSION HEIGHT
TURBULENCE
TOPOGRAPHY & SURFACE ROUGHNESS
TEMPERATURE
RADIATION
CLOUD COVER
WIND

Figure 4.3[81] Elements of a mathematical model for relating pollutant emissions to ambient air quality.

Table 4.3 Various types of dispersion models based on type of release.

Model	Characteristics	Remarks	Reference
Puff	*Quasi-instantaneous and short-term releases.* *Release time and sampling times are very short compared to the travel time from the source to the receptor.*	*Limited data available to estimate puff diffusion coefficients.* *Most puff models assume a Gaussian concentration distribution within the plume and as such overlook the in-puff fluctuations.*	*[81,90]*
Plume	*Continuous releases.* *Release time is much greater than the time of travel.*	*Gaussian plume models.* *Fluctuating plume models.* *K models* *Statistical models.* *Eddy simulation models.*	*[81,91]*
Fluctuating Plume-Puff	*Hybrid model, that simulates emissions as a series of continuously emitting puffs.* *Assumes that the dispersion is separated in two parts: one due to the instantaneous spreading out of the Gaussian plume in the crosswind and vertical directions, and the other one due to the meandering of the entire plume around its mean position.*	*Suitable for odour modelling.* *Attempts to predict the peak concentration as a discrete puff passes a given receptor.*	*[83]*

4.4 Model Selection

When selecting an appropriate dispersion model for the prediction of odour , it is important to consider the relevant time frame of odours (from the perception point of view) and the characteristics of the odour sources. The issues related to odour modelling have been described in *section 4.2*. Based on the factors discussed *in section 4.2* and on the availability of various types of data (described in *section 4.5*), some of the regulatory models have been chosen and adapted to the problem of odour.

4.4.1 Use of Commercial Software for Odour Modelling

How do we use a commercial software? How do we adapt the built-in environment of a particular software to our specific need? How do we utilise various types of data available and feed them into the package? These issues have been explained in APPENDIX-VII (Requirement of data for commercial software on atmospheric dispersion modelling). In the following sub-sections various commercial software will be dealt with. The MPTER *(version-1992)*[53] and COMPLEX-I *(version-1992)*[53] are US-EPA (*United States Environmental Protection Agency*) products, while *UK-ADMS-(version 1.5)*[52] is developed by CERC (*Cambridge Environmental Research Consultants Ltd.*). Specific features of each software will be discussed along with the general features. The applicability of each package with regard to the choice of field study location, availability of data, and specific problems of odour will also be discussed.

MPTER

MPTER (Multiple Point source model with TERrain adjustments) provides a method of estimating air pollutant concentrations from multiple sources in both rural and urban environments. The model can also make adjustment for slight terrain variations. Although the algorithm is based upon Gaussian modelling assumptions and incorporates the Pasquill-Gifford dispersion parameter values, several technical options and variety of parameter values can also be entered. MPTER estimates the resulting concentrations upto a maximum of 180 receptors from a maximum of 250 point sources. Periods from one hour to one year may be simulated, with all output controlled by the user. The main features of the algorithm include:

- Averaging periods of longer than 1 hour.
- Handling hourly meteorological data for 1 year.
- An optional terrain adjustment as a function of stability class.
- Inclusion or omission of stack downwash.
- Inclusion or omission of buoyancy-induced dispersion.
- Input of wind profile power law exponents as functions of stability.

COMPLEX-I

Complex-I is a second-level screening technique for evaluating the impact of sources in *rural complex terrain* as described in section 5.2.1 of the Guideline on Air Quality Models (revised) [53]. *Preprocessed meteorological data* (PMD) may be used as input to Complex I.

COMPLEX-I is a Multiple Point Source code with terrain adjustment, where horizontal plume spreading is uniform across a 22.5 degree sector. Most of its features are common to MPTER. Additional features of COMPLEX-I are:

1. Calm processing

   A check for calm conditions is performed for each group of averaging periods and resulting concentrations for the hour are set equal to zero. Averaging periods containing 1 or more calm hours are divided by the total number of non-calm hours in the period or 75% of the averaging period or whichever is greater.

2. Valley-type screening option

   Processing is performed in a similar manner to *the short-term screening mode of the valley model*. For each wind direction input the valley screening option estimates the maximum 24-hour concentration expected at each user provided receptor. The model assumes that the given wind direction exists for any 6 hours of a 24-hour period (*This is accomplished in the model by reducing the user supplied one-hour emission rate to 6/24 of its actual value*). The valley screening option includes an algorithm for the treatment of complex terrain effects on concentration. Plume height above stack base is assumed to remain constant after distance to final plume rise. In effect, as the plume approaches the elevated surface, the plume height decreases. It is further assumed that the plume centreline comes no closer than 10 meters to the elevated terrain. If the terrain extends above this level, the plume centreline is adjusted so that it remains 10 meters above the ground. Any plume height which is initially within 10 meters of the ground is assumed to remain at its initial height above ground, regardless of downwind terrain elevations. Deflection of the plume by terrain is simulated through the attenuation of concentration with height for terrain above centreline height. A factor is applied which has a value of unity at and below the elevation of the plume centreline, but decreases linearly with increasing height to zero at and above 400 meters above the undisturbed plume

centreline. The attenuation scheme is not applied to plumes with heights initially less than 10 meters.

Amongst the worst affected areas of our test case Landfill Site is the Marston Vale, which is a shallow valley (average elevation is +45.0 metres above the mean sea level), average elevation of the site being +68.0 metres above the mean sea level. This was the main reason for using COMPLEX-I instead of MPTER.

UK-ADMS

UK-ADMS (Atmospheric Dispersion Modelling System) uses recent atmospheric boundary layer physics characterised by two basic parameters: *boundary layer height (h) and Monin Obukhov length (L_{MO})* [92]. In unstable conditions, the Monin-Obukhov length is negative. Under such conditions, the magnitude of the length is a measure of the height above the ground at which convective turbulence is more important than mechanical turbulence generated by friction at the earth's surface. In stable conditions the Monin-Obukhov length is positive. Then it is a measure of the height above the ground above which vertical turbulent motion is greatly inhibited by the stable stratification. Monin-Obukhov length is defined as

$$L_{MO} = \frac{u_*^3}{\kappa g F_{\theta_o} / (\rho c_p T_o)} \qquad \textbf{-(4.3)}$$

where u_* is friction velocity at the earth's surface , κ (=0.4) is the von Karman constant, g is the acceleration due to gravity, and F_{θ_0} is the surface heat flux, ρ and c_p are respectively the density and specific heat capacity of air, and T_0 is the surface temperature. Features of UK-ADMS(Version 1.5) include,

- Treatment of buoyant or slightly denser than air releases.
- Steady release of any duration including instantaneous releases.
- Partial penetration of an elevated inversion.
- Treatment of Complex Terrain with the airflow model FLOWSTAR.
- Effects of buildings including main wake and recirculating region.
- Fluctuations and effect of meandering.
- Interfacing with Ordnance Survey digitised terrain data directly for use with complex terrain module.

Some basic differences between MPTER/COMPLEX-I and UK-ADMS will be given in Table 4.4.

4.4.2 Modelling concentration fluctuations

Most of the regulatory dispersion models calculate hourly ensemble means. An ensemble mean will underestimate the maximum measured values since in-plume turbulent fluctuations will have been neglected. If the averaging time used is less than one hour, the difference between the ensemble average concentration, as predicted by the model, and the maximum measured concentration increases significantly. There are two methods of including fluctuations:

- In order to include large scale meandering on the ensemble mean, measurements of the standard deviation of the mean wind direction, σ_θ, are done or the same is estimated from empirical formulae [45].
- In order to include in-plume turbulent fluctuations, it is found that the calculated concentration is not deterministic and the best way of expressing it is in a probabilistic term (e.g. the probability of exceeding a threshold value).

UK-ADMS considers both the meandering and the turbulent fluctuations of the plume.

Table 4.4 Table showing features of MPTER/COMPLEX-I and UK-ADMS comparatively.

Basic feature

Model feature	MPTER/COMPLEX-I	UK-ADMS
Type of Release	Passive or buoyant releases of gases and/or particles	Passive, buoyant or slightly denser than air releases of gases and particles.
Source geometry	Single or multiple point releases at ground level or elevated.	Single and multiple point, line, area and volume releases, at ground level or elevated.
Emission characteristics	Releases of at least 1 hour; allows for variation of release rate on time-scales greater than 1 hour	Steady release of any duration including instantaneous releases.
Concentration Model	Gaussian model using Pasquill-Gifford stability classes.	Gaussian model in neutral and stable conditions. Non-Gaussian in convective conditions allowing for the skewed nature of convective turbulence.
Spread due to variation in wind direction	Not modelled	Based on measurements.
Plume Rise	Model based on Briggs.	Lagrangian model.
Treatment of inversion	Plume either above or below capping inversion.	Allows partial penetration of an elevated inversion.

Table 4.4 (contd.)

Boundary Layer Structure			
	Meteorological data requirements for input to modelling system	Wind speed and direction, Pasquill Stability category, boundary layer height.	Wind speed and direction; either cloud cover, time or day and day of year, or surface heat flux, or Monin Obukhov length; boundary layer height; precipitation.
	Meteorological data requirements for input to the concentration model	Wind speed and direction, Pasquill Stability category, boundary layer height. For long term averages: Joint probability distribution of the above or long sequences of hourly meteorological data.	Wind speed and direction; Monin Obukhov length; boundary layer height; precipitation. For long term averages: Joint probability distribution of the above or long sequences of hourly meteorological data.
	Surface Roughness	Can only specify 'Urban' or 'Rural'.	Value can be specified.
	Calms	Modelled	Not modelled
Complex Effects	Complex Terrain with changes in surface elevation and roughness.	Simply estimates terrain height changes without consideration of effects of hills on flow.	Uses a modified version of the airflow model FLOWSTAR which allows for the effect of changes in surface elevation and surface roughness on the flow.
	Buildings	Parameterises downwash in main wake, no cavity.	Based on model for flow over buildings; includes main wake and recirculating region.

Table 4.4 (contd.)

	Dry Deposition	Includes gravitational settling, but no turbulent deposition.	Treats turbulent diffusion, deposition and gravitational settling.
	Wet Deposition	Not modelled	Uses wash-out co-efficients based on precipitation rate.
	Concentration fluctuations (Short term variation in concentration for odour and toxicity prediction)	Not modelled	Calculates probability distribution of concentration for averaging times less than 1 hour.
User Interface and Utilities	User Interface	Codes written by US-EPA run using prepared data files for specified model options.	Code has user interface which runs under Microsoft Windows on a PC.
	Utilities	No graphical output	A routine for reading Ordnance Survey digitised terrain data directly for use with the complex terrain module. Windows based graphical output.

4.5 Data Requirement

Successful application of a dispersion model depends on the availability of sufficient data. The next consideration is the quality of the data. Depending on the accuracy of sampling and measurement techniques, analytical procedures and intermediate pre-processing steps, the accumulated data could be graded and thereafter could be retained or rejected. This issue has been dealt in details in APPENDIX-VII.

4.5.1 Emission Data

All the sophisticated dispersion models need reasonably accurate emission data. Once the sources of potential odour are identified within the operational facility (either a waste transfer building or a landfill site) samples are collected with a suitable strategy considering fluctuations in emissions from temperature changes in the waste as well as operational changes within the waste transfer building and the landfill site. The process of collecting samples from a waste transfer building is inherently different from that for a MSW landfill site.

Emissions, Sampling Strategy and computation of Source Strength:
The sampling details for the *waste transfer building* have been described in Chapter 3 (*section 3.2.1*). Once the samples were collected, they were sent to the odour laboratory for an olfactometry analysis on the same day. The mean threshold value for each sample was calculated using the Dravniek's [71] method. The mean threshold value (ou/m^3) was multiplied by a volumetric flow rate to give the odour strength in ou/s. A fixed ventilation rate was used for each set of computations which was calculated on the basis of the minimum extraction required to prevent a positive air pressure inside the building resulting in leakage of odour. Details of calculation for ventilation exhaust rates , following the procedure in Valentine et al [69], are given in APPENDIX-IV.
It is difficult to quantify emissions from a large area source of typically indefinite geometry and with a spatially inhomogeneous surface like a Municipal Solid Waste (MSW) landfill. There are large number of potential odour sources in a landfill site and each of them is of indefinite geometry and quite a large area. These are usually divided into number of sources of smaller area and the source strengths are equivalently adjusted so that the total strength remains the same.

Table 4.5 A sample emission data of the landfill site for 1998 (with extension).

ID Code	No.	X - (kms)	Y - (kms)	Emission (ou/sec)	Z-Lev (m)	Temp (deg K)	Diameter (m)	Velocity (m/sec)	Elv (m)
f	1	496.38	240.26	3727	0.5	288	0.5	0.02	68
k	2	496.52	239.57	3727	0.5	288	0.5	0.02	70
m	3	496.52	239.91	5324	0.5	288	0.5	0.03	74
o	4	496.57	240.27	5324	0.5	288	0.5	0.03	74
ab	5	496.61	240.61	5324	0.5	288	0.5	0.03	71
s	6	496.45	241.14	3727	0.5	288	0.5	0.02	62
v	7	496.75	239.52	5324	0.5	288	0.5	0.03	67
tipping area	44	496.2	240.8	486	0.5	288	5	0.1	72
3 tanker trenches	45	496.61	240.61	48000	0.5	288	3	0.5	68
Power plant flare	46	496.96	239.85	0	8	1000	0.4	10	60
Power plant	47	497.04	240.16	2889	15	288	0.4	10	67

Two methods for assessing the emissions from the landfill site have been discussed in *Chapter 3* (*section 3.3 and 3.4*). Each method has its own merits and demerits. The first one is a direct emission measurement approach- the enclosure approach using an emission isolation flux chamber (the *Lindvall hood*). The second approach is based on an *indirect method* of emission rate measurements based on micrometeorological modelling that uses simple meteorological measurements, suitable odour sampling methods, and analysis of the odour samples based on principles of olfactometry. The overall accuracy and precision of both the methods will depend on the biases and variability associated with the emission source, the sampling method and the analytical methods for analysing the odour samples.

The requirement of emission data for standard commercial packages have been listed in APPENDIX-VII. The emission data generated for *MPTER*, *COMPLEX-I* and *UK-ADMS* are given in the following tables for the waste transfer building and the landfill site. Table 4.5 gives a sample emission data for part of the landfill site for the year 1998 with extension of the site.

4.5.2 Meteorological Data

Meteorological data are as important as the others when used with dispersion models. It is the meteorology that controls atmospheric turbulence patterns and in a way the entire

dispersion process. Each commercial software of dispersion modelling has its specific requirement of meteorological data. Some of the packages are supported by *meteorological pre-processors* that can process standard data sets from the meteorological offices (or National Weather Service, as it is called in the United States of America). These pre-processors can customise the data sets according to the need of the software code. Each of *MPTER* and *COMPLEX-I* can handle meteorological data pre-processed by the program called RAMMET. Proper running of these pre-processor programmes results in a one year period of records with one record for each calendar day. Twenty-four values of each of the following parameters are contained in this record:

- Pasquill-Gifford stability class
- Wind speed (at anemometer height)
- Ambient air temperature
- Wind flow vector (wind direction $\pm 180°$)
- Mixing layer height

Alternatively, meteorological data can be read from a sequential data file. A sample format of the meteorological data file is given in Table 4.7. The meteorological data required for UK-ADMS are mentioned in APPENDIX-VII. The nearest representative meteorological station was at Bedford SAWS (United Kingdom, Easting 5049, Northing 2598, Altitude 85m, DCNN 3440, latitude= 5213N, longitude 0028W). The data for mixing height came from the meteorological station at Wittering (United Kingdom, Easting 5048, Northing 3032, Altitude 80m, DCNN 4396, latitude= 5237N, longitude 0027W). Table 4.7 gives an example data-set of specific hourly meteorological parameters for direct input to UK-ADMS.

SOLAR

A meteorological pre-processor has been coded for generation of stability classes, just in case it is not provided. This routine computes Pasquill-Gifford stability classes (as given in Table 4.8), from class A to class F [93] using wind speed, solar insolation and

Table 4.6[53] Meteorological data format for *MPTER* and *COMPLEX-I*.

Variable	Format	Description	Units
JYR	Free	Year of met data	2 digits

DAY1	Format	Julian Day	3 digits
JHR		Hour	2 digits
IKST		Stability class for the hour	-
QU		Wind speed for this hour	m s^{-1}
QTEMP		Ambient air temperature for the hour	Kelvin
QTHETA		Wind direction for the hour	Degrees azimuth
QHL		Mixing height for the hour	meters

Table 4.7[54] Data set of specific hourly Meteorological Parameters for UK-ADMS.

Variable	Format	Description	Units
9	Free	Number of Parameters	-
STATION DCNN	Format	Station Number	4 digits
YEAR		Year	4 digits
TDAY		Julian Day Number	2 digits
THOUR		Hour (GMT)	1 digit
T0C		Temperature	0.1 deg C
U		Wind Speed	m s^{-1}
PHI		Wind Direction (Direction wind is coming from)	
P		Precipitation	0.1 mm
CL		Total Cloud Amount	Oktas

cloud cover. The solar insolation is estimated with solar altitude, which in turn is calculated with the following data.

The data required are:

- Julian day number (d) of the year
- Time *(T)*, measured in hours
- Latitude (ϕ) and longitude (Λ) of the location
- Cloud cover (CC)

Computation of the Solar Elevation Angle (alt)[94]

Let ϕ be the latitude (measured north of the equator), and Λ the longitude (east of the Greenwich meridian) of the site on the earth's surface. *T* is the time., measured in hours and expressed as Greenwich Mean Time, and *d* is the day called the *Day number*.

The *equation of time* expresses the difference in position between the true sun and a fictitious mean sun which appears to move uniformly across the sky. It is given approximately by equation 4.6.

$$CC = CL/8.0 \quad \textbf{-(4.4)}$$

$$CONV = \pi/180° \quad \textbf{-(4.5)}$$

$$E = \langle [2.47 * \sin\{1.97 * (d - 80)\}] - [1.92 * \sin\{0.986 * (d - 3)\}] \rangle \quad \textbf{-(4.6)}$$

The sun's declination is given approximately by

$$\delta = \sin^{-1}[0.3987 * \{\sin(0.986 * \langle d - 80 \rangle)\}] \quad \textbf{-(4.7)}$$

and its hour angle by

$$H = (15T) - 180.0 + \Lambda + E \quad \textbf{-(4.8)}$$

Equations 4.6 to 4.8 give the sun's position as a function of time. The hour angle H and the declination δ are converted to altitude *a* using equation 4.10.

$$a = [\{\sin(CONV * \delta)\} * \{\sin(CONV * \phi)\}]$$
$$b = [\{\cos(CONV * \delta)\} * \{\cos(CONV * \phi)\} * \{\cos(CONV * H)\}] \quad \textbf{-(4.9)}$$

The solar elevation angle,*alt*, is given by:

$$alt = \{\sin^{-1}(a + b)/CONV\} \quad \textbf{-(4.10)}$$

alt	Insolation
$\geq 60°$	Strong
$\geq 35°$ or $\leq 60°$	Moderate
$\geq 15°$ or $\leq 35°$	Slight

Then the Pasquill-Gifford's stability classes are computed using Table 4.8.

Table 4.8 Pasquill Dispersion Classes[93].

	Surface Wind Speed (m/s)				
Insolation/Cloud Cover	**< 2.0**	**2 to <3**	**3 to <5**	**5 to <6**	**≥ 6**

Day	Strong Insolation	A	A-B	B	C	C
	Moderate Insolation	A-B	B	B-C	C-D	D
	Slight Insolation	B	C	C	D	D
Day or Night	Overcast	D	D	D	D	D
Night	Thin overcast or ≥ 0.5 cloud cover	-	E	D	D	D
	≤ 0.4 cloud cover	-	F	E	D	D

∗ *A, very unstable; B, unstable; C, slightly unstable; D, neutral; E, slightly stable; F, stable.*

Notes:

1) Strong insolation corresponds to a solar elevation angle of 60° or more above the horizon.

2) Moderate insolation corresponds to a solar elevation angle of 35° to 60°.

3) Slight insolation corresponds to a solar elevation angle of 15° to 35°.

4.5.3 Receptor Data

The *refined modelling analysis* used a 2.0 km x 2.0 km Cartesian receptor grid centred over the landfill site, with a grid spacing between receptors of 100 meters. This grid was representative and could encompass the points of maximum impact.

The real terrain elevations of all those grid locations were obtained from the **Land-Form PANORAMA**[3] **Digital Terrain Model Data (DTM)** produced by the **Ordnance Survey** of United Kingdom. DTM consists of height values at each intersection of a 50 metre horizontal grid, the values have been mathematically interpolated from the contours on the Landranger maps. Variations in DTM accuracy are to be expected depending upon the nature of the ground. DTM height accuracy is no greater than one half of the vertical interval of the source contour data. The data has been captured in 20 km x 20 km tiles, and is available for the whole country. A code was developed, called *PANORAMA* to extract the terrain data from the entire tile in a format suitable for *MPTER, COMPLEX-I* and *UK-ADMS.*

For the *community impact analysis* around the MSW landfill site, discrete monitors' locations were chosen. These monitors are the regular community sniffers within the odour annoyance survey programme (arranged by *IERC, Cranfield University*). Receptors were modelled at the actual terrain elevations determined from the reduced

OS data. Table 4.9shows an example of the receptor file in a format accepted by *MPTER* and *COMPLEX-I*.

Table 4.9 A table showing the receptor co-ordinators of the monitors' locations.

Monitor No.	Eastings[4] (km)	Northings[4] (km)	Receptor Height above local ground level (m)	Receptor ground-level elevation[4] (m)
1	502.2	242.5	1	50
2	502.2	242.4	1	50
3	499.6	241.3	1	41
4	499.7	243.5	1	48
5	500.3	245.3	1	52
6	500.9	245.6	1	54
7	498.7	239.1	1	60
8	496	237.8	1	79
9	499.8	242.6	1	40
10	496.3	238.2	1	87

4.5.4 Specific Model Control Options

There are a number of user specified options to be used with both MPTER and COMPLEX-I to tailor them to the specifications of the particular analysis. The regulatory default option was selected for each of the facility analyses, so that buoyancy-induced dispersion, final plume rise, stack-tip downwash and calm wind processing would be automatically used. The complex terrain and the valley screening options were additionally employed, specially for the case studies of the MSW landfill site, considering the physical location of the site.

4.6 Case Studies

This section assesses the following two cases elaborately:

a) The dispersion of odour from a waste transfer station in the North London area, UK. The basic models used for analysing the extent of dispersion were *UK-ADMS* **(***version 1.5***)** and US-EPA's *MPTER* (A Multiple Point Gaussian Dispersion Algorithm with Optional Terrain Adjustment). The two models have been extensively run for various meteorological conditions and source values based on site measurements.

b) The odour dispersion analysis for a MSW landfill site having large number of point and area sources. This landfill site is very close to several community based areas and several tests have been carried out to predict the overall impact of odour in these locations around the landfill site.

4.6.1 Case 1: Waste Transfer Depot

Both MPTER and UK-ADMS have been extensively used to study various cases with different meteorological conditions with samples taken from the waste transfer depot. Figure 4.4 and Figure 4.5 compare the results predicted by UK-ADMS and MPTER . It is observed that the two models compare well at a distance greater than 500 metres downwind from the source. The hourly mean odour concentrations were predicted by both models under a variety of conditions and each case has been compared. The results indicate that when a wind velocity of 5.0 m/sec is applied the mean odour level falls sharply from 1695.0 ou/m^3 at the source to 0.5 ou/m^3 at about 1.5 km from the source along the centreline. In most of the cases the concentration predicted by UK-ADMS along the plume axis is more than MPTER for given distances downwind.

Figure 4.4 shows how the hourly average odour concentrations drop downwind at distances greater than 500 metres from the source along the centreline. Figure 4.5 shows the odour concentrations downwind very near to the source within a range of 500 metres and it is very well observed that the two software differ greatly near the source. This could be due to the fact that the plume meandering effect is taken care of in the UK-ADMS and not in the COMPLEX-I/MPTER.

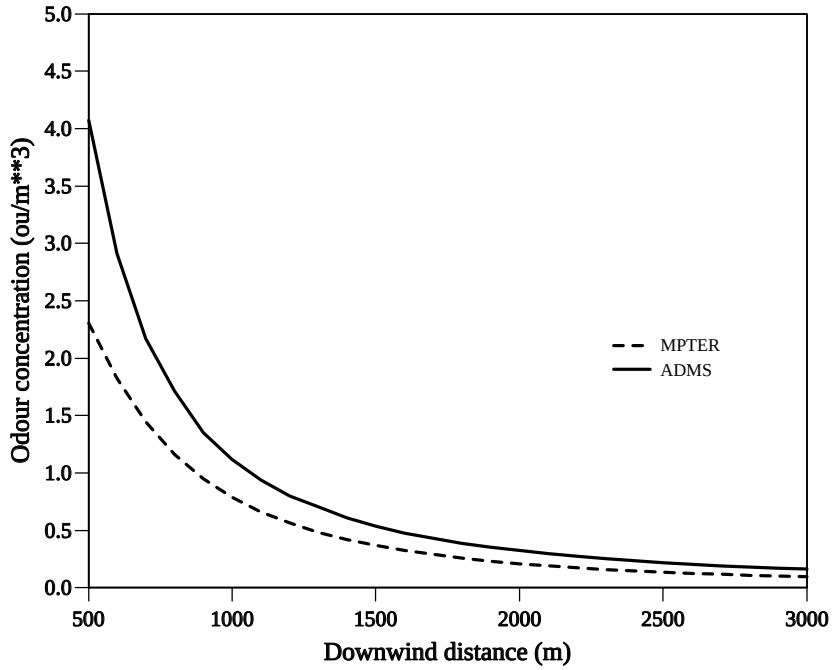


Figure 4.4 Hourly average odour concentrations downwind *(500.0m<x<3000.0m). Source at: 0.0,0.0. Averaging time: 1 hr. u= 5.0 m/s. θ= 270.0 °. P-G Stability class: A.*

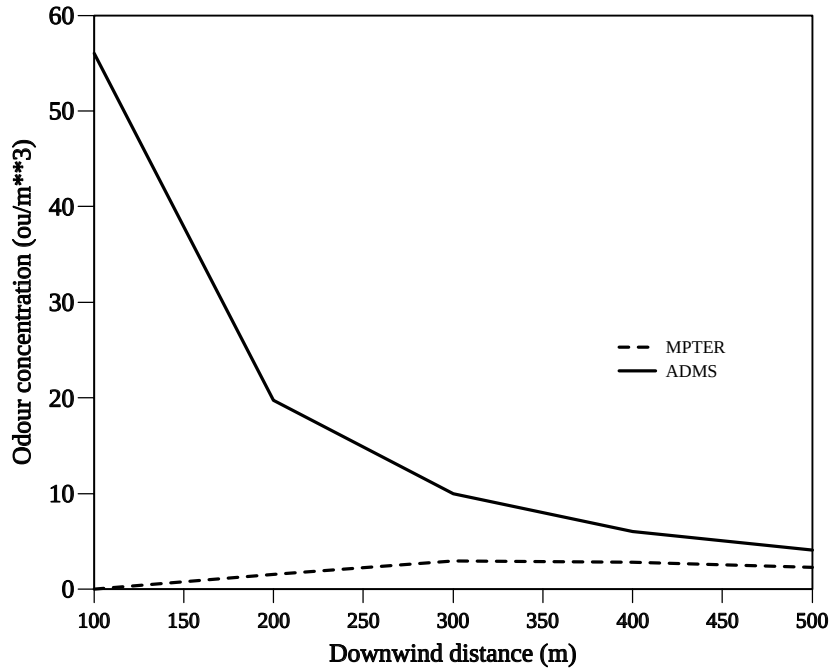


Figure 4.5 Hourly average odour concentrations downwind *(0.0m<x<500.0m). Source at: 0.0,0.0. Averaging time: 1 hr. u= 5.0 m/s. θ= 270.0 °. P-G Stability class: A.*

The source strength used is 1695.0 ou/m^3 which corresponds to the maximum (average) concentration of the six samples tested for their odour strength by olfactometry (*Forced-Choice technique*). The sampling time for this particular sample was 8 minutes

(11:03-11:11, September 19th, 1995) and the strength has been determined by averaging the results of the six panellists. The levels predicted by MPTER are far below the detectable limits. **SRI** reports that at an odour concentration between 10 and 4 ou/m^3 the emitted odour intensity reduces from a *distinct* odour to a *faint* odour and clearly these levels are greatly exceeded at the point of emission. UK-ADMS predicts an odour level greater than 10 ou/m^3 (*distinct*) up to a distance of 300 meters downwind from the source, whereas the odour level is reduced to less than 4 ou/m^3 (*faint*) beyond approximately 500 metres downwind. In view of this and the complaints received from the nearby community it is clear that MPTER underpredicts the entire scenario.

Figure 4.6 gives the variation of odour concentrations (hourly average) crosswind from the source at various distances downwind. It is observed that at a distance of only 100.0 metres away from the plume centreline 250.0 metres downwind of the source, the odour concentration falls sharply to 2.55 ou/m^3 which is well below the detectable limit though the peak is at 13.6 ou/m^3 along the centreline. At distances further downwind the rate of dispersion along the crosswind direction is quite high and the effective odour levels are well below the detection threshold. At 500 metres downwind from the source the odour level falls down to 3.57 ou/m^3 about 50.0 metres away on either side of the plume centreline.

Figure 4.7 represents the variation of odour levels downwind for various averaging times from 1 hour to 3 minutes. It is evident that the rate of dispersion and advection are strongly affected by averaging time. Typically the odour level averaged for just 3 minutes could be almost double that of an hourly average concentration at any particular distance. Figure 4.8 depicts how surface odour concentration predicted by ADMS varies with distance downwind and wind velocity for a source strength of 1695.0 ou/m^3. The odour level changes with varying wind velocities with a maximum occurring when wind velocity is approximately 1.5 m/sec. The effect of wind speed is negligible beyond 7 m/sec.

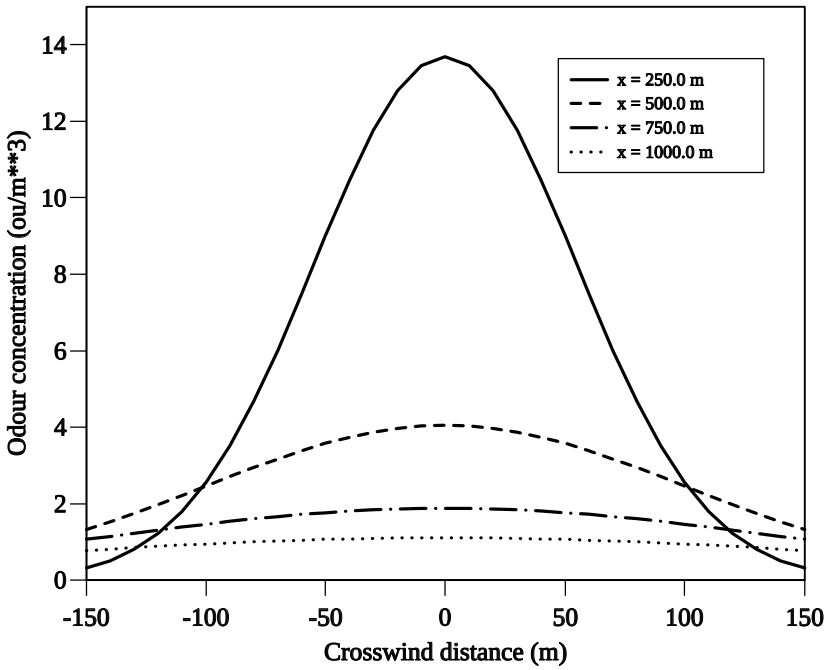


Figure 4.6 Hourly average odour concentrations crosswind from the source. *Software:* ***UK-ADMS-1.5****. Source at: 0.0,0.0. Averaging time: 1 hr. u= 5.0 m/s. θ= 270.0 °.*

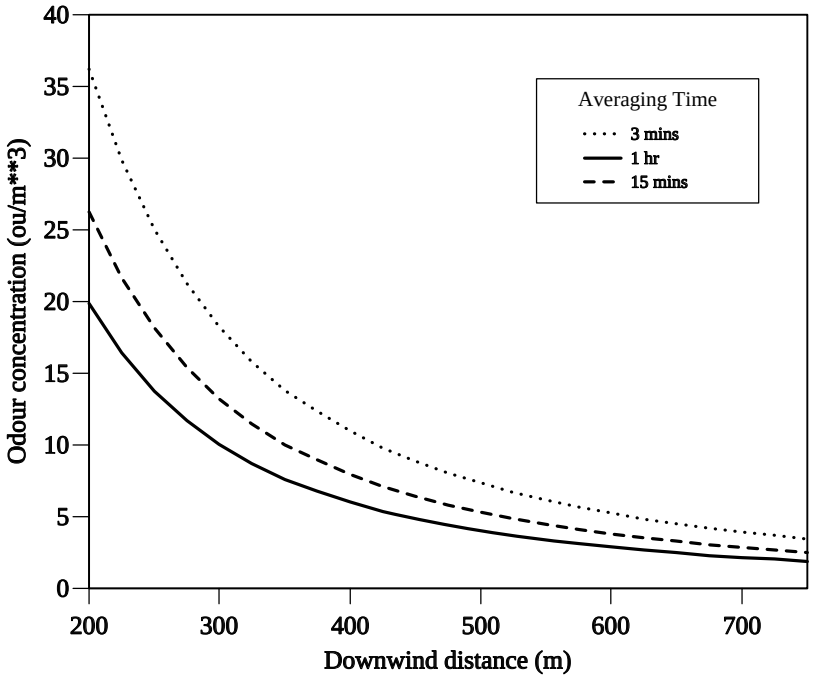


Figure 4.7 Odour concentrations downwind with various averaging times. *Software:* ***UK-ADMS-1.5****. Source at: 0.0,0.0. u= 5.0 m/s. θ= 270.0 °.*

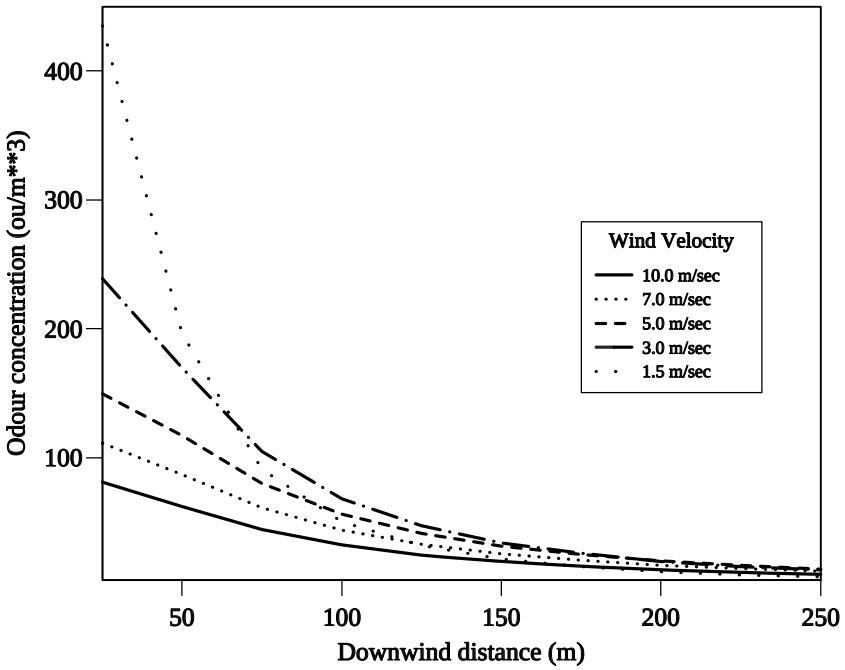


Figure 4.8 Odour concentrations downwind with various wind velocities. *Software: **UK-ADMS-1.5**. Source at: 0.0,0.0. Averaging time: 1 hr. θ= 270.0 °.*

Isopleths for overall odour levels around the transfer depot have been generated. Figure 4.9 shows the hourly average isopleths of odour concentrations for three samples taken between 1100 and 1200 hours on September 19, 1995.

Figure **4.10** is for 15 minutes average and indicates a similar pattern, although higher levels.

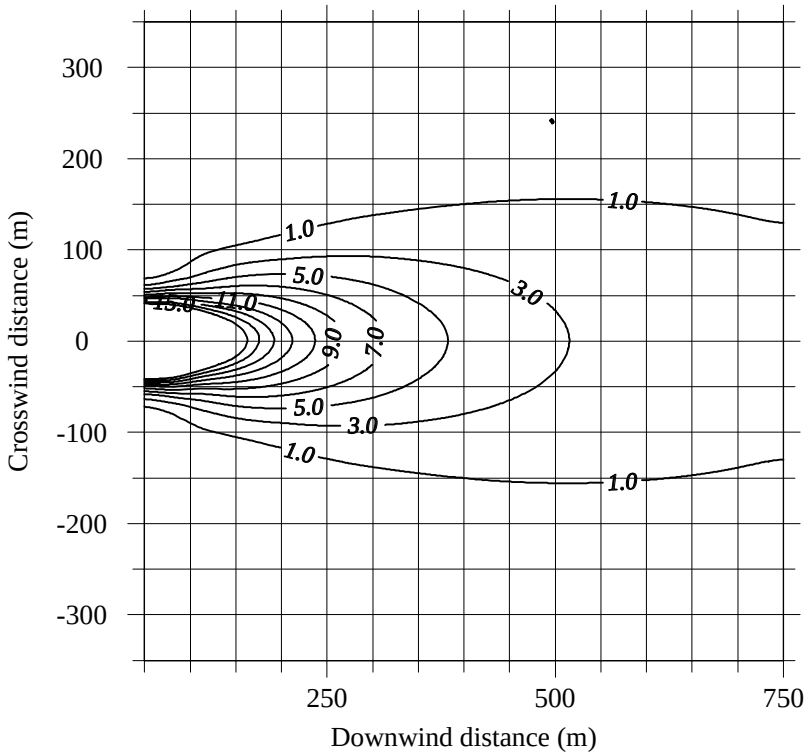


Figure 4.9 An isopleth plot of hourly average odour concentrations (ou/m^3) in and around the Waste Transfer Depot. *Meteorological data: September 19, 1995 between 1000-1200 hours. Software:* ***UK-ADMS-1.5****. θ= 270.0 °.*

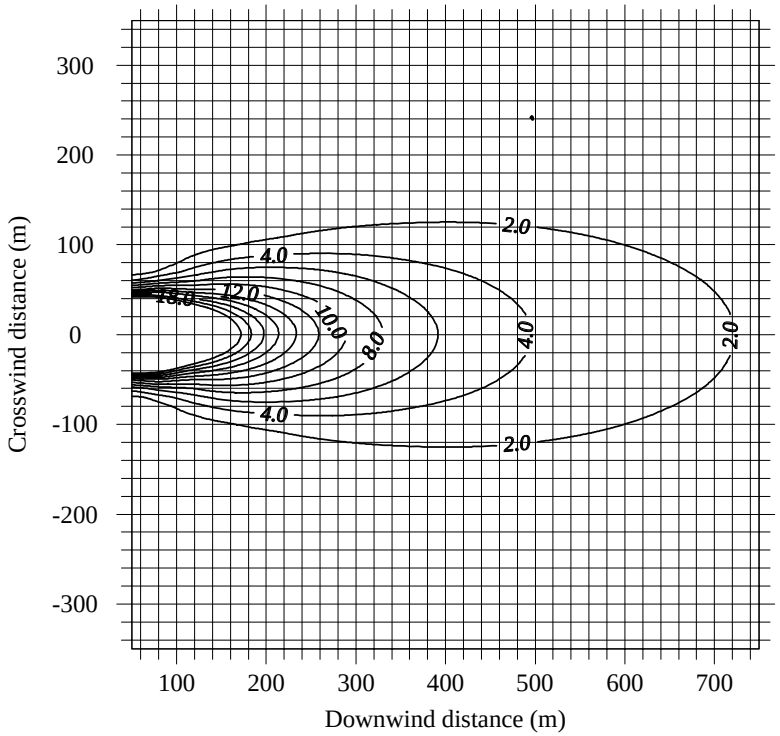


Figure 4.10 An isopleth plot of average *(15 minutes)* odour concentrations (ou/m^3) in and around the Waste Transfer Depot. *Meteorological data: September 19, 1995 between 11:03-11:11 hours. Software:* ***UK-ADMS-1.5****. θ= 270.0 °.*

4.6.2 Case 2: MSW Landfill Site

The case of the MSW landfill site has been studied with COMPLEX-I and UK-ADMS for various meteorological conditions and averaging times. Results are given for the year 1998 in Figure 4.11 to Figure 4.25. Figure 4.11 to Figure 4.13 give a picture of the maximum odour concentration around the landfill site for 1 hour, 10 minutes and 3 minutes averaging time with COMPLEX-I. The same locations are affected more with 3 minutes averaged concentration as compared to hourly and 10 minutes averaged ones. From the results of SRI two odour thresholds **(3.0 ou/m^3 and 5.0 ou/m^3)** have been found critical for various samples from the landfill site. Figure 4.14 and Figure 4.15 give a picture of the frequency of occurrence of events where odour levels crossed these critical thresholds (nearly the *detection* and *recognition*) in the surrounding areas, on the basis of an hourly averaged concentration. Figure 4.16 to Figure 4.19 give a similar picture with different averaging times and naturally we find that the same region is affected worse with a shorter averaging time. Figure 4.20 to Figure 4.25 give a comparative picture of the entire scenario with respect to the use of COMPLEX-I and UK-ADMS. As seen in the previous case study with the waste transfer depot, we find the the concentrations predicted by UK-ADMS are in general more that that by COMPLEX-I near the source. The shape of the isopleth is squarish for COMPLEX-I outputs, where as the same is quite smoother for UK-ADMS. The first reason could be the use of a virtual source in the COMPLEX-I module since there is a restriction of the height of the sources to be 10.0 meters. The other reason could be the fact that the COMPLEX-I module used was a multiple source one, whereas the results of the single source UK-ADMS (version 1.5) have been added on the same nodes for all the sources. Theses cases will be dealt with more elaborately in *Chapter 6* (*Results and Discussion*) having cases with source strengths varying over the years, from 2004 to 2008. *Community modelling* will also be dealt with in *Chapter 6,* where the results from the dispersion models are compared with the real complaints received from the regular community sniffers. Without these comparisons it is difficult to determine the better model for the particular scenario of the MSW landfill site.

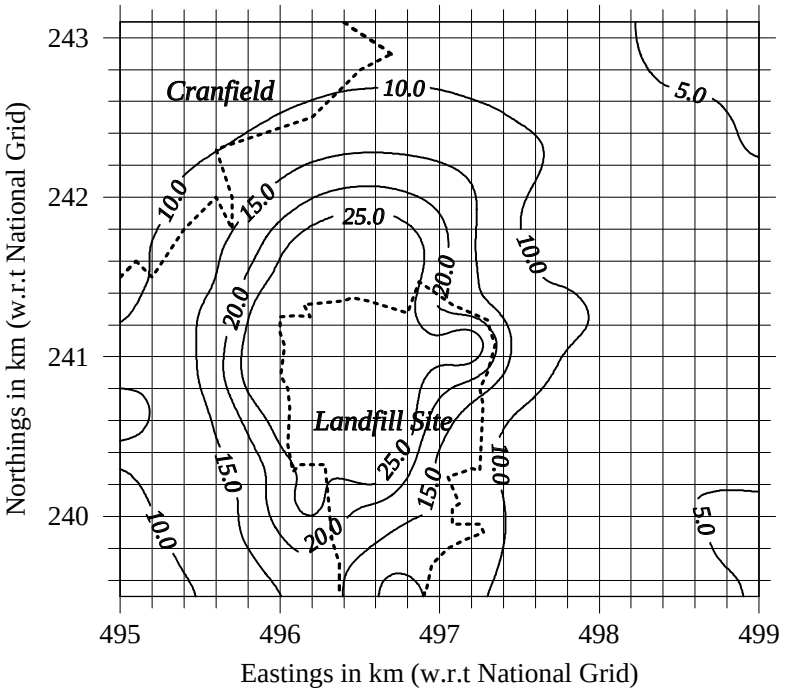


Figure 4.11 An isopleth plot of maximum hourly average odour concentrations (ou/m^3) in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

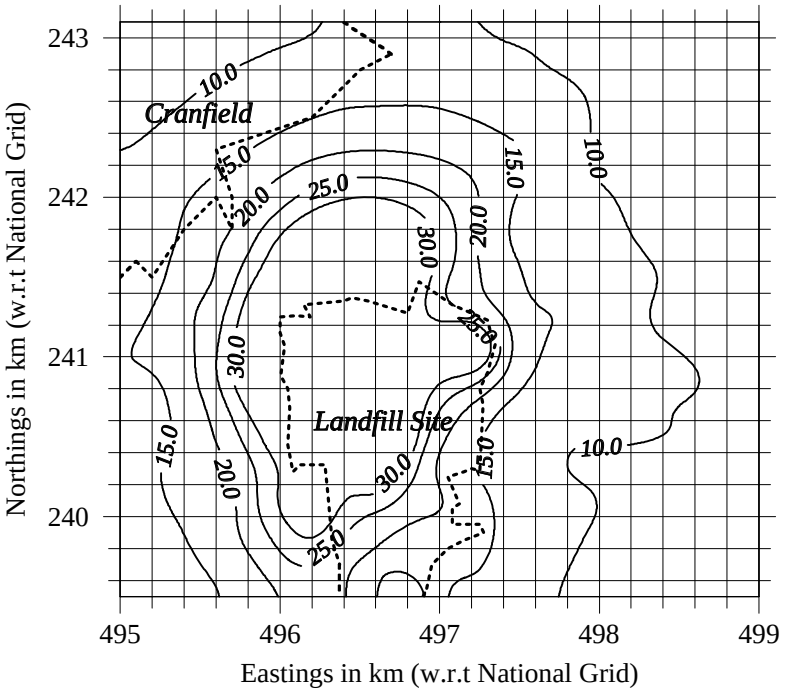


Figure 4.12 An isopleth plot of maximum *(10 minutes average)* odour concentrations (ou/m^3) in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

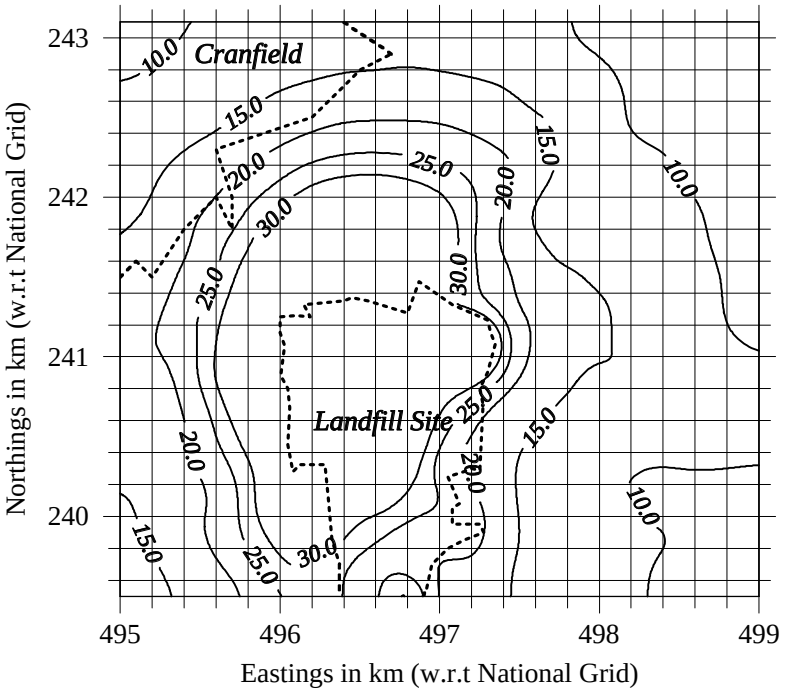


Figure 4.13 An isopleth plot of maximum *(3 minutes average)* odour concentrations (ou/m^3) in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

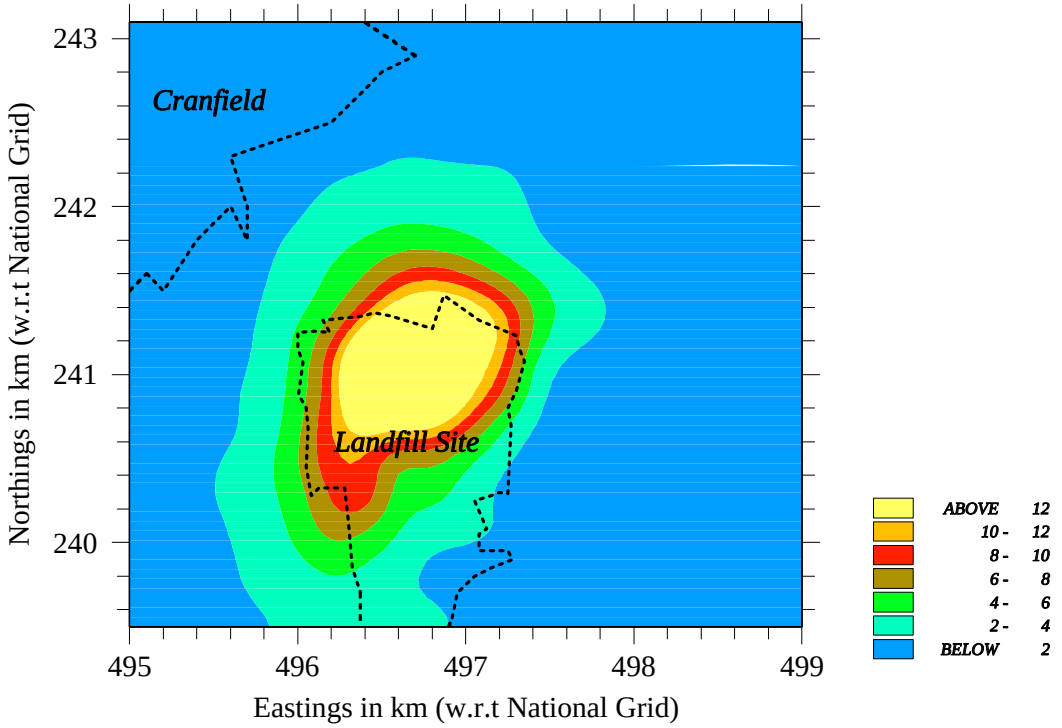


Figure 4.14 A contour plot of percentage frequency of odour levels *(hourly average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

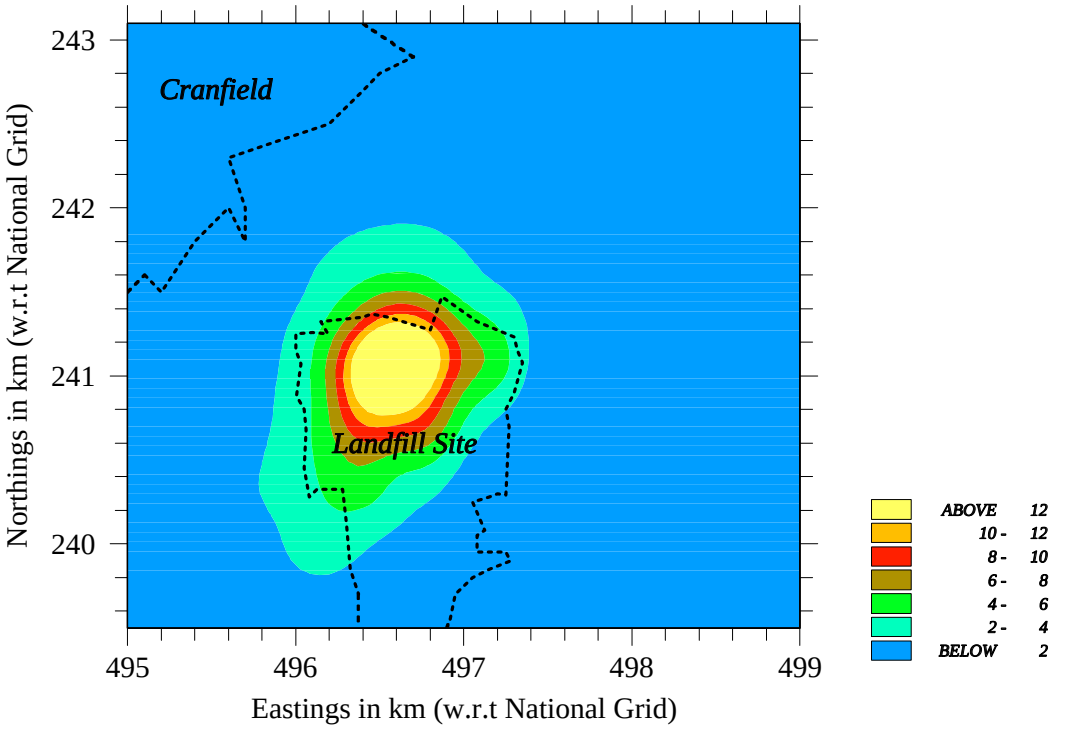


Figure 4.15 A contour plot of percentage frequency of odour levels *(hourly average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

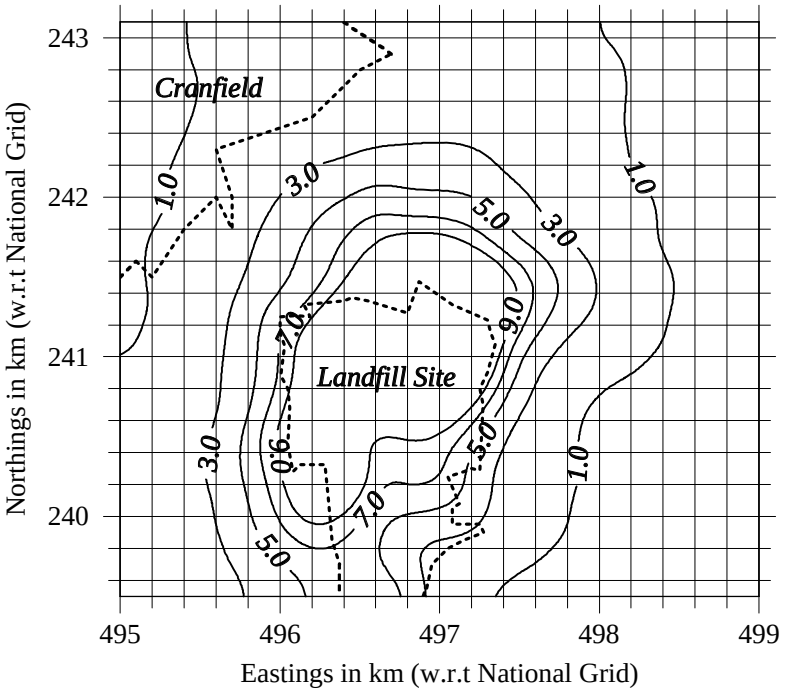


Figure 4.16 A contour plot of percentage frequency of odour levels *(10 minutes average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

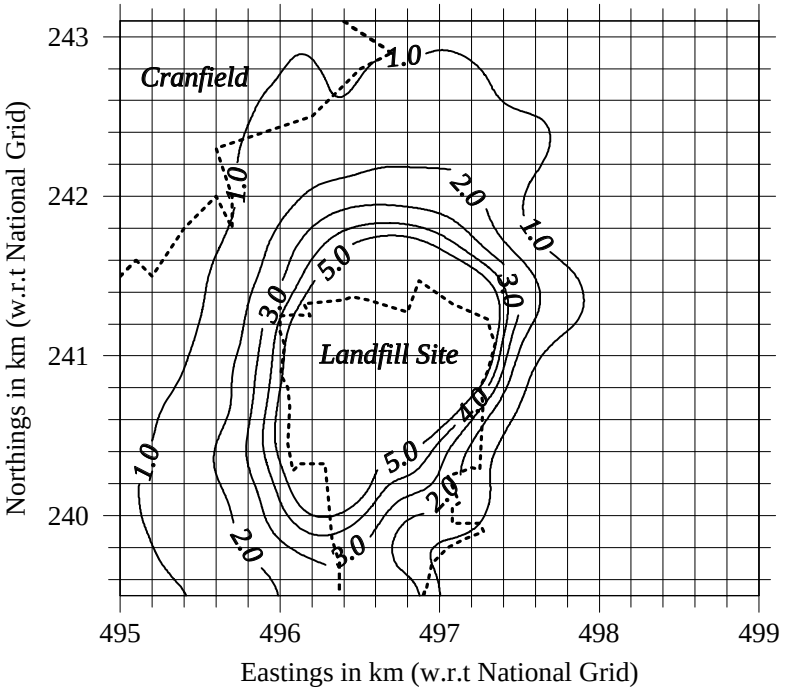


Figure 4.17 A contour plot of percentage frequency of odour levels *(10 minutes average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

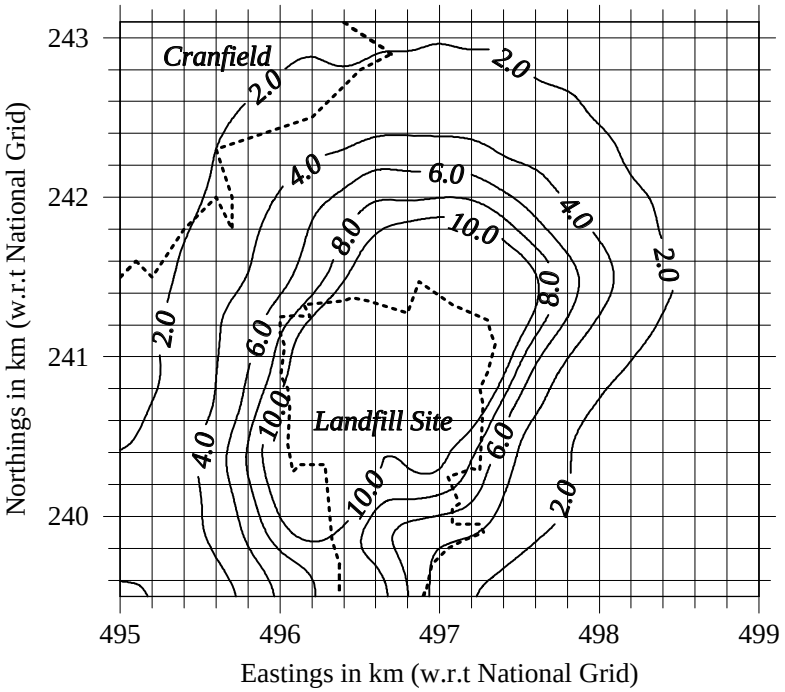


Figure 4.18 A contour plot of percentage frequency of odour levels *(3 minutes average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

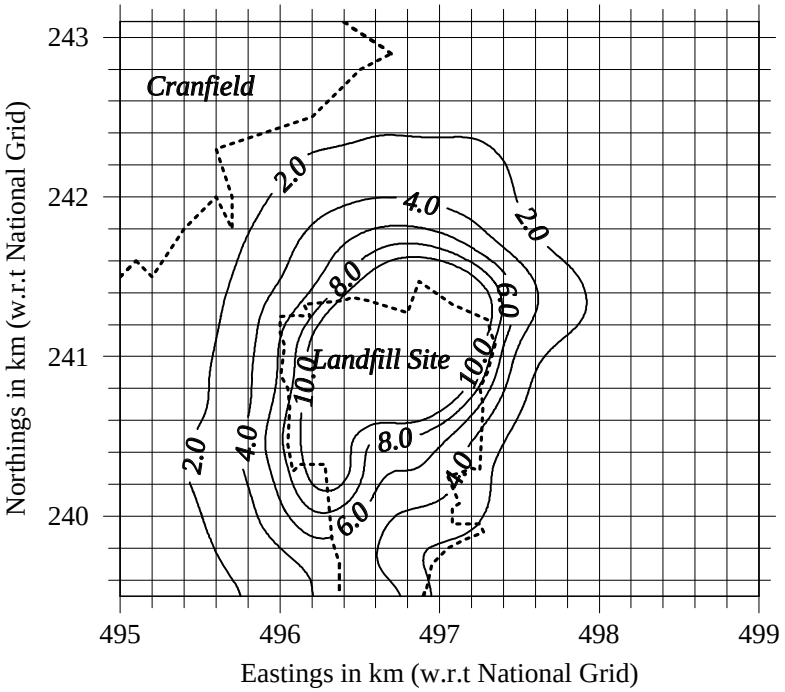


Figure 4.19 A contour plot of percentage frequency of odour levels *(3 minutes average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

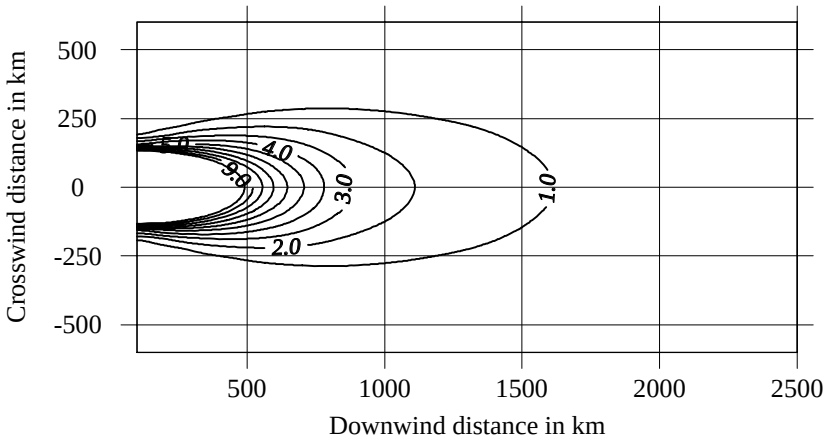


Figure 4.20 An isopleth plot of *hourly average* odour concentrations (ou/m^3) along the mean wind direction away from the MSW Landfill Site. *Hourly average meteorological data: 13:00 PM, 26th August'1997. Software:**UK-ADMS (Version-1.5)***.

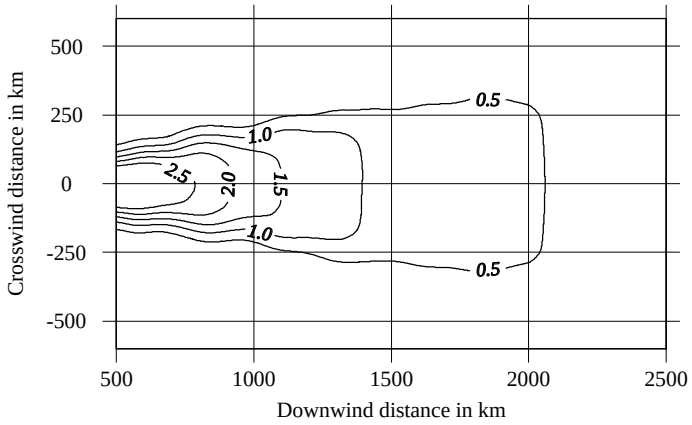


Figure 4.21 An isopleth plot of *hourly average* odour concentrations (ou/m^3) along the mean wind direction away from the MSW Landfill Site. *Hourly average meteorological data: 13:00 PM, 26th August'1997. Software:**COMPLEX-I***.

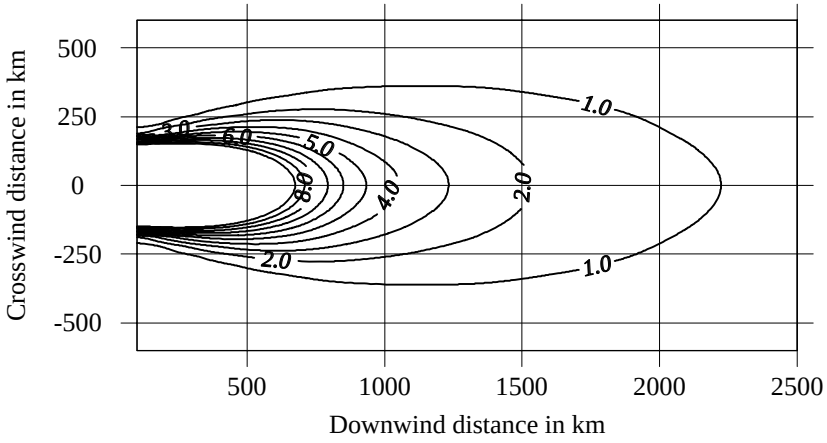


Figure 4.22 An isopleth plot of *10 minutes average* odour concentrations (ou/m^3) along the mean wind direction away from the MSW Landfill Site. *Hourly average meteorological data: 13:00 PM, 26th August'1997. Software:**UK-ADMS (Version-1.5)***.

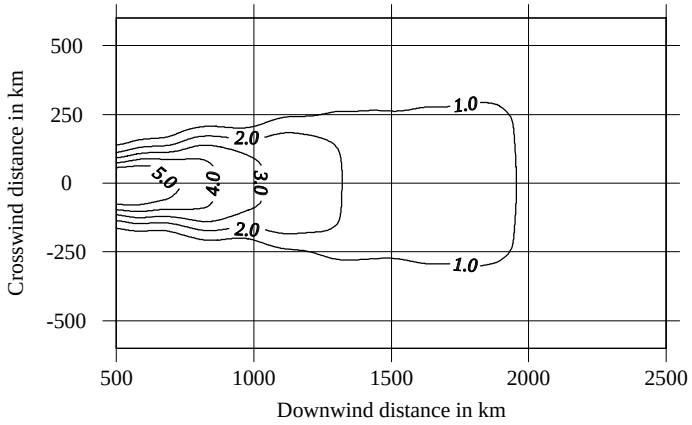


Figure 4.23 An isopleth plot of *10 minutes average* odour concentrations (ou/m^3) along the mean wind direction away from the MSW Landfill Site. *Hourly average meteorological data: 13:00 PM, 26th August'1997. Software:**COMPLEX-I**.*

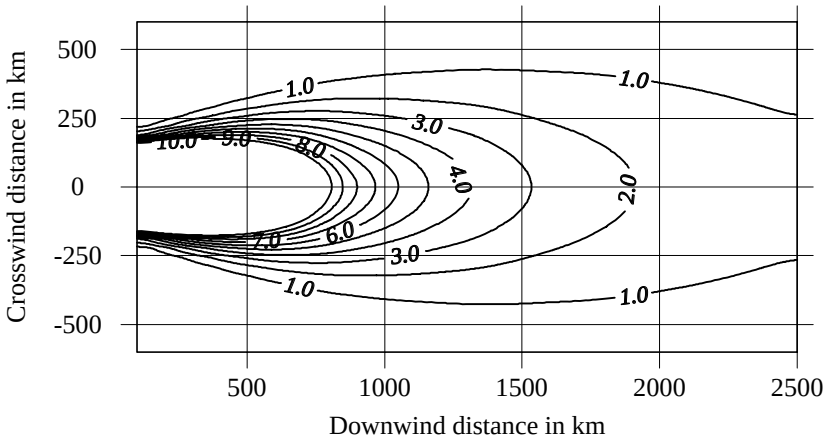


Figure 4.24 An isopleth plot of *3 minutes average* odour concentrations (ou/m^3) along the mean wind direction away from the MSW Landfill Site. *Hourly average meteorological data: 13:00 PM, 26th August'1997. Software:**UK-ADMS (Version-1.5)**.*

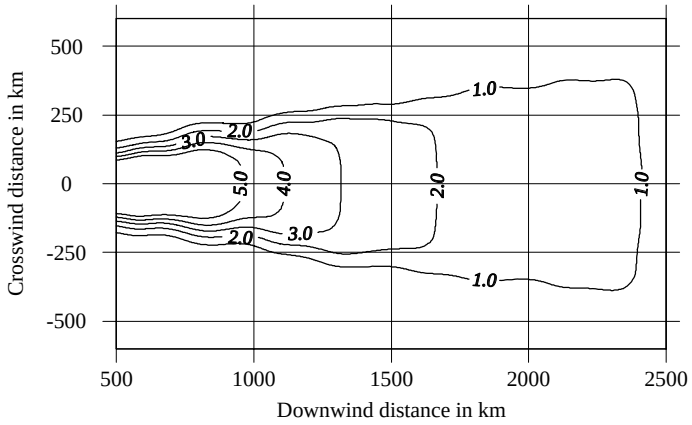


Figure 4.25 An isopleth plot of *3 minutes average* odour concentrations (ou/m^3) along the mean wind direction away from the MSW Landfill Site. *Hourly average meteorological data: 13:00 PM, 26th August'1997. Software:**COMPLEX-I**.*

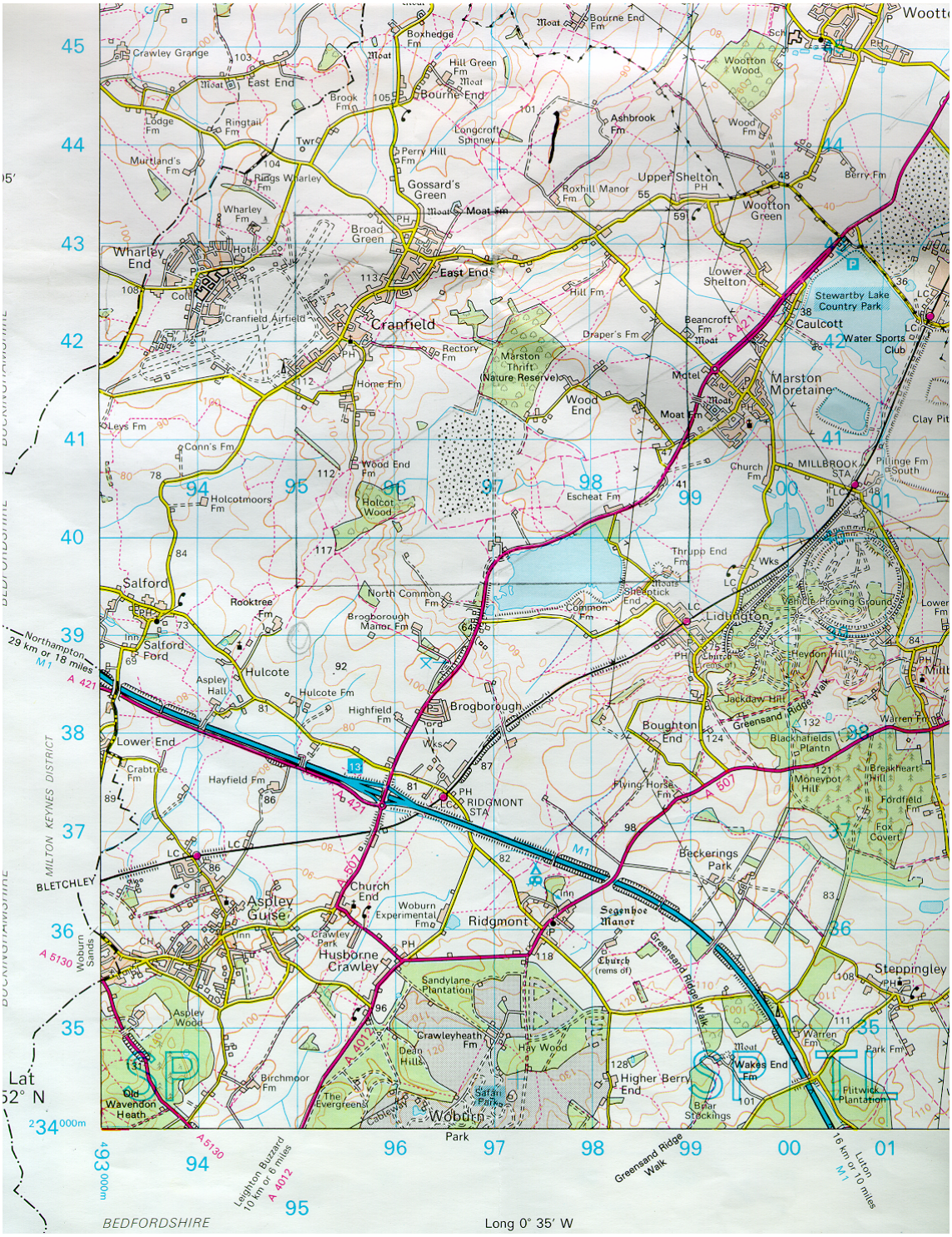


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Figure 4.26[4] Part of the Landranger-Map titled "Bedford, Huntington and surrounding areas" showing regions affected by the MSW Landfill site. The co-ordinates correspond to the actual Eastings and Northings in km.

4.7 Conclusion

In general the concentration predicted by UK-ADMS is greater than that predicted by MPTER/COMPLEX-I. For a particular case MPTER/COMPLEX-I uses one average stability class (Pasquill category) for all the variations in meteorological conditions within the hour and does not account directly for the turbulent factors of the atmosphere (mean flow and turbulence are independent of the boundary layer height). In reality both the mean flow and turbulence vary extremely with the boundary layer height. The approach of UK-ADMS is quite different in this respect. It accounts for the effect of the local boundary layer depth at each stage of computation in terms of the stability class and gives a better and more realistic picture of the local atmospheric conditions. MPTER/COMPLEX-I uses Pasquill-Gifford stability classes which correspond to broader limits for all micro-meteorological conditions and the entire approach is semi-quantitative.

The approach of ADMS is to find out a stability class qualitatively and then using a set of semi-empirical expressions for the dispersion parameters as is done in MPTER/COMPLEX-I. For the same set of meteorological factors and emission conditions ADMS tends to predict less dispersion when compared to MPTER/COMPLEX-I, giving rise to higher odour concentration levels. This is supported by the fact that UK-ADMS involves both the concepts of meandering and in-plume fluctuations within the *fluctuation module* of the software.

In view of the complaints received from the nearby community for the case of waste transfer depot, it could be concluded that MPTER underpredicted the average scenario as the odour levels predicted by MPTER were always less than 4 ou/m^3, the lowest detection threshold for the samples tested by olfactometry, even for the sample with highest odour concentration. The models compare well at distances greater than 500 metres downwind from the source whereas UK-ADMS, we believe to be more reliable close to the source (less than 500 metres) as compared to MPTER because of its better representation of the local dispersion processes. Thus UK-ADMS could be a better tool for predicting odour dispersion, particularly because odour impacts are predominantly at short ranges.

However, depending on the geographical position of the odour source and the surrounding topography, COMPLEX-I has been found a better option for our second case study with the MSW landfill site. This is mainly because the site is located very

near a deep valley, with an average elevation of +45.0 metres from the mean sea level as compared to the average elevation of +68.0 metres of the landfill site. The *valley screening option* of COMPLEX-I could be utilised in the particular situation. However UK-ADMS has also been used for the community modelling part of the overall study. The choice of one model over the other, particularly for the community modelling, should be established after considering the complaints statistics and this issue is discussed in detail in *Chapter 6 (Results and Discussion)*.

Chapter 5

5. Analysis of Perception

In this Chapter we will make an attempt to relate odour concentrations predicted by the physical models to the perceived nuisance within the surrounding community of a potential odour source, which depends on the human response. Nuisance is a broad term including time variation and strength of smell. The strength of smell is characterised by the odour intensity and offensiveness, terms defined in the APPENDIX-II. For many purposes these are taken as functions independent of the temporal history. As we go through this chapter, various intensity scaling systems will be discussed, then the basic psychophysical functions that can successfully relate the perceived intensity with the odour concentration. The development of methods will include:

- Measurement of odour concentration and intensity
- Model selection and parameter estimation techniques
- Evaluation of the models with statistical analysis

The results will be discussed afterwards with the nine samples taken from various locations within the MSW landfill site. In conclusion, there will be an attempt to rank the models according to their performance and one or two model(s) will be selected as the basis for community modelling, to be dealt in *Chapter 6*. One of these psychophysical models, already discriminated on the basis of its performance, will be used to convert the intensity scales reported by the community sniffers to odour concentration (ou/m^3) in *Chapter 6*. Else, the odour concentrations (ou/m^3) predicted

by the dispersion model(s) in *Chapter 4*, will be converted to intensity scales with these relationships.

5.1 Introduction

Odours from landfill wastes comprise complex mixtures of a large number of volatile compounds. Gas chromatography analysis can reveal which compounds are present but cannot predict much about their contribution towards odour. Odour concentration, intensity and offensiveness can be measured. Odour concentration is a measure of the detectability of the odour as assessed by a panel of people. In olfaction, as in the other sensory modalities, the bulk of psychophysical data concerns the attribute of intensity. General techniques and theory of sensory measurement have been derived largely from the investigation of intensity, and consequently this attribute has served as a prototype for the study of sensation. Odour intensity [95] is defined as the perceived magnitude of a stimulus. Odour intensity and offensiveness are subjective measures of the strength and unpleasantness of an odour as assessed by a panel of people. Odours of equal concentration will not necessarily be of equal perceived intensity or offensiveness. Although the intensity can be perceived directly without any knowledge of the odour concentration, it is necessary to establish the relationship between the intensity of an odour and the odour concentration. The standards and regulations based on odour concentration could be correlated using this relationship. The relationship is far more important when used in conjunction with dispersion modelling, in terms of comparing the resultant odour concentrations at the receptors (locations of potential complainants), as obtained from the dispersion analysis, with those obtained by reducing the intensity scales of the odour complaints to odour concentration levels. The idea could also be utilised by legislators to establish minimum ***separation distances*** between the landfill site and zones of potential complaints based on objective criteria.

The objective of this part of the research was to develop a relationship between odour intensity and odour concentration by using data collected from various sensitive areas of the Municipal Solid Waste landfill site.

5.2 Scales of Measurement

It is desirable to define a scale of odour magnitudes. This is for measuring the relation between one odour intensity and another. A well-known classification of scale types was formulated by S.S.Stevens [60], and comprises of nominal, ordinal, interval, and ratio scales. Table 5.1 [64] offers a summary of the properties, permissible transformations, and permissible statistics for the four types of scales.

A ***nominal scale*** is derived when numerals are used to classify aspects of objects or events without any reference to their order. The particular labels used to identify classes are irrelevant for the structure of the scale and they can be interchanged or substituted with other labels. The only requirements are that each class of the original scale retain a label that allows it to be discriminated from every other class, and that a change in label does not cause items included in one class to cross the boundary into another class.

An ***ordinal scale*** is formed by the procedure of rank ordering. The nominal scale incorporates the relation of *equality*, whereas the ordinal scale gives additionally the relation *greater than*. The structure of the scale is undisturbed by any transformation that preserves order, i.e., transformation by any increasing monotonic function. Hence, the structure of the scale is undisturbed if the conventional designations 1,2, and 3 to represent ordinally decreasing magnitude are transformed into logarithms, squares etc. Psychophysical methods based on ordinal scaling directly include rating scales, pair comparisons, and the procedure of rank ordering. However, both nominal and ordinal scales are not enough to derive a functional relation, such as that between concentration and odour intensity. The properties of neither scale are isomorphic to the numerical system of arithmetic, and these scales can be utilised only to perform a basic statistical analysis.

An ***interval scale*** comes into the picture when it is necessary to determine the *equality of intervals* on top of *equality* and *rank order*. Measurement on an interval scale permits specification of the distance between any two scale values. The unit of measurement and the location of the zero point are both arbitrary and usually set by convenience. Various psychophysical techniques lead to interval scales of sensation directly.

The ***ratio scale*** incorporates the operations of *equality*, *rank order*, *equality of intervals*, and *equality of ratios*. An extremely important practical advantage of ratio

scales is that they permit values to be expressed in terms of percentages. Ratio scaling is a widely used method of intensity measurement and requires panellists to assign numbers proportional to the sensory magnitude. A reference odour is often presented, with an assigned value, to give the panellists a base point. An overview of methods used for scaling odour intensity is given by Hangartner [55]. Cross continuum matching is a form of ratio scaling where panellists are required to match the sensation to some other continuum, such as to a reference odour [7].

Table 5.1[64] A classification of Scales of Measurement.

Scale	**Basic empirical operations**	**Mathematical group-structure**	**Permissible statistics**	**Examples**
Nominal	*Determination of equality*	*Permutation group* $x' = f(x)$, *where* $f(x)$ *means any one-to-one substitution*	*Number of cases* *Mode* *Contingency* *Correlation*	*Assignment of type or model numbers to classes*
Ordinal	*Determination of greater or less*	*Isotonic group* $x' = f(x)$, *where* $f(x)$ *means any increasing monotonic function*	*Median* *Percentiles* *Order correlation*	*Hardness of minerals* *Grades of leather*
Interval	*Determination of the equality of intervals or of differences*	*Linear group* $x' = ax + b$ $a > 0$	*Mean* *Standard deviation* *Product moment* (r) *Order correlation*	*Temperature (Fahrenheit and Celsius)* *Potential energy*
Ratio	*Determination of the equality of ratios*	*Similarity group* $x' = cx$ $c > 0$	*Geometric mean* *Harmonic mean* *Percent variation*	*Length, density, Temperature (Kelvin) Brightness (brils)*

Psychophysical scaling typically concerns the construction of interval and ratio scales. The classical way to measure sensory magnitude by indirect means was devised by

Gustav Fechner. He began with Weber's observations that the ability to resolve small differences between stimuli is approximately proportional to the magnitude of stimulation, i.e., $\Delta\phi = k\phi$, where ϕ is stimulus magnitude and $\Delta\phi$ is the smallest difference in stimulation that can be perceived (the *just noticeable difference* or jnd). Fechner then assumed that, whenever stimulation was changed by an amount equal to a jnd, sensation magnitude was changed by a constant amount. A common way to construct a scale of sensory magnitude from direct interval judgements is to use the method of *category estimation*. It uses a scale consisting of equally spaced categories. Panellists are required to assign a category which best describes their perception of the odour intensity to each concentration of the odour presented to them. Category scales form part of the GermanVDI guidelines on odour measurement [96] and have been used by Pain *et al* [97] and Clarkson and Misselbrook [98].

While *category estimation* is the most popular of the direct interval scaling techniques, *magnitude estimation* is the most popular of the direct ratio scaling techniques. In this case, the sniffer is presented with a series of stimuli in irregular order. He is supposed to tell how intense they seem by assigning numbers to them. The first stimulus is called any number that seems appropriate to the sniffer and then he is supposed to assign successive numbers in such a way that they reflect his subjective impression. He is allowed to use fractions, whole numbers, or decimals, but he should make each assignment proportional to the intensity as he perceives it [99].

5.3 Psychophysical Functions

In order to describe the mathematical relationship between perceived odour intensity and concentration various questions need to be addressed. It is doubtful whether one type of mathematical function could describe the growth of intensity for all types of odours or odour mixtures. Even if there would have been just one type of function, the next question would have been on the variation of the parameters of the equation from one odorant to the other. Since there is no linear relationship between scales produced by direct interval scaling and those produced by direct ratio scaling, it is to be expected that the two techniques give rise to different mathematical descriptions for the same psychophysical function. This is true for olfaction like all other sense modalities.

S.S.Stevens [60] proposed that the growth of sensation ψ on all prothetic continua is a power function of stimulus magnitude ϕ, i.e., $\psi = k\varphi^{\beta}$. This was derived from the results of direct ratio scaling for a number of sensory continua. This relationship, also well known as the ***psychophysical power law***, has now been verified for various sensory continua [61,100]. The important parameter of the above equation is β, the growth parameter. Its size varies from one sensory continuum to another. For brightness vision it is 0.3, and accordingly a tenfold change in luminance causes slightly more than a twofold change in perceived brightness, i.e., $(10/1)^{0.33}$=2.1 [64]. Several scientists have showed that the olfactory sensation grows as a power function of concentration [101-105]. The form of the function might be approximately the same for all odorants, β varies from one odorant to the other. Hence, a given change in stimulus concentration may produce a large change in the intensity of one substance, while a small change in the intensity for another substance. Fechner proposed that the magnitude of sensation is linearly related to the logarithm of stimulus magnitude. ***Fechner's logarithmic law*** did not find much support from category scaling in various sense modalities. In olfaction, category scales obtained by Engen and Lindstrom [64] and by Gregson *et al* [64] did not support the logarithmic relation. On the other hand Katz and Talbert [64] found that psychophysical functions for most substances were in accord with the logarithmic relation and they tested it for about 55 odorants.

It has been investigated by several researchers that the functional relation between response magnitude and concentration obtained via neurophysiological recording would have the same form as that obtained from psychophysical decisions. **Beidler** [64] proposed a *fundamental taste equation* to account for the growth of neurophysiological responses from taste receptors and from the chorda tympani nerve of various species. Beidler's equation is

$$r = \frac{RK\phi}{1 + K\phi} \qquad \textbf{-(5.1)}$$

where ϕ is concentration, r is the neural response, K is the equilibrium constant and R is a constant that reflects the maximum neural response from a particular type of olfactory receptor. An equation of this form has been found to describe the growth of the receptor potential in a number of other sensory systems [106]. This has been also

supported from the results of intensity category scaling [63]. Laffort [64] suggested that the fundamental taste equation may be modified to describe psychophysical functions for odour intensity obtained by direct interval and direct ratio scaling. Laffort's modification is

$$\psi = \left(\frac{\phi}{1 + \phi \psi_{\max}^{-1/\beta}} \right)^{\beta} \qquad \textbf{-(5.2)}$$

Both Beidler's and Laffort's expressions imply that, at the high end of the perceived sensation, equal ratio increments would cause a smaller and smaller increments in sensation. Such a trend has been observed for the growth of the integrated neural discharge in the olfactory nerve and the olfactory bulb. This trend has been observed only occassionally in the psychophysical functions of human observers [64].

5.4 Methodology

A method was proposed to measure odour intensity and threshold dilution ratio simultaneously by using a dynamic dilution forced-choice olfactometer. Several experiments were carried out and data of odour intensity and threshold dilution ratio were obtained.

5.4.1 Measurement of Odour Concentration and Intensity

Odour Sampling

Samples of odour emissions were collected from the knock-out-pots (KOP) and from the waste surface. The Knock out pots and gas well heads had conveniently fixed gas sampling ports, a sampling tube was connected to this and the gas sample sucked from the port into a Nalophan odour bag, contained in a barrel, using the lung principle. Duplicate samples were taken from each well or KOP (refer the site-map of the landfill site [5]). KOP B is a sampling point on the western ring main collecting gas from stages 3 and 4, KOP C collects gas from stage 2, the day variation from day to day is small. W28H and W1H are samples of gas from horizontal wells in the stage 4A area. Samples of odour emissions were collected from the waste surface using two methods.

The ***cover sheet method*** is a simple one, useful for making comparisons between different surfaces. Odours from waste and capped areas were collected in this way. An odour free sheet was used to cover an area of about 4m x 4m, supported in the middle to enclose a volume. The gas concentration beneath the sheet was allowed to equilibrate for a standard period of 10 minutes, duplicate odour samples were taken within the next 10 minutes. The cover sheet was weighted at the edges to form a seal against the waste surface. The other method used a portable flux chamber called ***Lindvall Hood*** (See Figure 3.2) for collecting samples from waste surfaces, freshly tipped and those one day old. With this equipment a controlled flow of air is passed over the surface. The flexible air inlet hose is positioned at least 10m upwind of the sampling area, the air passes through the fan and then through an activated charcoal filter to reduce the odour concentration of the inlet air. The hood covers 1.5 m^2 and the air velocity is of the order of 0.1 ms^{-1}. At each sampling position duplicate samples of inlet and outlet air were taken over a period of about 10 minutes immediately after the fan was started.

Olfactometry

This is an objective method of expressing the strength or concentration of an odour. The method used determines how many times a sample must be diluted with odour-free air to be at the threshold of detection by 50 percent of the panel. The number of required dilutions defines the odour concentration in Odour Units (OU). These tests are carried out in laboratory conditions with trained and selected panelists. Recommendations on procedures and materials to be used in olfactometric measurements are given by Hangartner *et al* [107].

In this study odour concentration was measured using an "Olfactomat" dynamic dilution olfactometer (Project Research Co., Amsterdam). The sample was presented to an odour panel using the forced-choice method. Six dilutions of each sample, differing from each other by a factor of two, were presented to the panelists three times. Dilutions were made using odour-free air supplied by a compressor fitted with carbon filters and an air dryer. The olfactometer has two sniffing ports, one containing the diluted sample air and the other odour-free air. For each presentation, panelists indicated via a keyboard which port delivered the odorous air. In order to put greater confidence on the panelists' responses, they were also asked to indicate whether their choice was a "guess" (as it would have to be if the

odour presented was below their personal threshold level), or whether they had an "inkling" that their choice was correct (when the odour was close to the threshold level) or whether they were "certain" their choice was correct.

The mean threshold value for each sample was calculated using the Dravniek's [71] method.

Odour Intensity

The assessment of odour intensity indicates the effect of differing odour dilutions on the likely smell sensation for an individual. Odour intensity measurement involves measuring people's perception of the strength of an odour at a range of suprathreshold concentrations. Different types of odour require differing dilutions to gain an equivalent reduction in their impact or sensation. Intensity tests give an indication of the level of dilution required to change odour strengths. Measurements of intensity are determined by the "sniffing" panel using a subjective scale (usually 0-6) from *no odour* to *extremely strong.* Depending upon odour type and selection of the panel high confidence levels can be achieved from these qualitative judgements. From these measurements relationships can be derived between odour concentration and perceived intensity as assessed by a panel.

Odour intensity was measured using a category estimation technique. Following the determination of odour concentration, ranges of suprathreshold dilutions were presented in random order. The panelists were required to indicate their perception of intensity at each dilution according to the following scale.

0	No odour	4	Strong odour
1	Very faint odour	5	Very strong
2	Faint odour	6	Extremely strong odour
3	Distinct odour		

Mean intensity scores were obtained at each dilution presented to the panel. The concentration of the odour at each dilution was calculated as the sample concentration divided by the dilution factor.

5.4.2 Model selection and estimation of model parameters

Depending on the suitability, various psychophysical functions were chosen to demonstrate the relationship between perceived intensity and odour concentration for the samples drawn from the landfill site.

Model 1: This is based on the Weber-Fechner law, which states that equal ratio changes in olfactory sensation differences correspond to equal changes in the stimulus magnitude.

$$I = k_1 \log C + k_2 \qquad \textbf{-(5.3)}$$

where I stands for a perceived intensity and C stands for the corresponding threshold odour concentration, and k_1 and k_2 are constants.

Model 2: This is based on Steven's psychophysical power law (described in section 5.3) and implies that equal ratio changes in sensation magnitude correspond to equal changes in the stimulus magnitude.

$$I = k_1 (C)^{k_2} \qquad \textbf{-(5.4)}$$

where k_1 is a constant of proportionality and k_2 depends on the type of odorant [60,61].

Model 3: Beidler's Model, as described in section 5.3, relates the response magnitude with concentration as follows,

$$I = \frac{k_1 k_2 C}{1 + k_2 C} \qquad \textbf{-(5.5)}$$

Model 4: Based on Laffort's expression (described in section 5.3) this Model can be described as,

$$I = \left(\frac{C}{1 + k_2 C} \right)^{k_1} \qquad \textbf{-(5.6)}$$

5.4.3 Parameter Estimation Method

The nonlinear ***Levenburg-Marquardt*** parameter estimation method [65,108] was used to obtain the parameters in each of the four models. In this method, we usually define a merit function chi-squared (χ^2), and determine the best-fit parameters by its minimisation. The parameters are iteratively adjusted, due to nonlinear dependences, to minimise chi-squared in order to achieve a global minimum. We start with a set of trial values for the parameters to be estimated, which are gradually improved and the procedure is then repeated until χ^2 effectively stops decreasing. A sensitivity matrix was derived for the four models for the odour intensity function with respect to the parameters k_1 and k_2.

The ***sensitivity matrix*** can be written as:

For *Model 1*:

$$\frac{\partial I}{\partial k_1} = \log C$$

$$\frac{\partial I}{\partial k_2} = 1.0 \qquad \textbf{-(5.7)}$$

For *Model 2*:

$$\frac{\partial I}{\partial k_1} = C^{k_2}$$

$$\frac{\partial I}{\partial k_2} = k_1 C^{k_2} \cdot \log C \qquad \textbf{-(5.8)}$$

For *Model 3*:

$$\frac{\partial I}{\partial k_1} = \frac{k_2 C}{(1 + k_2 C)}$$

$$\frac{\partial I}{\partial k_2} = \frac{k_1 C}{(1 + k_2 C)^2} \qquad \textbf{-(5.9)}$$

For *Model 4*:

$$\frac{\partial I}{\partial k_1} = \left(\frac{C}{1+k_2 C}\right)^{k_1} \cdot \log\left(\frac{C}{1+k_2 C}\right)$$

$$\frac{\partial I}{\partial k_2} = -k_1 \cdot \left(\frac{C}{1+k_2 C}\right)^{(k_1+1)} \qquad \textbf{-(5. 10)}$$

5.4.4 Evaluation of the four models[109]

Inference about the nonlinear regression parameters require the evaluation of the following statistical parameters:

1. The minimized chi-squared function, $\boldsymbol{\chi^2}$, which is the least-squares measure of fit (the smallest χ^2 gives the best model). The χ^2 minimization is a useful means for estimating parameters even if the measurement errors are not normally distributed.
2. The *uncertainties* associated with the estimate of each parameter, formally termed as the ***standard error*** σ. These are the square-root of the error term covariance matrix C_{ij} of the fit. The closer this value is to zero, the better the fit.

When the method used to estimate the parameters is χ^2 minimization, there is a natural choice for the shape of the confidence intervals. If the confidence level and the degrees of freedom are known the confidence interval ∂a for each of the fitted parameters can be computed as:

$$\partial a_1 \cong \pm\sqrt{\Delta\chi^2_\upsilon}\sqrt{C_{11}} \qquad \textbf{-(5.11)}$$

where $\Delta\chi^2_\nu$ are given in tables as functions of confidence levels and degrees of freedom (ν). This relation is approximate and holds good when

- The fit is good.
- The error terms *(noise)* in the nonlinear regression model are normally distributed and
- The sample size is large.

5.4.5 Estimation of the noise

We know that,

$$\chi^2 = \frac{\sum (y - \hat{y})^2}{\sigma^2}, \qquad \textbf{-(5.12)}$$

$$\Rightarrow \chi^2 \propto \frac{1}{\sigma^2}$$

Hence estimate of σ^2 is important in all model fitting technique that use χ^2 estimates. In order to estimate the standard deviation of odour intensity measurement data *(reported both as an integer category and a fraction in case of odour intensity measurement and reported only as an integer in the community survey reports)*, we assume:

$$E(\sigma^2) = \int \rho(x) \cdot (x - \bar{x})^2 \cdot dx \Big/ \int \rho(x) \cdot dx \qquad \textbf{-(5.13)}$$

$$\Rightarrow E(\sigma^2) = \int_{\bar{x}-1/2}^{\bar{x}+1/2} (x - \bar{x})^2 \cdot dx \qquad \textbf{-(5.14)}$$

$$\Rightarrow E(\sigma^2) = \frac{x^3}{3}\Bigg|_{-1/2}^{1/2} = \frac{1}{12} \qquad \textbf{-(5.15)}$$

When the sample size is large, the Gaussian distribution can be approximated as a Poisson's and the mean is approximately equal to the variance. Thus,

$E(\sigma^2) \approx \sigma^2$

Thus, the value of σ is $1/\sqrt{12} = 0.288$. Now, each reported intensity level was an arithmetic mean of n number of reported data, each of which was an integer. The actual noise (population) was:

$$noise = \frac{\sigma}{\sqrt{n}}$$

When $n = 4$, $\sigma = 0.144$ and $n = 6$, $\sigma = 0.1175$.

5.5 Results and Discussion

Table 5.2 shows the mean odour concentration of various odour samples from the municipal solid waste landfill site. Table 5.3 gives the details of the olfactometry analysis carried out for finding out the perceived odour intensities of various dilutions of the samples when presented to the trained panellists. Parameter estimation results are given in Table 5.4 where the uncertainties and confidence intervals of each parameter are presented for each of the four models (described in section *5.4.2*) for various

Table 5.2 Sampling details.

Date	**Source of sample**	**Sample index**	**Collection time**	**Odour concentration (ou/m^3)**
10/11/97	Knock-out-pots	KOP C	12:00	147,520
12/11/97	Knock-out-pots	KOP C (2)	14:15	107,648
12/11/97	Knock-out-pots	KOP W (3)	13:00	801,920
10/11/97	Horizontal wells	W28H (1)	14:00	1,155,019
12/11/97	Horizontal wells	W1H (1)	12:30	641,024
10/11/97	Waste surfaces*	Filling (1)	13:10	1355
12/11/97	Waste surfaces*	Filling (3)	11:05	937
24/11/97	Waste surfaces#	Day 3 1a outlet	12:17-12:22	148
24/11/97	Waste surfaces#	Day 3 2b outlet	12:38-12:41	273
24/11/97	Waste surfaces#	Day 3 3b outlet	12:54-12:57	142

* Samples collected by *cover sheet* method.
\# Samples collected using Lindvall Hood.

samples. Models are ranked according to their performance in the nonlinear least squares fit and rated with their respective values of χ^2(see Table 5.4). **Error! Reference source not found.** gives the ranges of residual intensities (defined as: *Residual Intensity = Predicted Intensity-Measured Intensity*) with respect to the four models tested.

Figure 5.1 gives the example of how the measured odour intensity varies with the odour concentration for the odour sampled from the knock-out-pot KOPC with respect to each of the four models. The performance of Model 1 was best with a rank of 1 out of 4 based on the estimate of minimum χ^2 and quite low values of uncertainties on k_1(=0.04) and k_2(=0.05). The corresponding 95% confidence intervals were worked out with a χ^2 estimate for each of the parameters. The widths of the interval with regard to both model parameters look quite narrow. In Figure 5.2 residual intensities are plotted against measured odour concentration. It did not show any serious departures from the model assumptions with the residuals ranging from –0.4 to +0.2. Models 2 and 3 had a similar regression trend with the residuals ranging from 0.36 to 0.7 (Model 2) and –0.4 to 0.6 (Model 3), however both of them showed higher values of χ^2 than Model 1. Model 4 had a larger value of χ^2=10.09 and was preferentially discarded. Thus it could be concluded that Model 1 (based on the Weber-Fechner law) and the corresponding regression function could be accepted for the intensity analysis of the odour sample from KOPC.

Similarly, for another sample from the knock-out-pots KOPC2 Model 2 performed best, while Model 1 was ranked second and for KOPW3 again Model 1 did best while Model 2 was ranked 4. It could be concluded that for odour samples from various knock-out-pots of the landfill site Model 1 could demonstrate the intensity-concentration relationship best.

The next set of samples tested were from the filling areas of freshly tipped wastes. Model 1 and Model 2 both performed well with close values of χ^2 and low uncertainties on the estimated parameters. The levels of odour and the corresponding intensities for the samples from freshly tipped wastes could be best related with Model 1 and Model 2 (based on Steven's Power law). The samples taken from various horizontal wells showed a slightly different trend and in this case Model 4 (based on Laffort's model) performed best, predicting the lowest values of χ^2. However, the estimated χ^2 values of Model 3 (based on Beidler's equation) were very near to those estimated by Model 4. For the sample w1h1, Model 3 had a χ^2 value of 2.2 with uncertainties estimated on k_1 and k_2 being 0.002 and 0.001 respectively, and a precise and narrower confidence interval as well. On the other hand, Model 4 had a lower χ^2 value of 1.76 though, the uncertainty on k_1 was 8.3 and the corresponding confidence

interval was quite wide. It could be inferred that Model 3 and 4 both correlate the intensity with odour concentration equally capably for samples from the horizontal wells. Figure 5.6 gives a picture of the overall performance of all the models based on the goodness of fit.

It should be noted that the assumptions behind equation 5.11 were not quite applicable in case of our study since the sample size was restricted by the number of dilution levels of the PREC (Project Research Co., Amsterdam) olfactometer (ranging from 1 to 14) used for all the experiments. A more rigorous set of validation experiments was not possible with the resources available, although these initial results are quite encouraging.

5.6 Conclusion

The analysis of perception of odour samples from a municipal solid waste landfill site was done using various well-known psychophysical models and respective parameters for each of the models were estimated and the overall performance of the model was tested against sets of data from the olfactometry analysis. The following inferences were drawn:

- Any one model, based on one of the well-known psychophysical laws could describe the relationship between odour intensity and odour concentration (ou/m^3) and based on it a theoretical model could be developed with estimated regression parameters.
- *The Weber-Fechner law performed better than Power Law since the scaling technique used was category estimation and not ratio scaling*. However, these two laws, which were supposed to be the most widely used laws did not always perform the best for all types of odour samples from various sources of the landfill site. In the above analysis, Model 1(based on Weber-Fechner law) was ranked 1 in case of 5 samples out of 9 and it has been found more representative of the *less intense* odour samples.
- Depending on the nature of the odour sample and its range of intensity levels Beidler's and Laffort's models did fit the data quite well on certain occasions (see Table 5.6). Model 3 (based on Beidler's equation) scored 2 in the ranking scale on 5

occasions out of 9 occasions (see Table 5.6) with extremely low uncertainties on both k_1 and k_2. *Laffort's* equation has represented the intensity-concentration relationship better for comparatively *more intense* odour samples.

- In case of the particular samples analysed it has been found that frequency of intensity scales reported have been mostly in the lower range of intensity scales (*refer* **Error! Reference source not found.**). This was not quite useful for using the results as calibrations for higher intensity scales and the concentrations obtained from those relationships were fictitious for the higher intensity scales (refer Table 6.5).
- In cases where the analysis gives rise to situations where it could be difficult to discriminate one model with respect another and two models are quite close after analysing their performance, it is recommended to compare the real intensity data reported by the community sniffers with the intensities obtained from the selected models in conjunction with dispersion modelling results. For example, the odour concentration values obtained by a suitable dispersion model at the receptors (locations of the community sniffers) could be compared with the odour concentration data that have been reduced from the intensity data reported by the community sniffers using one of the models that had been already discriminated by the above model selection procedure. In Chapter 6 this issue will be discussed and all the models will be used for the particular category intensity scale which has been used for the community sniffers. An average value of each of the parameters for respective models (those which have already been estimated from the 9 different samples from the MSW landfill site), may be a first guess to start with.
- In order to estimate the performance of a particular model to describe the relationship between odour intensity and odour concentration for various sources within the landfill, more research and measurements are necessary.

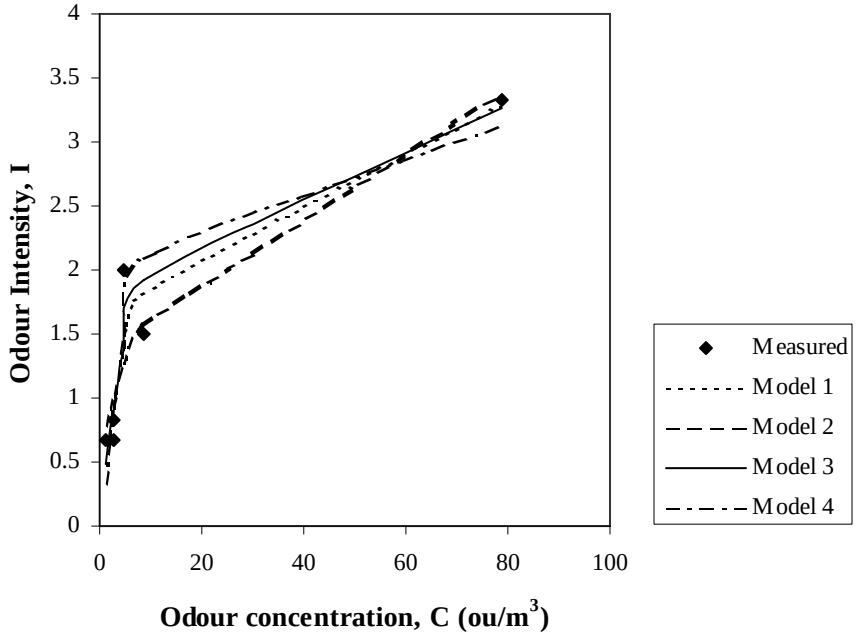


Figure 5.1 Comparison of the measured data with models for the KOPC.

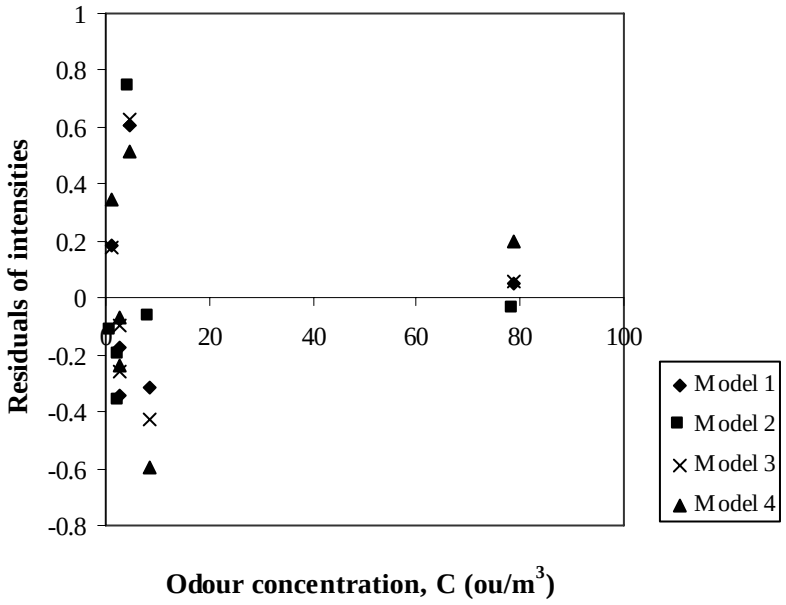


Figure 5.2 Plot of residual intensities for the four models for KOPC.

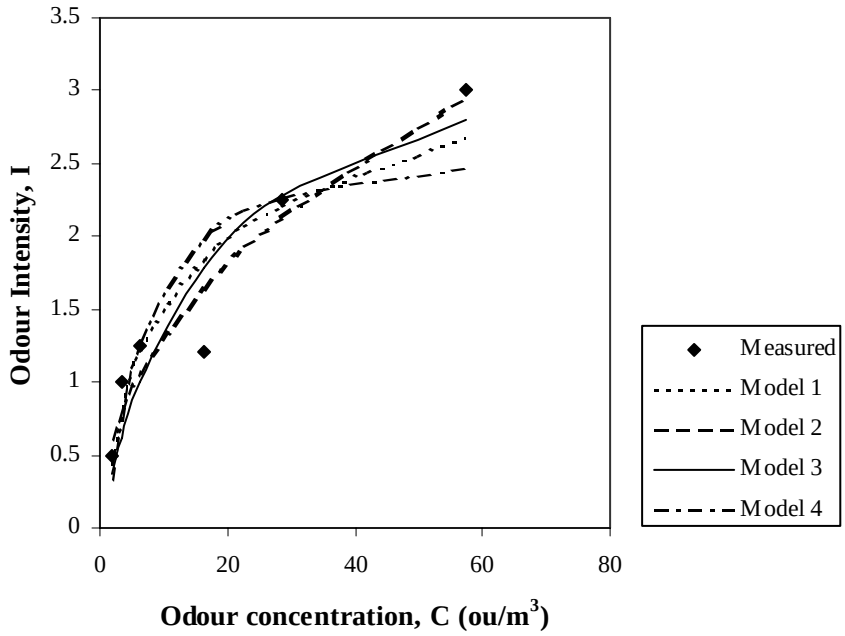


Figure 5.3 Comparison of the measured data with models for the KOPC2.

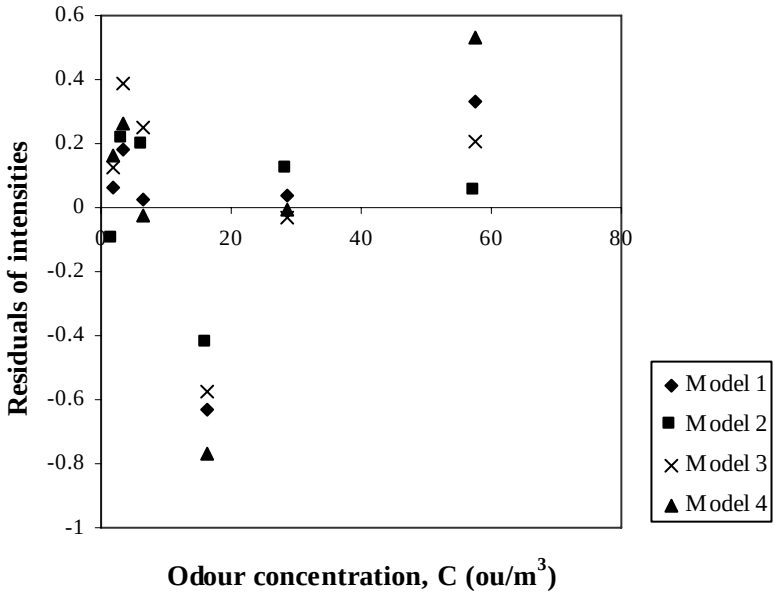


Figure 5.4 Plot of residual intensities for the four models for KOPC2.

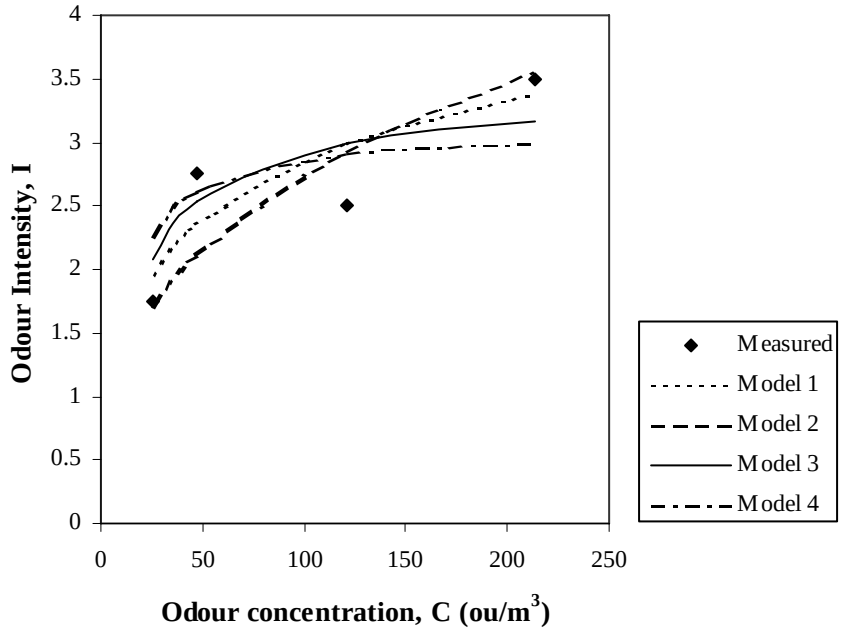


Figure 5.5 Comparison of the measured data with models for the KOPW3.

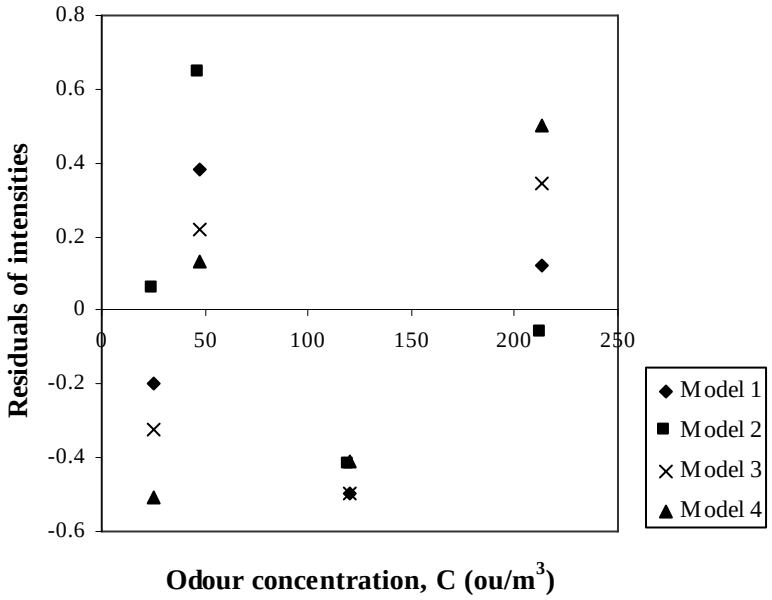


Figure 5.6 Plot of residual intensities for the four models for KOPW3.

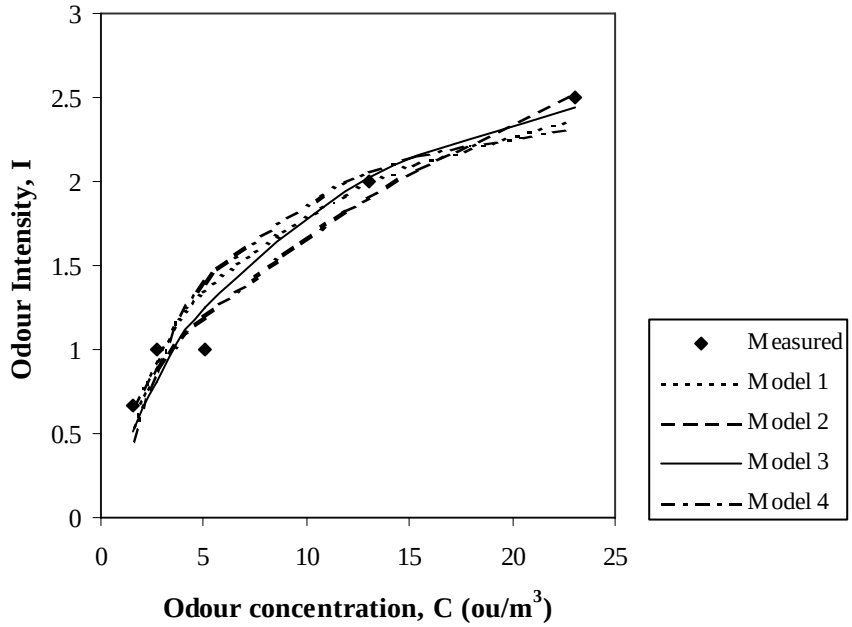


Figure 5.7 Comparison of the measured data with models for the Filling 1a.

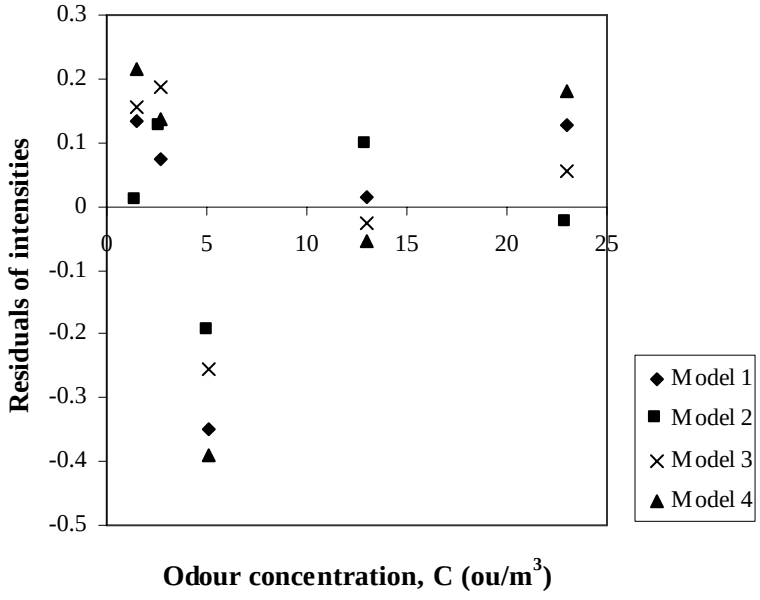


Figure 5.8 Plot of residual intensities for the four models for Filling 1a.

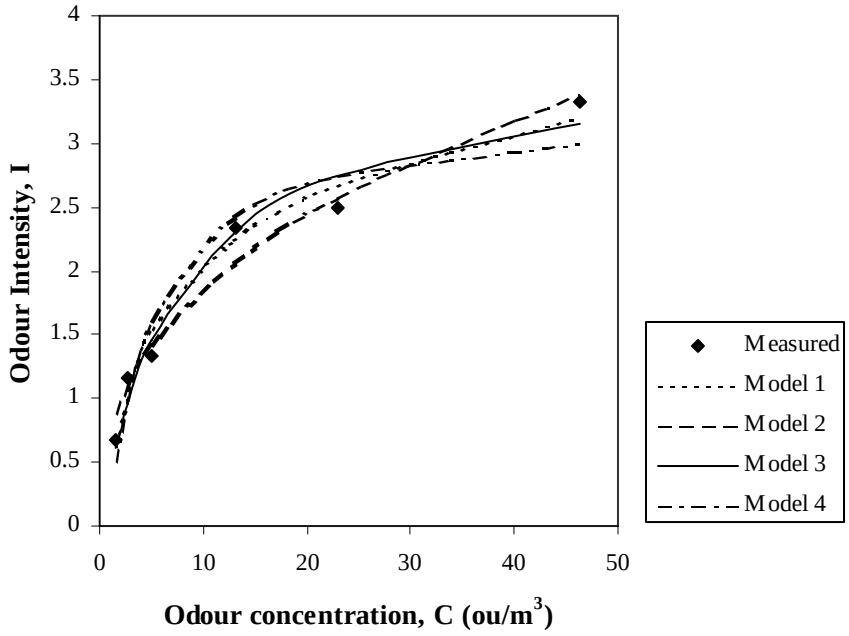


Figure 5.9 Comparison of the measured data with models for the Filling 1b.

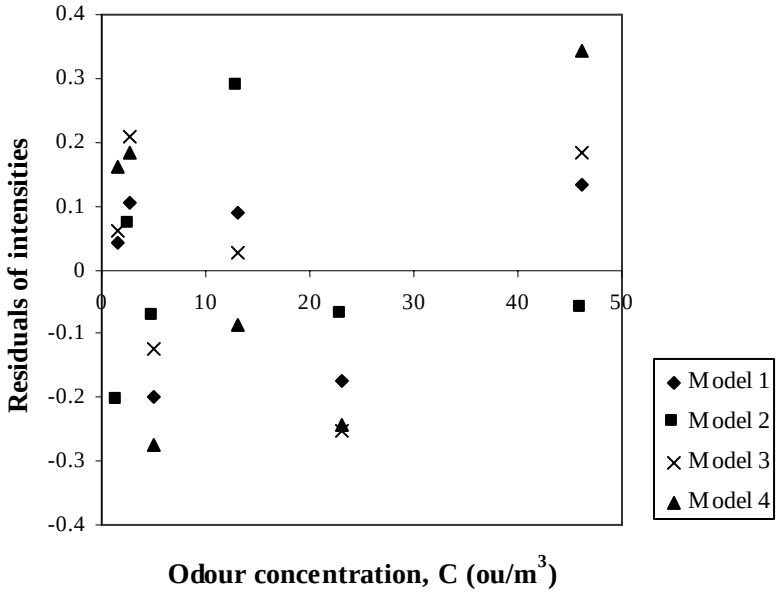


Figure 5.10 Plot of residual intensities for the four models for Filling 1b.

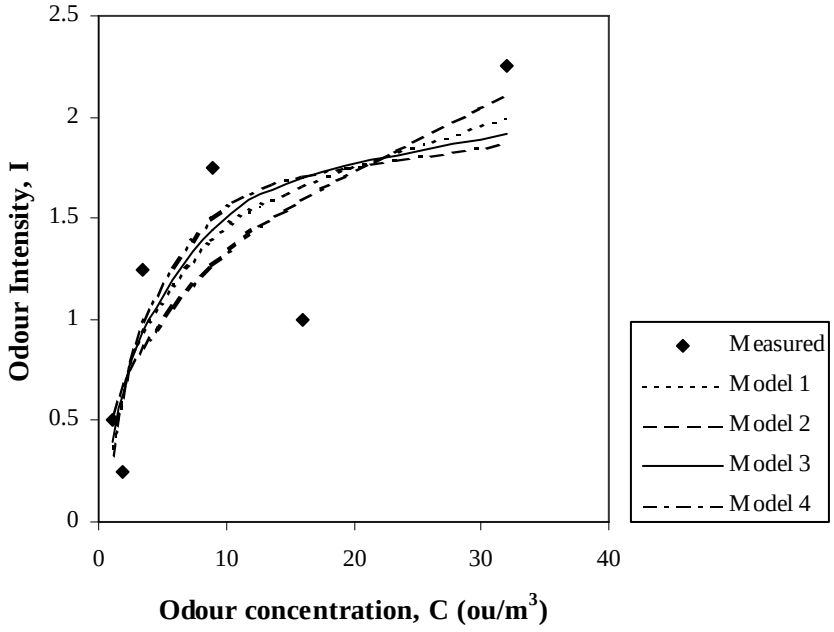


Figure 5.11 Comparison of the measured data with models for the Filling 3.

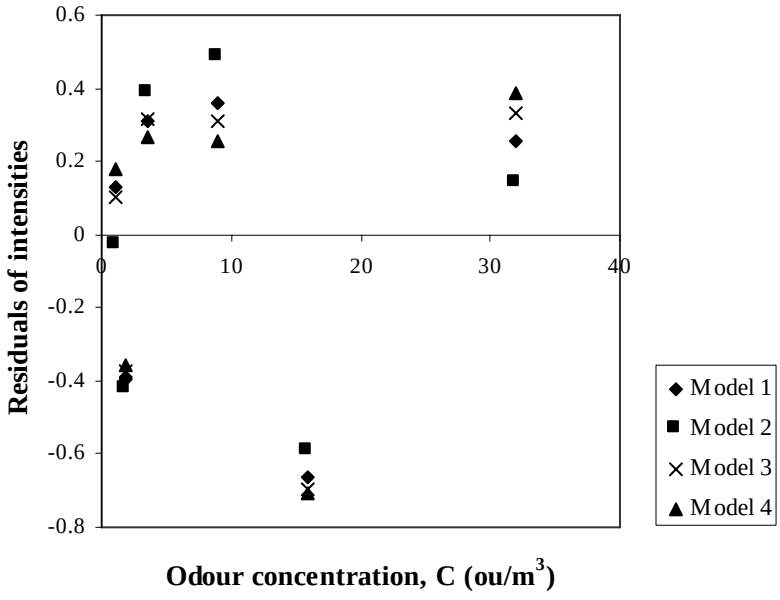


Figure 5.12 Plot of residual intensities for the four models for Filling 3.

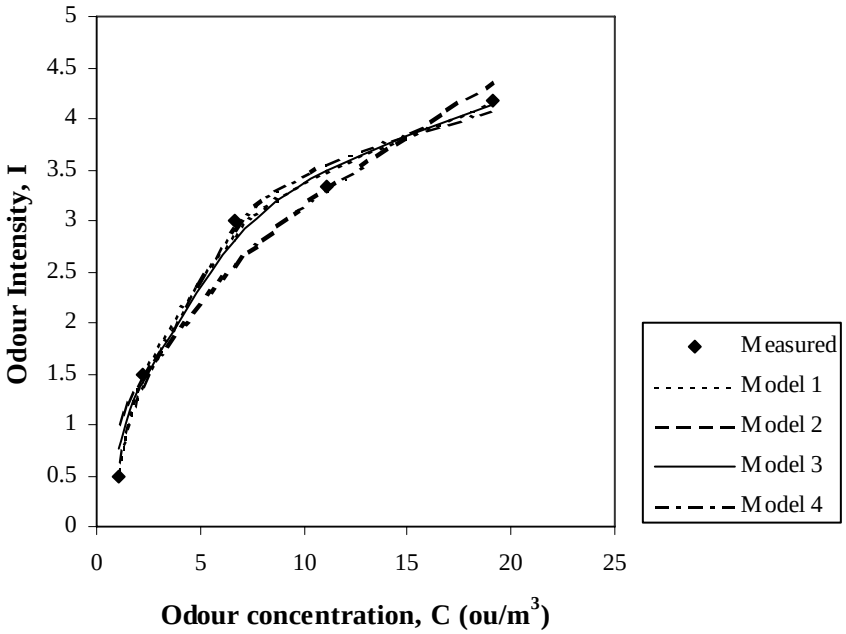


Figure 5.13 Comparison of the measured data with models for the Day3 2b.

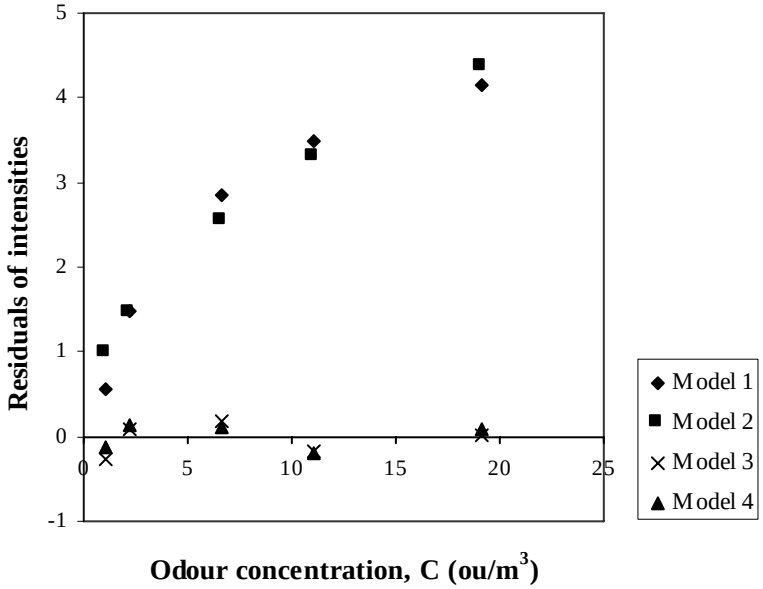


Figure 5.14 Plot of residual intensities for the four models for Day3 2b.

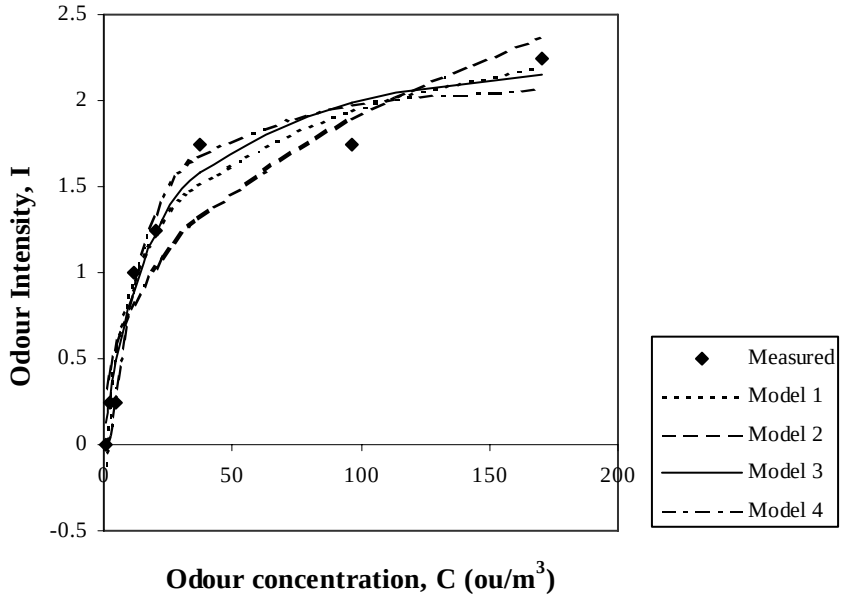


Figure 5.15 Comparison of the measured data with models for the W1H1.

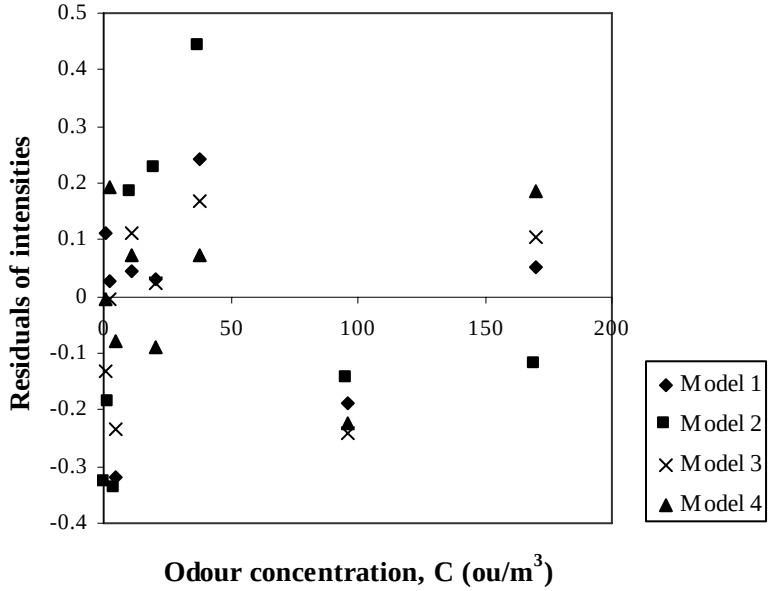


Figure 5.16 Plot of residual intensities for the four models for W1h1.

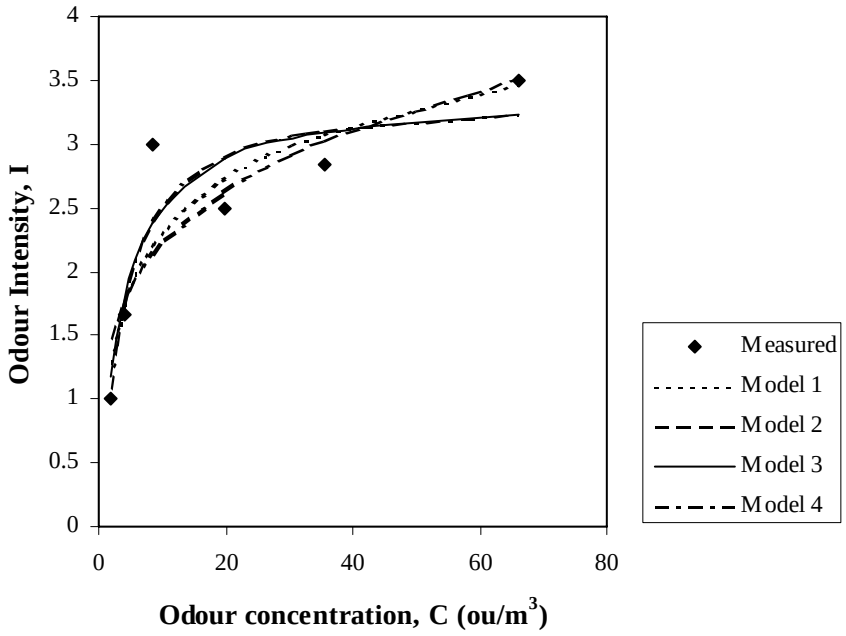


Figure 5.17 Comparison of the measured data with models for the W28H1.

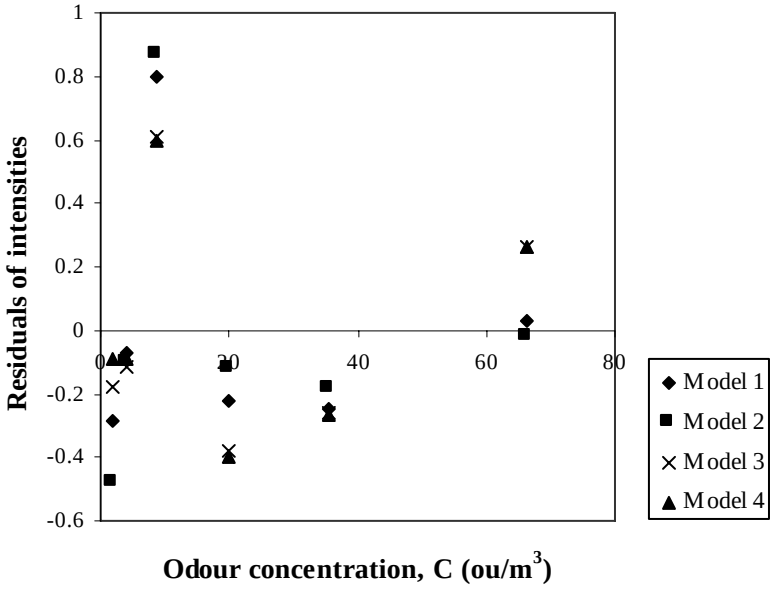


Figure 5.18 Plot of residual intensities for the four models for W28H1.

Table 5.3 Odour intensities (I) and corresponding odour concentrations (C_i).

Samples														
	Step	2	3	4	5	6	7	8	9	10	11	12	13	14
	D_i	7.7	14.3	29.3	58.8	103.9	265.9	496.1	884.4	2053	4384	9093	19119	38191
KOP C	C_i			78.669			8.668	4.646	2.606	1.185				
	I			3.33			1.5	2.0	0.83	0.67				
KOP C (2)	C_i			57.4	28.605	16.188	6.325	3.39	1.901					
	I			3	2.25	2.5	1.25	1.0	0.5					
KOP W (3)	C_i				213.1	120.6	47.123	25.257	14.16	6.10	2.86	1.378		
	I				3.5	2.5	2.75	1.75	2.0	1.0	0.25	0.0		
W28H (1)	C_i						66.21	35.5	19.9	8.57	4.01	1.936	0.921	0.461
	I						3.5	2.83	2.5	3.0	1.167	1.0	1.0	0.167
W1H (1)	C_i				170.34	96.4	37.67	20.19	11.32	4.88	2.284	1.10		
	I				2.25	1.75	1.75	1.25	1.0	0.25	0.25	0.0		
Filling (1)	C_i				23.04	13.04	5.1	2.73	1.53	0.66	0.31	0.15		
	I				2.5	2.0	1.0	1.0	0.67	0.16	0.0	0.0		
Filling (3)	C_i			31.97	15.93	9.01	3.52	1.88	1.06	0.456	0.214			
	I			2.25	1.0	1.75	1.25	0.25	0.5	0.0	0.0			

Table 5.3 (contd.)

Samples														
	Step	2	3	4	5	6	7	8	9	10	11	12	13	14
	D_i	7.7	14.3	29.3	58.8	103.9	265.9	496.1	884.4	2053	4384	9093	19119	38191
Day 3 1a	C_i	19.22	10.3	5.99	3.6	1.19	0.57							
	I	4.0	4.0	3.50	2.67	1.33	0.33							
Day 3 2b	C_i		19.12	11.07	6.65	2.20	1.05	0.56						
	I		4.16	3.33	3.0	1.5	0.5	0.67						
Day 3 3b	C_i	18.43	9.93	5.75	3.45	1.14	0.54							
	I	4.5	3.83	3.5	2.83	1.33	0.5							

C_i has got the unit of ou/m^3, D_i and I are dimensionless.

Table 5.4 Results of Parameter Estimation.

Sample	Model	k_1	k_2	d.f.	χ^2	$\rho(\chi^2)$	Uncertainties on		Model Rank	95% Confidence limits (k_1)		95% Confidence limits (k_2)	
							k_1	k_2		Lower	Upper	Lower	Upper
KOPC	1	0.372	1.536	4	7.804	0.90	0.047	0.051	1	-0.081	0.825	1.045	2.027
	2	0.741	0.347	4	8.898	0.963	0.016	0.006	3	0.586	0.896	0.293	0.402
	3	3.583	0.134	4	8.238	0.951	0.010	0.003	2	0.385	0.574	0.101	0.167
	4	2.800	0.652	4	10.095	0.961	0.382	0.031	4	-0.906	6.506	0.350	0.955
KOPC2	1	0.018	1.508	4	6.597	0.841	0.084	0.073	2	-0.796	0.833	0.798	2.218
	2	0.447	0.466	4	3.506	0.523	0.018	0.011	1	0.271	0.622	0.355	0.577
	3	3.598	0.061	4	7.246	0.876	0.004	0.002	3	0.180	0.257	0.045	0.076
	4	4.063	0.783	4	11.798	0.981	1.245	0.046	4	-8	16.143	0.335	1.231
KOPW3	1	-0.212	1.542	6	8.404	0.79	0.049	0.032	1	-0.835	0.411	1.132	1.952
	2	0.549	0.349	6	19.915	0.997	0.012	0.005	4	0.389	0.708	0.287	0.411
	3	3.398	0.062	6	9.999	0.890	0.002	0.001	3	0	0.240	0.051	0.073
	4	7.124	0.852	6	9.175	0.912	2.545	0.041	2	-25.45	39.703	0.322	1.383
Filling 1a	1	0.244	1.562	3	1.945	0.416	0.097	0.112	3	-0.530	1.019	0.660	2.463

Table 5.4 (contd.)

Sample	Model	k_1	k_2	d.f.	χ^2	$\rho(\chi^2)$	Uncertainties on		Model Rank	95% Confidence limits (k_1)		95% Confidence limits (k_2)	
							k_1	k_2		Lower	Upper	Lower	Upper
	2	0.532	0.496	3	0.759	0.140	0.028	0.020	1	0.304	0.761	0.339	0.653
	3	3.343	0.118	3	1.535	0.789	0.018	0.008	2	0.253	0.535	0.052	0.183
	4	2.706	0.689	3	3.041	0.614	0.743	0.053	4	-3.256	8.667	0.266	1.113
Filling1b	1	0.301	1.741	4	1.310	0.140	0.074	0.070	1	-0.414	1.016	1.064	2.418
	2	0.734	0.399	4	1.715	0.212	0.022	0.009	2	0.520	0.949	0.311	0.488
	3	3.679	0.129	4	1.937	0.550	0.014	0.005	3	0.340	0.608	0.080	0.178
	4	2.651	0.640	4	3.842	0.572	0.504	0.047	4	-2.233	7.535	0.186	1.094
Filling 3	1	0.342	1.096	4	10.858	0.971	0.058	0.065	1	-0.219	0.904	0.470	1.722
	2	0.519	0.405	4	11.250	0.976	0.026	0.017	2	0.271	0.241	0.767	0.569
	3	2.208	0.208	4	11.323	0.887	0.038	0.023	4	0.091	0.829	-0.014	0.430
	4	2.212	0.723	4	11.317	0.976	0.634	0.048	3	-3.937	8.361	0.253	1.193
Day3 2b	1	0.488	2.863	3	0.585	0.100	0.078	0.096	1	-0.138	1.114	2.094	3.631
	2	0.970	0.509	3	5.930	0.885	0.029	0.012	4	0.734	1.206	0.416	0.603
	3	5.545	0.154	3	1.784	0.653	0.034	0.009	3	0.585	1.124	0.080	0.228
	4	1.637	0.372	3	1.159	0.237	0.352	0.076	2	-1.186	4.460	-0.238	0.982

Table 5.4 (contd.)

Sample	Model	k_1	k_2	d.f.	χ^2	$\rho(\chi^2)$	Uncertainties on		Model Rank	95% Confidence limits (k_1)		95% Confidence limits (k_2)	
							k_1	k_2		Lower	Upper	Lower	Upper
W1h1	1	-0.158	1.057	6	2.598	0.142	0.044	0.031	3	-0.717	0.401	0.665	1.448
	2	0.316	0.392	6	6.846	0.664	0.012	0.009	4	0.157	0.475	0.280	0.505
	3	2.387	0.052	6	2.200	0.099	0.002	0.001	2	0.100	0.149	0.039	0.065
	4	9.408	0.920	6	1.766	0.99	8.297	0.049	1	-96.79	115.60	0.293	1.547
W28h1	1	0.877	1.423	4	10.034	0.889	0.089	0.072	3	0.016	1.737	0.723	2.122
	2	1.261	0.245	4	12.594	0.960	0.035	0.008	4	0.924	1.596	0.168	0.321
	3	3.413	0.272	4	8.459	0.986	0.057	0.020	2	0.372	1.486	0.080	0.465
	4	1.433	0.426	4	8.114	0.912	0.473	0.115	1	-3.154	-0.691	6.020	1.543

Table 5.5 Range of residual intensities for various models.

Samples	**Range of residuals**			
	Model 1	**Model 2**	**Model 3**	**Model 4**
KOPC	-0.34 – 0.60	-0.36 – 0.73	-0.42 – 0.62	-0.59 – 0.51
KOPC2	-0.63 – 0.32	-0.42 – 0.19	-0.57 – 0.38	-0.77 – 0.53
KOPW3	-0.49 – 0.43	-0.61 – 0.64	-0.49 – 0.41	-0.50 – 0.50
Filling 1a	-0.35 – 0.13	-0.19 – 0.12	-0.25 – 0.18	-0.38 – 0.21
Filling 1b	-0.19 – 0.13	-0.20 – 0.28	-0.25 – 0.21	-0.27 – 0.18
Filling 3	-0.66 – 0.36	-0.59 – 0.48	-0.69 – 0.33	-0.70 – 0.38
Day3 2b	-0.14 – 0.15	-0.49 – 0.45	-0.27 – 0.19	-0.20 – 0.13
W1h1	-0.32 – 0.24	-0.34 – 0.44	-0.24 – 0.16	-0.18 – 0.19
W28h1	-0.28 – 0.79	-0.48 – 0.86	-0.26 – 0.61	-0.39 – 0.59

Table 5.6 Frequency of the range of intensity levels.

Range of intensity scales	$0 < I \leq 1.0$	$1.0 < I \leq 2.0$	$2.0 < I \leq 3.0$	$3.0 < I \leq 4.0$	$4.0 < I \leq 5.0$
Frequency	29	15	14	7	2

Table 5.7 Overall model performance.

Rank	**Model 1**	**Model 2**	**Model 3**	**Model 4**
1	5	2	0	2
2	1	2	4	2
3	3	1	4	1
4	0	5	1	4

Chapter 6

6. Results and Discussion

This Chapter attempts to correlate the predictions of the atmospheric dispersion modelling with the community odour survey records to analyse the potential of the test case MSW landfill site to have an impact in the surrounding community.

6.1 Introduction

In this Chapter an effort has been given to correlate the results of Chapters 3,4 and 5 and analyse the overall scenario of the odour impact within the surrounding community of the MSW landfill site. Two schemes have been tested separately:

Community modelling:

A number of sniffers have been selected to participate in the year-round odour survey programme, organised by the International Ecotechnology Research Centre *(IERC)*, Cranfield University, Cranfield, UK.

- All the positive records, reported by the community sniffers have been analysed and the consistency of each sniffer in terms of intensity scaling has been judged.
- Each odour survey record reporting odour has been compared with the results of the predictive dispersion model. Separate intensity-concentration plots have been fitted for each of the sniffers whose reports have been found logically consistent with regard to the intensity scaling.

Refined Modelling:

Refined modelling will be used to do some case studies with the model, which has been already validated with the community modelling. Further, the case studies will form a basis to develop guidelines for the ***separation distances*** of the landfill site from the surrounding community. In this scheme a Cartesian receptor grid (4.0 km x 3.5 km) with 100 m grid spacing has been used to study the impact on the surrounding area.

- In order to design the overall emission inventory for the total MSW landfill site the *specific emission rates* for the area sources have been adapted from the results of Chapter 3. These specific emission rates are computed by the new micrometeorological model, based on the concept of footprint of scalar odour concentrations, as described in Chapter 3.
- The short-term mode of COMPLEX-I has been used to analyse most of the dispersion estimates.
- A set of average coefficients have been found out for all the equations based on the psychophysical laws, as described in Chapter 5, from various types of samples taken from different sources within the landfill and on different days. An attempt has been made to predict odour concentrations from these equations with the category scales of 1 to 7. This method has not been quite effective for quite a few situations especially for intensity scales greater than or equal to 4, in a scale of 1 to 7, though.

6.2 Model Validation

Each component of the overall OIM has been validated separately in the previous chapters. In this chapter we will make an attempt to validate the integrated model with community responses.

6.2.1 Emission assessment

This particular module has been validated in Chapter 3 (*see section 3.6*). Results of the new micrometeorological model have been validated with the Lindvall hood measurements.

6.2.2 Dispersion Modelling

This particular module has been validated in Chapter 4 (*see section 4.6.2*). The predictions of MPTER/COMPLEX-I have been compared with the odour concentrations predicted by UK-ADMS (version 1.5).

6.2.3 Analysis of Perception

The four models based on different psychophysical laws/functions have been fitted with the measured intensity-concentration data from the olfactometric measurements. A number of statistical parameters have been used to test the goodness of fit.

6.3 Community Modelling: Case studies with the MSW Landfill Site

This study was designed to identify the extent and nature of the neighbourhood odours attributable to the emissions from a local MSW landfill site. Reported odour would be correlated with the dispersion estimates, where possible. For this community "sniffers" from around the landfill site were selected, considering the history of complaints made to the County Council and an initial screening for the likelihood of maximum impacts based on the historic meteorological data (RAF Wyton's meteorological data for the year 1994 was used for some initial test cases). There was an odour survey programme designed by the International Ecotechnology Research Centre (IERC), Cranfield University, Cranfield, UK. The regular odour monitors have been chosen based on certain guidelines, as mentioned in [58], each of them has been tested with n-butanol with regard to their sensitivity to odour intensity, capacity of recognition, category scaling and reproducibility. Sniffer locations were specified at actual terrain elevations determined from the U.K Ordnance Survey **Landform PANORAMA** [3] Digitised Terrain Model (DTM).

Table 6.1 gives the details of the regular odour monitors. Figure 6.1 gives a picture of the locations of the monitors around, as well as the potential odour sources within the MSW landfill site.

Table 6.1 Details of the locations of all the community monitors.

Monitors ID	Address_2	GRE[4]	GRN[4]	Terrain elevation (metres)
M0001	Stewartby	50220	24250	50
M0002	Marston Mortaine	49960	24130	50
M0003	Wootton Green	49970	24350	41
M0004	Brogborough	49600	23780	48
M0005	Marston Mortaine	49980	24260	52
M0006	Brogborough	49630	23820	54
M0007	Kempston	50360	24670	60
M0008	Cranfield	49590	24260	79
M0009	Kempston	50200	24690	40
M0010	Cranfield	49610	24260	87
M0011	Cranfield	49500	24170	46
M0012	Wootton	50040	24490	113
M0013	Stewartby	50240	24200	50
M0014	Lidlington	49900	23880	48
M0015	Cranfield	49560	24320	112
M0016	Wootton Green	49970	24350	47
M0017	Cranfield	49550	24130	110
M0018	Cranfield	49670	24300	91
M0019	Cranfield	49410	24280	108
M0020	Wootton	50050	24530	40
M0021	Wootton	50040	24540	50
M0022	Stewartby	50180	24210	38
M0023	Kempston Hardwick	50320	24420	110
M0024	Stewartby	50220	24240	85

(Table 6.1 continued)

M0025	Wootton	50030	24530	108
M0026	Wootton	50090	24560	75
M0027	Lidlington	49870	23910	111
M0028	Kempston Hardwick	50270	24460	49
M0029	Kempston	50260	24680	50
M0030	Brogborough	49630	23830	49
M0031	Cranfield	49530	24210	111
M0032	Marston Moretaine	49970	24180	107
M0033	Cranfield	49500	24170	40
M0034	Lidlington	49890	23890	100
M0035	Cranfield	49600	24240	54
M0036	Upper Shelton	49900	24350	50
M0037	Kempston Hardwick	50270	24500	50
M0038	Stewartby	50220	24250	50
M0039	Upper Shelton	49900	24350	39
M0040	Wootton	50090	24560	48
M0041	Kempston	50360	24690	46
M0042	Stewartby	50310	24440	49

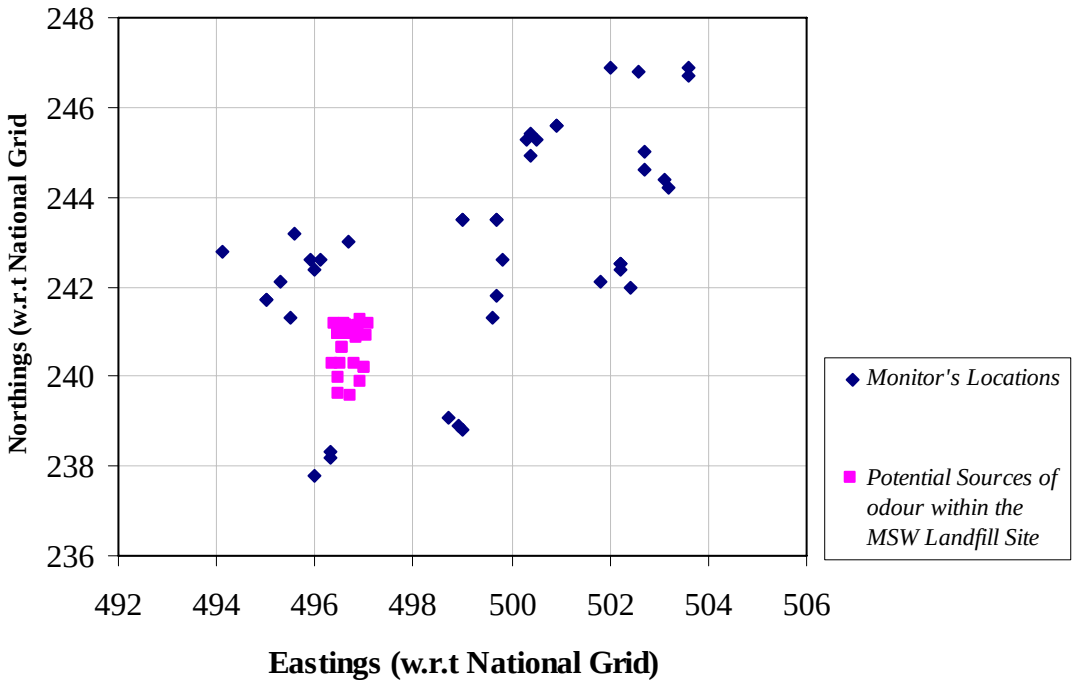


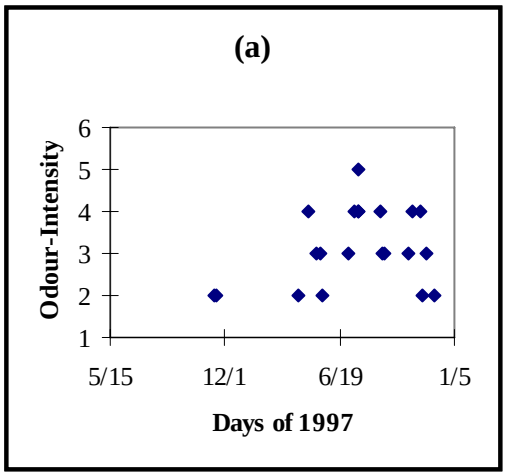
Figure 6.1 Map showing the potential sources of odour within the MSW Landfill site and locations of the community monitors around the site. Eastings and Northings are with reference to the Ordnance Survey National Grid.

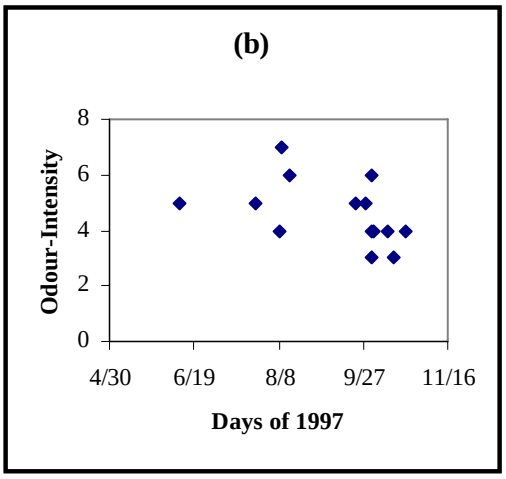
6.3.1 Actual positive records reported by regular community sniffers

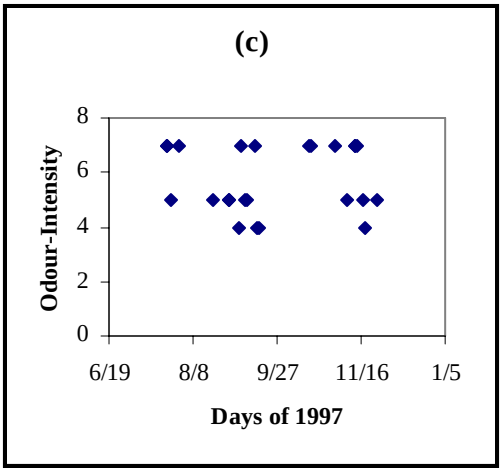
The community panel provides a more reliable tool than the complaints history to identify long-term trends in exposure to odours arising from the site. Odour records have been collected ever since 1994 and in Figure 6.2 all the positive records for the year 1997 have been noted for 10 of the 42 monitors. The format of the odour record is given in Table 6.2.

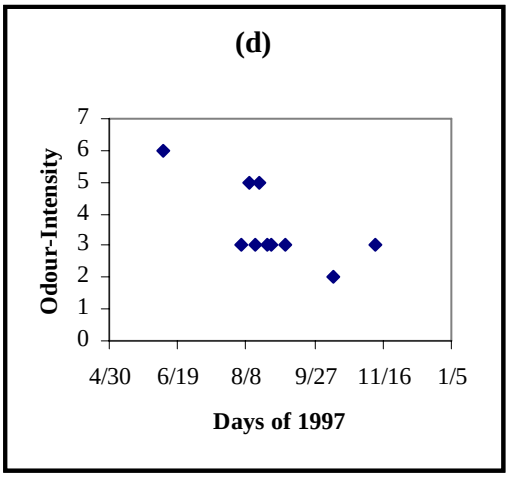
Table 6.2 A sample of positive records as sorted from all the records with a designed query. *GREs and GRNs are as per the National Grid [4].*

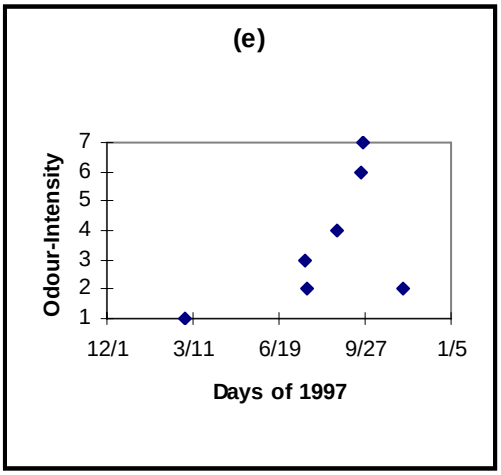
Monitor ID	GRE	GRN	Date	Time	Y/N	Origin	Scale	Certainty
M0001	50220	24250	09/04/97	09:00	Y	Landfill	2	1
M0001	50220	24250	24/04/97	11:30	Y	Landfill	4	1
M0001	50220	24250	09/05/97	10:20	Y	Landfill	3	1
M0001	50220	24250	17/05/97	10:30	Y	Landfill	3	1
M0001	50220	24250	21/05/97	08:30	Y	Landfill	2	1

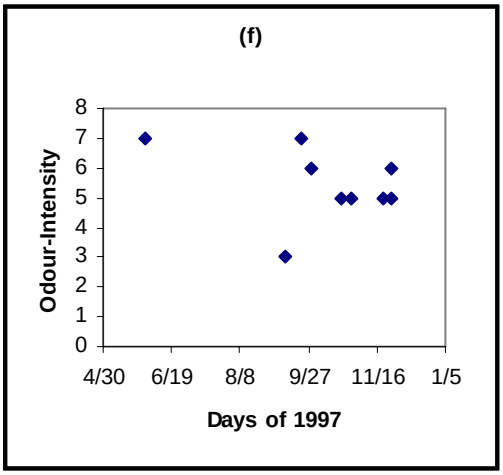

(a)
Odour-Intensity
6
5
4
3
2
1
5/15
12/1
6/19
1/5
Days of 1997


(b)
Odour-Intensity
8
6
4
2
0
4/30
6/19
8/8
9/27
11/16
Days of 1997


(c)
Odour-Intensity
8
6
4
2
0
6/19
8/8
9/27
11/16
1/5
Days of 1997


(d)
Odour-Intensity
7
6
5
4
3
2
1
0
4/30
6/19
8/8
9/27
11/16
1/5
Days of 1997


(e)
Odour-Intensity
7
6
5
4
3
2
1
12/1
3/11
6/19
9/27
1/5
Days of 1997


(f)
Odour-Intensity
8
7
6
5
4
3
2
1
0
4/30
6/19
8/8
9/27
11/16
1/5
Days of 1997

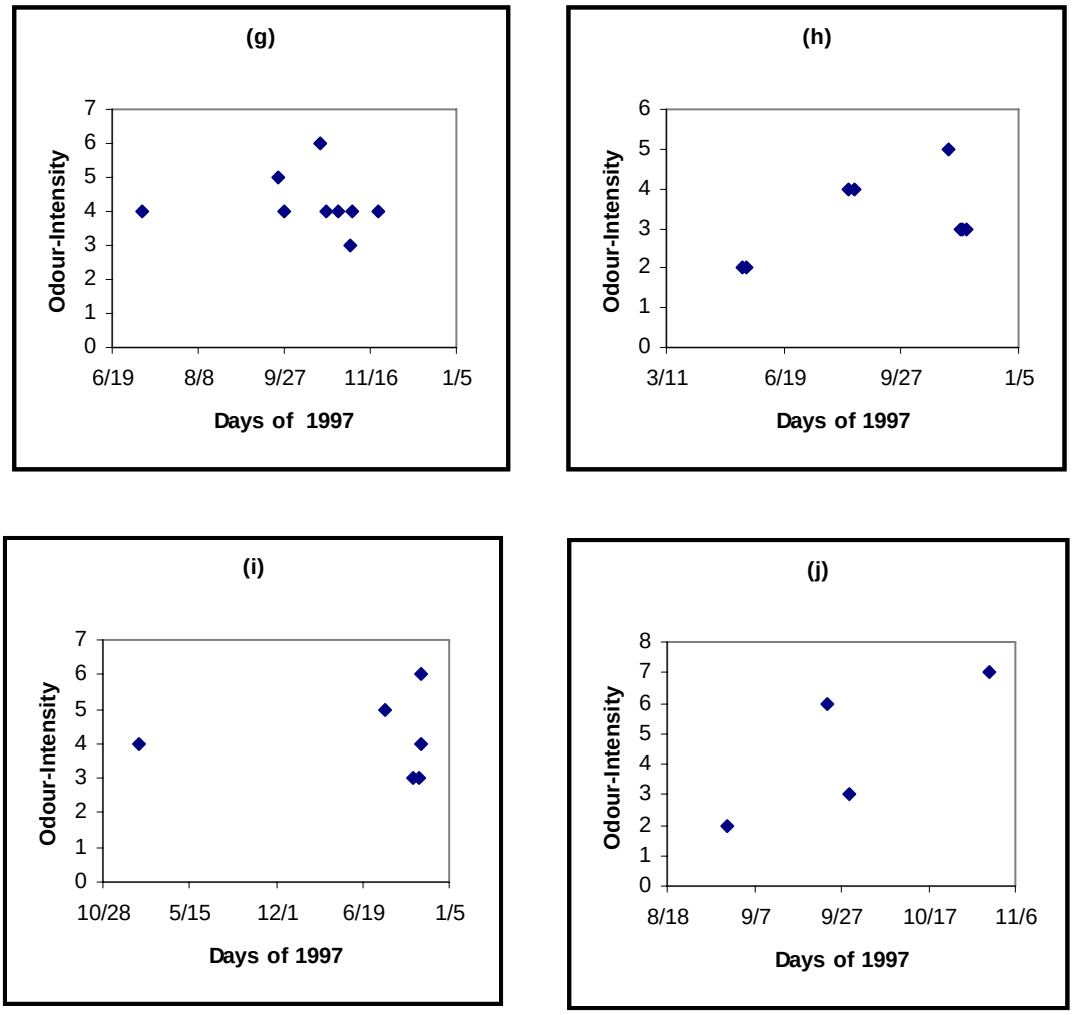


Figure 6.2 Positive records of complaints from the community sniffers in 1997.

(a) *M0001(50220,24250)* *(b)* *M0030(49630,23830)* *(c)* *M0032(49970,24180)*

(d) *M0026(50090,24560)* *(e)* *M0021(50040,24540)* *(f)* *M0039(49900,24350)*

(g) *M0028(50270,24460)* *(h)* *M0035(49600,24240)* *(i)* *M0008(49590,24260)*

(J) *M0024(50270,24460)*

*M**** represents the monitor identification number and the co-ordinates in () are with respect to the OS National Grid [1].*

In the next section these records are analysed with regard to the reported intensity scales and the dispersion estimates from the predictive model.

6.3.2 Analysis of Perception : Application of the Psychophysical Laws

It has been attempted to reduce the reported intensity scales (from odour monitors' reports) to an odour concentration value (ou/m^3) with each of the four expressions based on the four psychophysical laws, discussed in Chapter 5 in detail. Table 6.3 shows the estimated parameters (average) for these psychophysical expressions, as computed on the basis of the 11 samples from various locations within the landfill site. The intensity scales, as reported by the community sniffers, have been converted to odour concentration values (ou/m^3), as given in Table 6.4. The validated results are discussed in section 6.3.3 and 6.3.4. The parameters are quite sensitive to the intensity range of the samples. At higher intensity levels the concentrations predicted by the Beidler's model and Laffort's equation have been found erratic. The reason could be that the test samples were never more intense than 4 and we should really not attempt to go beyond tested ranges of intensity, rather extrapolation on these fitted models are quite critical. The source odours are, inherently, extremely strong, whereas the odour, as it reaches the location of the community monitors, is much less intense after dispersion during the course of its transmission from the original source. Human responses to these ranges of intensity are much different from the responses to the original highly intense samples off the landfill site. Here comes the difference between odour reported by trained panellists and the same by the common people living within the community. The trained panellists act like instruments and their reports giving intensity scales of odour have been found more consistent than the community sniffers.

Table 6.3 Average co-efficients obtained from the parameter estimation results, based on the four **Psychophysical Laws** described in Chapter 5.

Average Co-efficients	**Weber-Fechner Law**	**Power Law**	**Beidler's Model**	**Laffort's Equation**
k_1	0.252	0.674	3.462	3.782
k_2	1.592	0.401	0.132	0.673

6.3.3 Model predictions versus actual complaints

In this section the predictions of the short-term COMPLEX-I are compared with the actual complaint. We tried to correlate the reported intensity scales with the dispersion estimates at the same locations and the same time of the day with due meteorological considerations. The nature of the response has been found consistent, trends having been logarithmic for some of the monitors (matching closely with the profile of a Weber-Fechner logarithmic model). These trends are represented in Figure 6.3 to Figure 6.7. It should be noted that the coefficients of these trend lines are quite different from the k_1 and k_2 as given in Chapter 5. Monitors with ID M0001, M0008, M0024, M0030 and M0035 have been found quite consistent in reporting intensity scales when correlated with respect to the corresponding dispersion estimates. Table 6.5 gives some of the positive reports, the corresponding actual dispersion estimates and the intensity-concentration trends of the above mentioned monitors.

Table 6.4 The odour concentrations (in ou/m^3) against the odour intensity scales, as obtained by fitting average coefficients into the equations based on the four **Psychophysical Laws** from the parameter estimation procedure described in Chapter 5.

Intensity Scales	***Weber-Fechner Law***	***Power Law***	***Beidler's Model***	***Laffort's Equation***	***Standard Deviation***
1	2.95	2.67	3.07	3.06	0.18
2	12.52	15.06	10.35	6.27	3.72
3	53.19	41.40	49.15	13.35	17.96
4	225.94	84.85	-56.18	49.77	116.50
5	959.69	148.05	-24.58	-50.95	476.01
6	4076.37	233.31	-17.87	-19.85	2009.11
7	17314.67	342.71	-14.96	-13.29	8606.57

Table 6.5 Dispersion estimates corresponding to the intensity scales reported by some of the community monitors. Dispersion estimates are from the short-term COMPLEX-I output.

Monitor ID	Intensity scale (reported)	Dispersion estimates (Model output-ou/m^3)	Intensity-Concentration trend
M0001	2	1.125	y= 3.4039 Ln(x) + 1.4604
	3	1.725	
	4	2.059	
	5	2.750	
M0008	3	1.148	y= 1.9352 Ln(x) + 2.571
	4	2.393	
	5	4.046	
	6	4.850	
M0024	2	1.353	y= 3.5752 Ln(x) + 1.32
	3	1.413	
	5	2.872	
	6	3.651	
M0030	3	2.172	y= 4.1168 Ln(x) + 0.5124
	4	2.219	
	5	2.610	
	6	3.612	
	7	5.124	
M0035	2	1.805	y= 3.8477 Ln(x) + 0.2672
	3	1.996	
	4	2.214	
	5	3.612	
	4	2.214	

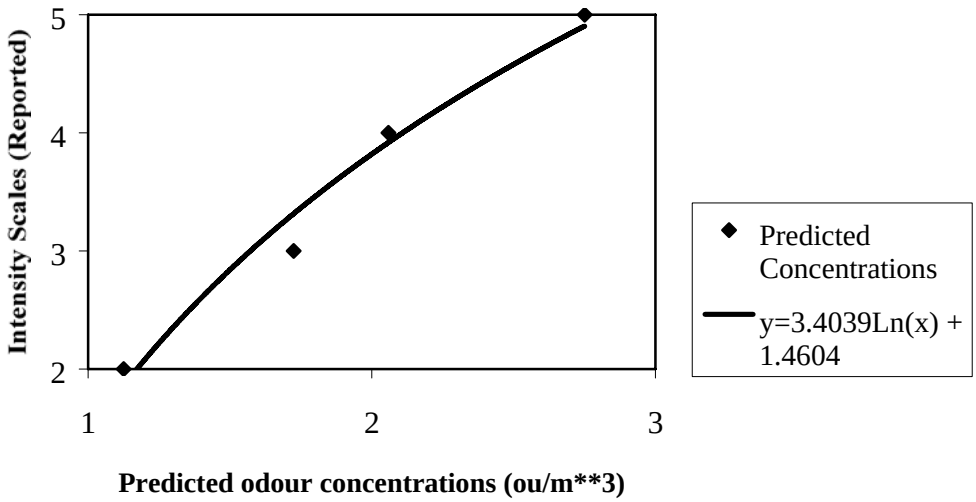


Figure 6.3 Predicted Concentrations *(by COMPLEX-I)* versus reported intensity scales at the location of monitor **M0001**. *Location: Cranfield. OS Grid reference: (495678,239450).*

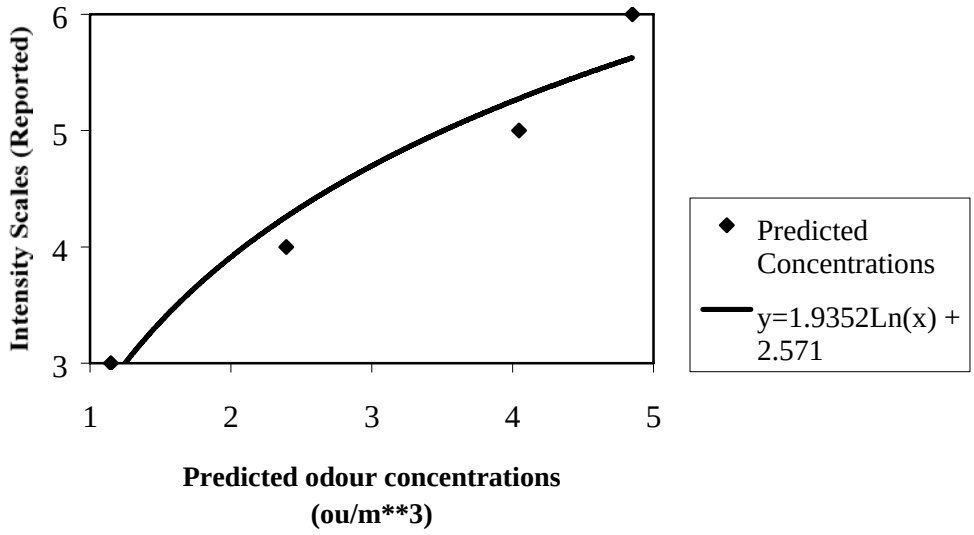


Figure 6.4 Predicted Concentrations *(by COMPLEX-I)* versus reported intensity scales at the location of monitor **M0008**. *Location: Cranfield. OS Grid reference: (495678,239450).*

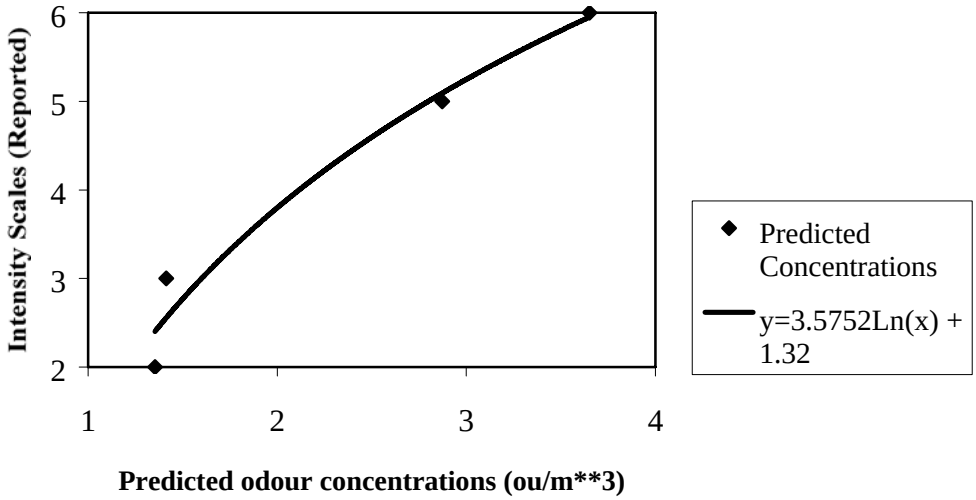


Figure 6.5 Predicted Concentrations *(by COMPLEX-I)* versus reported intensity scales at the location of monitor **M0024**. *Location: Cranfield. OS Grid reference: (495678,239450).*

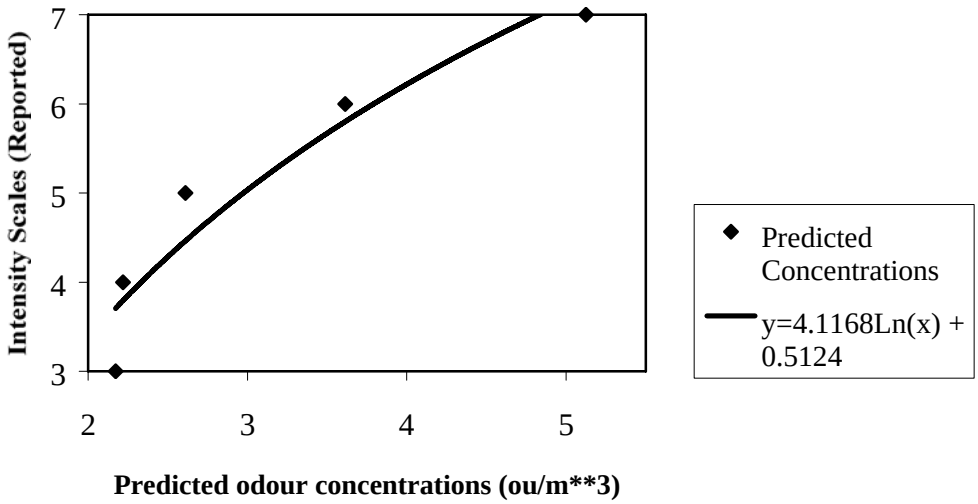


Figure 6.6 Predicted Concentrations *(by COMPLEX-I)* versus reported intensity scales at the location of monitor **M0030**. *Location: Cranfield. OS Grid reference: (495678,239450).*

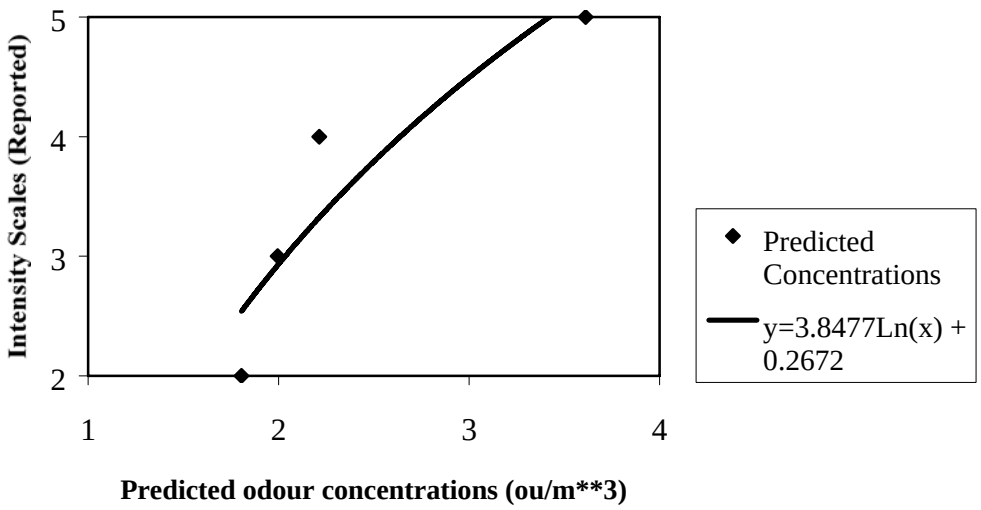


Figure 6.7 Predicted Concentrations *(by COMPLEX-I)* versus reported intensity scales at the location of monitor **M0035**. *Location: Cranfield. OS Grid reference: (495678,239450).*

6.3.4 Applicability of the Parameterised Models

The results given in the previous two sections reveal that the parameterised models, based on the four psychophysical laws, as described in Chapter 5, could be applied to the community odour annoyance analysis only with certain intensity ranges. *All the models should be tested and their parameters should be estimated with samples of odour at around the odour monitors' locations and not with odour evolved at the source* (i.e. the landfill site). At the same time we should try to check the individual sensitivity threshold and capability to discriminate between odours for each of the regular sniffers. Frequent checks would improve the validity and help our understanding of the differences between the performance of monitors.

The same models could be fitted with the source odour intensity data for various source odour concentrations very well, however the results should be specifically for relating the source odour intensity with concentration, not for scaling the intensity of odour from the dispersion estimates. From Table 6.4, we find that the models based on the Weber-Fechner law and the Power law fitted the data consistently for the entire range of the intensity scale, from 1 to 7. However, the other two models, based on the Beidler's law and Laffort's equation are quite inconsistent for intensity scales > 3.

6.4 Refined Modelling: Case studies with the MSW Landfill Site

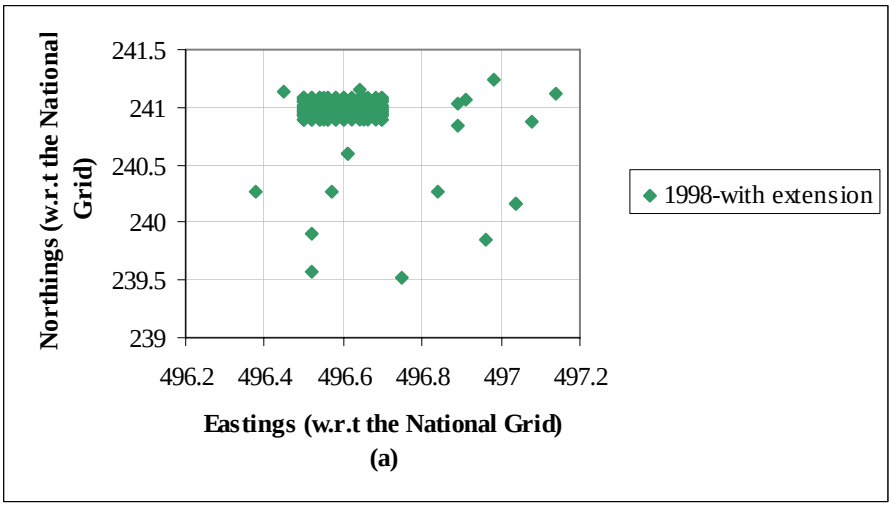
The refined modelling analysis used a 4.0 km x 3.5 km Cartesian receptor grid centred over the MSW landfill site, with a refined spacing between receptors of 100 metres. It was determined from initial screening level analyses that this grid would extend far enough to reach the point of maximum impact. Receptor points were modelled at actual terrain elevations determined from data the U.K Ordnance Survey **Landform PANORAMA** [2] Digitised Terrain Model (DTM). A small programme, called PANORAMA, was developed to reduce the DTM data into the required format for COMPLEX-I. The results are categorised into:

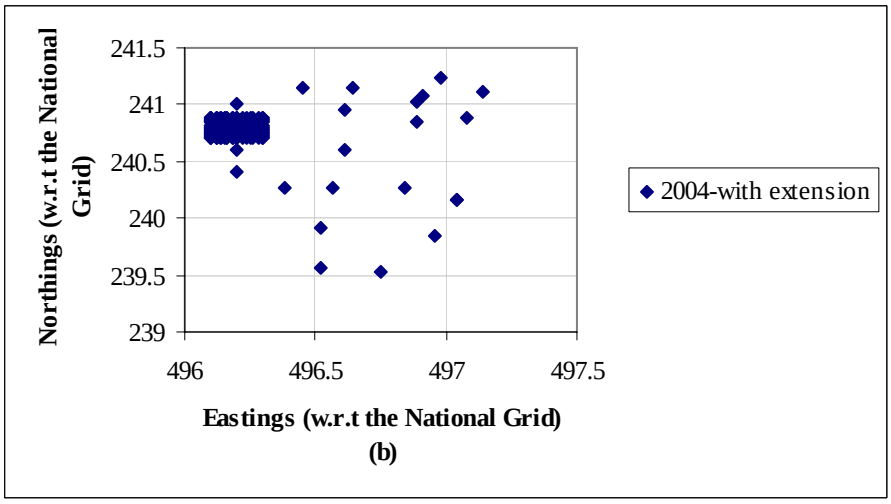
- Maximum Impacts observed at each of the receptor with 1 year's meteorological data.
- Percentage frequency of events with odour levels crossing two threshold limits of 3 ou/m^3 and 5.0 ou/m^3 at each of these receptor points.

To illustrate the impact of the possible extension of the landfill site the scenarios are presented year wise for 1998, 2004 and 2008 with variable conditions of the landfill and the yearly meteorological data of April'1997 until March'1998.

In these scenarios :

- 1998 has been presented as a baseline data source.
- 2004 has been chosen as a 'maximum impact year', with active landfill front in the South of the extension.
- 2008 as the situation directly after restoration of the site and after active landfill activities would be stopped.





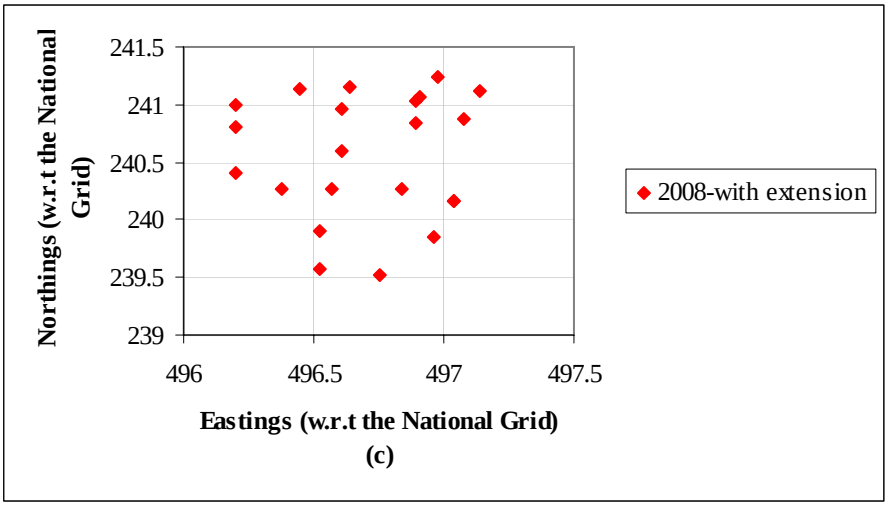


Figure 6.8 Potential odour sources within the landfill site ***with*** extension in the years, (a) 1998, (b) 2004, and (c) 2008.

6.4.1 Analysis: Year 1998 (with extension)

This case has been covered elaborately in Chapter 4 (*section 4.6.2*).

6.4.2 Analysis: Year 2004 (with extension)

This case has also been analysed with the short-term mode of COMPLEX-I for various meteorological conditions and averaging times. Results are given in Figure 6.9 to Figure 6.17. Figure 6.9 to Figure 6.11 give a picture of the maximum odour concentration around the landfill site for 1 hour, 10 minutes and 3 minutes averaging time. If we compare Figure 6.8 (a) with (b) it is observed that by 2004, the landfill progresses towards the west and a big band of the area towards the north would be partly/fully restored by then. The maximum contribution of these new sources would be a higher odour concentration in the *south-westerly regions* away from the landfill. The same locations are affected worse with 3 minutes averaged concentration (concentrations as high as 25.0 ou/m^3 in the south-westerly areas were observed) as compared to hourly and 10 minutes averaged (concentrations as high as 20.0 ou/m^3 in the south-westerly areas were observed) ones. However these show only the scenarios with maximum levels of odour. The percentage frequency of occurrence of such critical events having ranges of odour concentrations as high as 10.0 ou/m^3 - 25.0 ou/m^3 are very low. Figure 6.12 and Figure 6.13 give a picture of the frequency of occurrence of situations where odour levels crossed the thresholds of **3.0 ou/m^3** and **5.0 ou/m^3** in the surrounding areas, on the basis of an hourly averaged concentration. Cranfield and all other surrounding Farms and small villages are affected by the threshold concentration of 3.0 ou/m^3 for less than 2% of the time. Figure 6.14 to Figure 6.17 give a similar picture with different averaging times and naturally we find that the same region is affected more with a lower averaging time (e.g. Cranfield by 3% for 3 ou/m^3).

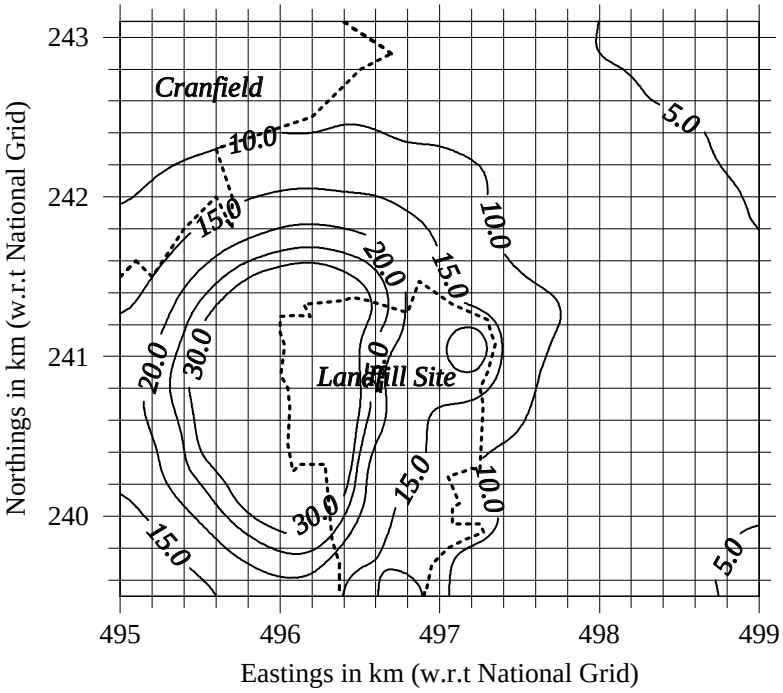


Figure 6.9 An isopleth plot of maximum hourly average odour concentrations (ou/m^3) in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

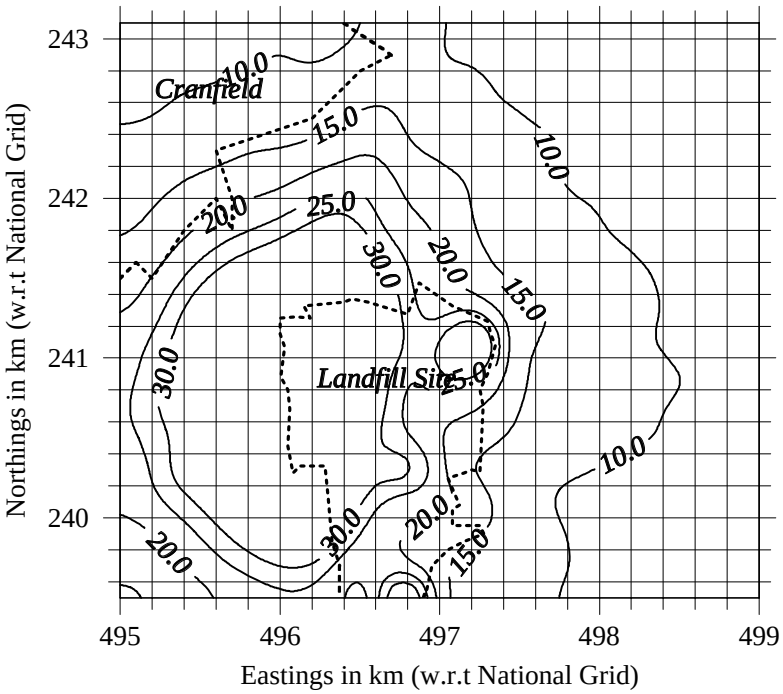


Figure 6.10 An isopleth plot of maximum *(10 minutes average)* odour concentrations (ou/m^3) in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

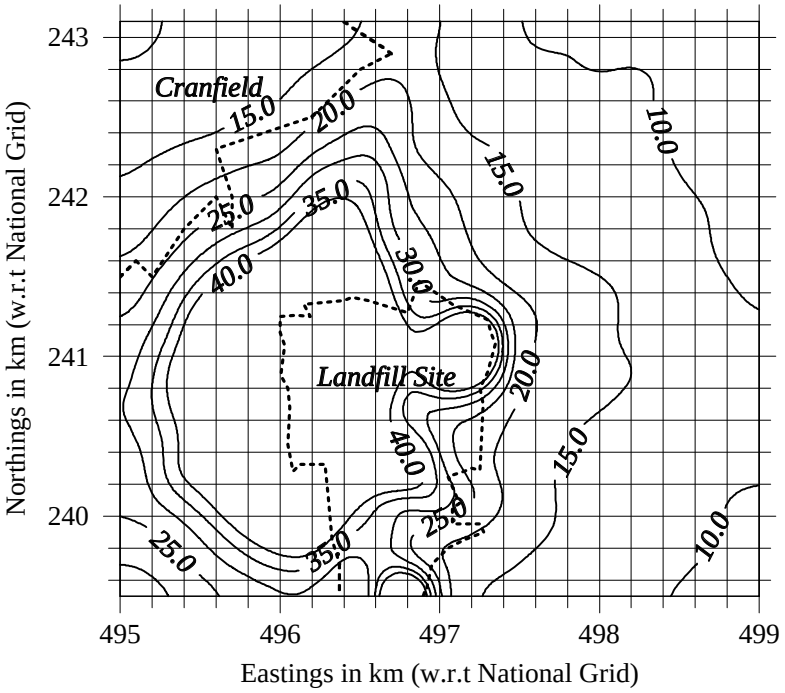


Figure 6.11 An isopleth plot of maximum *(3 minutes average)* odour concentrations (ou/m^3) in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

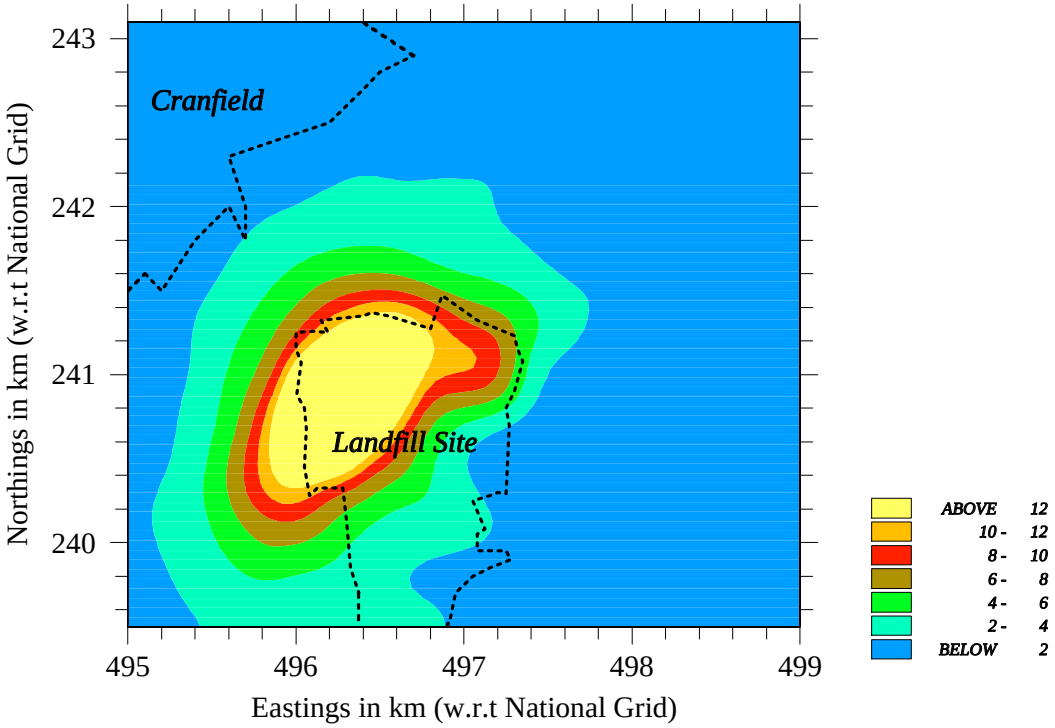


Figure 6.12 A contour plot of percentage frequency of odour levels *(hourly average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

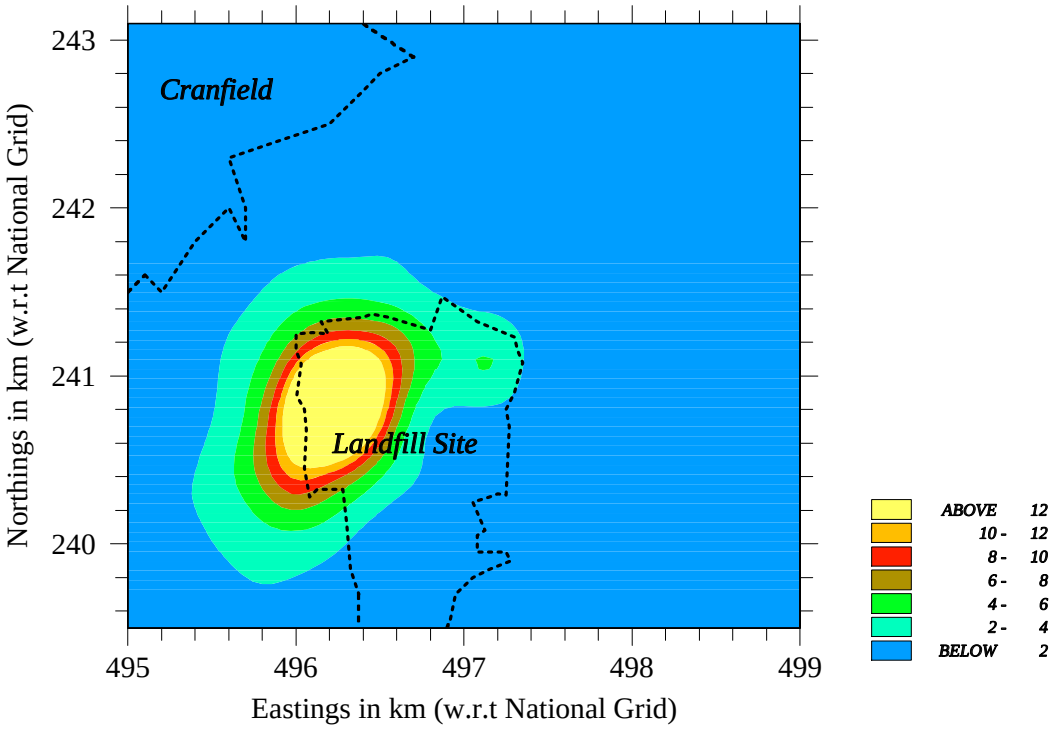


Figure 6.13 A contour plot of percentage frequency of odour levels *(hourly average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

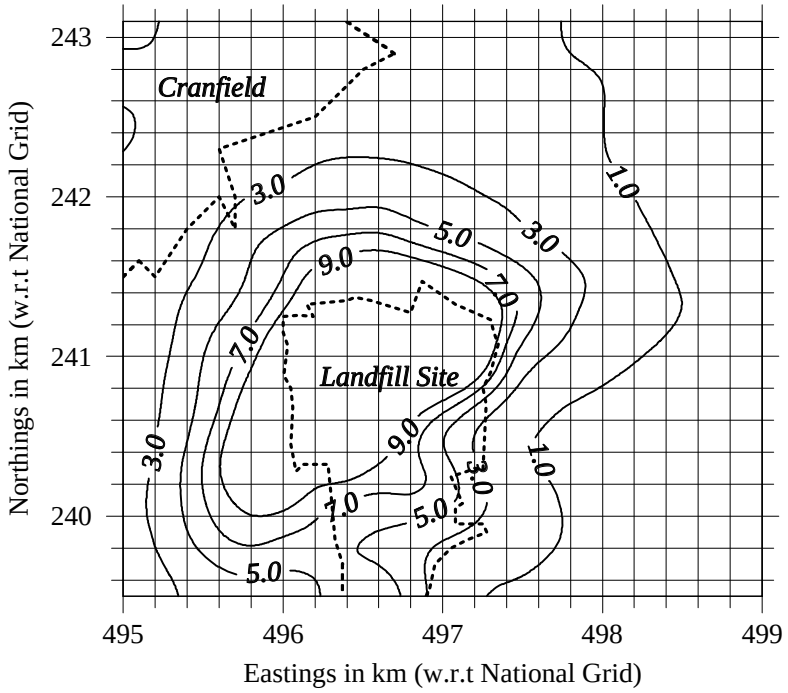


Figure 6.14 A contour plot of percentage frequency of odour levels *(10 minutes average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

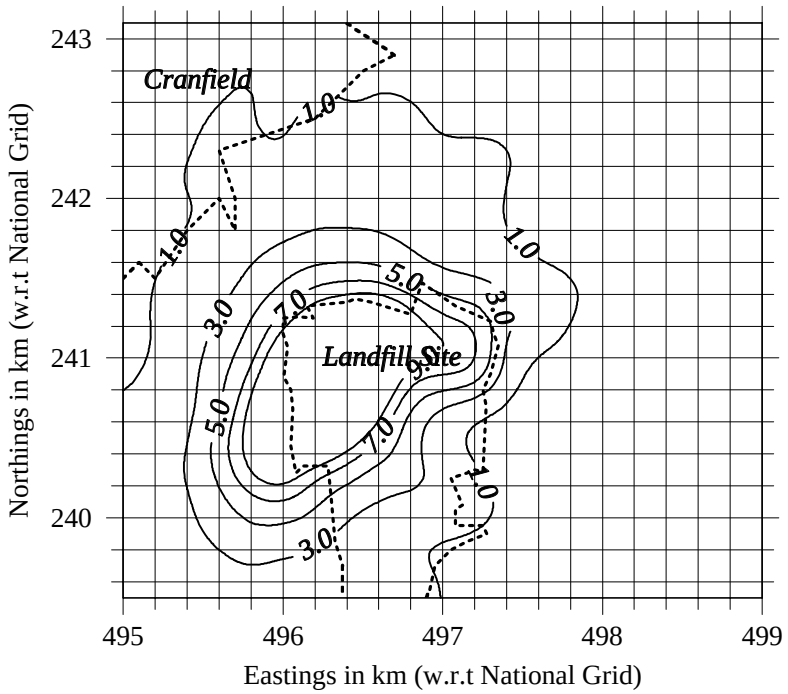


Figure 6.15 A contour plot of percentage frequency of odour levels *(10 minutes average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

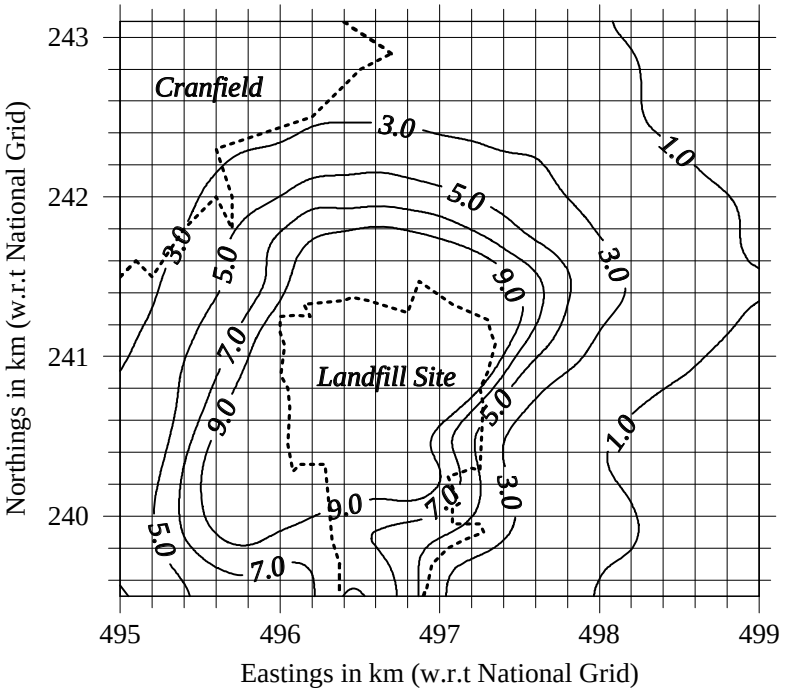


Figure 6.16 A contour plot of percentage frequency of odour levels *(3 minutes average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

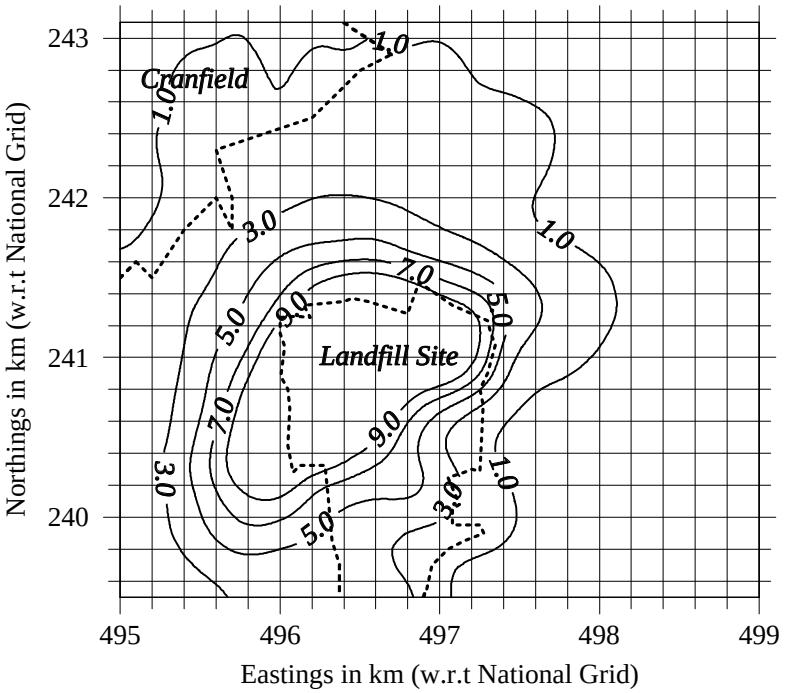


Figure 6.17 A contour plot of percentage frequency of odour levels *(3 minutes average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site in **2004**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

6.4.3 Analysis: Year 2008 (with extension)

In the year 2008, majority of the fillings fronts would be filled with wastes, compacted and partly restored for other uses. Hence regular contributions from the active and operational cells would not be there. This case has also been studied with the short-term mode of COMPLEX-I for various meteorological conditions and averaging times. Results are given in Figure 6.18 to Figure 6.26. Figure 6.18 to Figure 6.20 give a picture of the maximum odour concentration around the landfill site for 1 hour (approximately 3 ou/m^3 about 1.0 km north and 500 metres west of the landfill site), 10 minutes and 3 minutes averaging time. For 3 minutes averaging time, the stretch of 5 ou/m^3 is upto 2.5 kms towards the north of the landfill site. Both from Figure 6.21 and Figure 6.22 it is evident that almost all the areas around the landfill site the percentage frequency of odour levels crossing 3 ou/m^3 and 5.0 ou/m^3 is less than 1%, on the basis of an hourly averaged concentration. Figure 6.23 to Figure 6.26 give a similar picture with different averaging times.

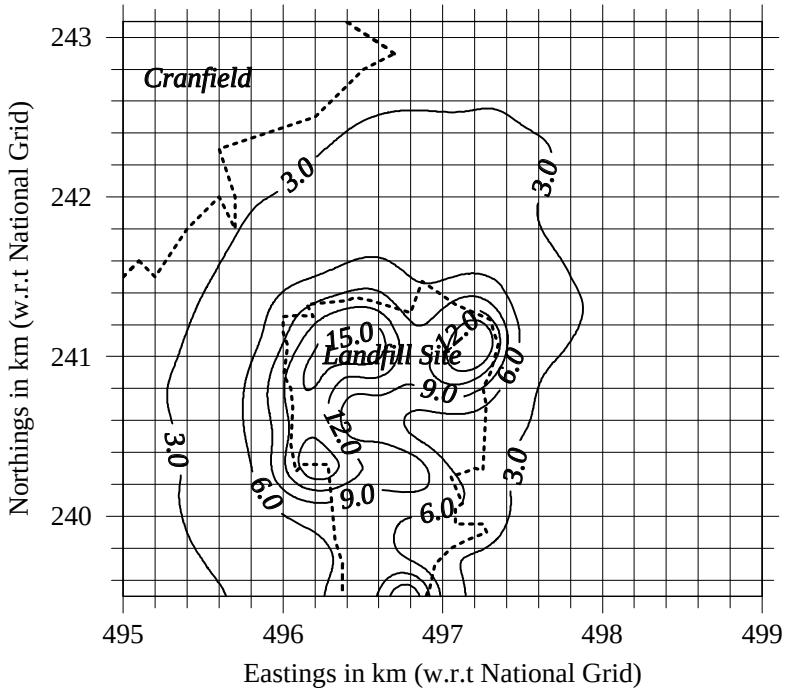


Figure 6.18 An isopleth plot of maximum hourly average odour concentrations (ou/m^3) in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

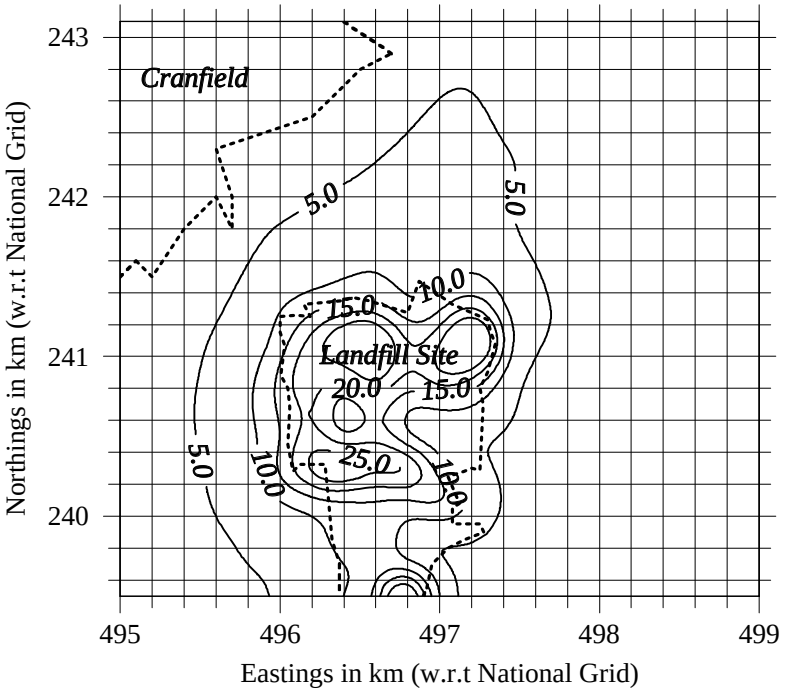


Figure 6.19 An isopleth plot of maximum *(10 minutes average)* odour concentrations (ou/m^3) in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

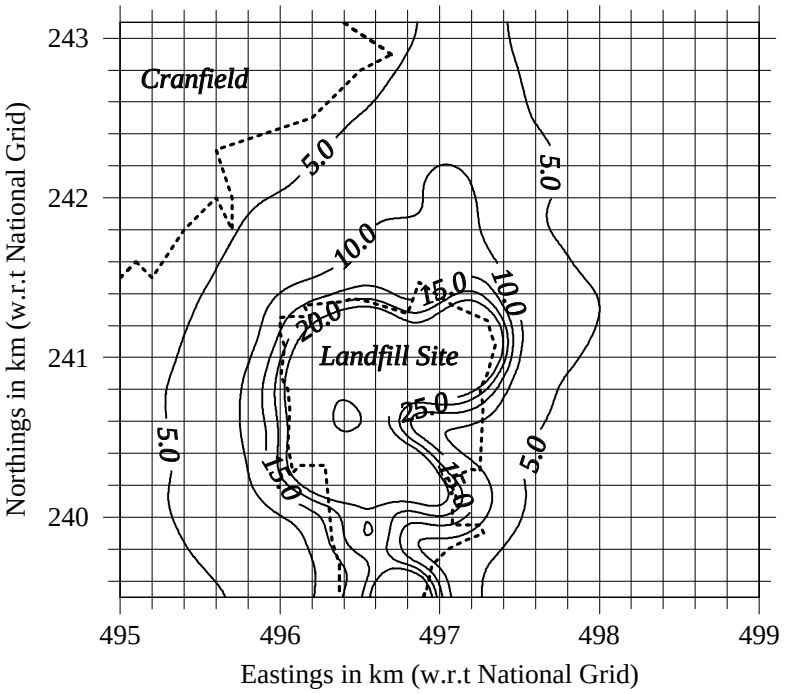


Figure 6.20 An isopleth plot of maximum *(3 minutes average)* odour concentrations (ou/m^3) in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

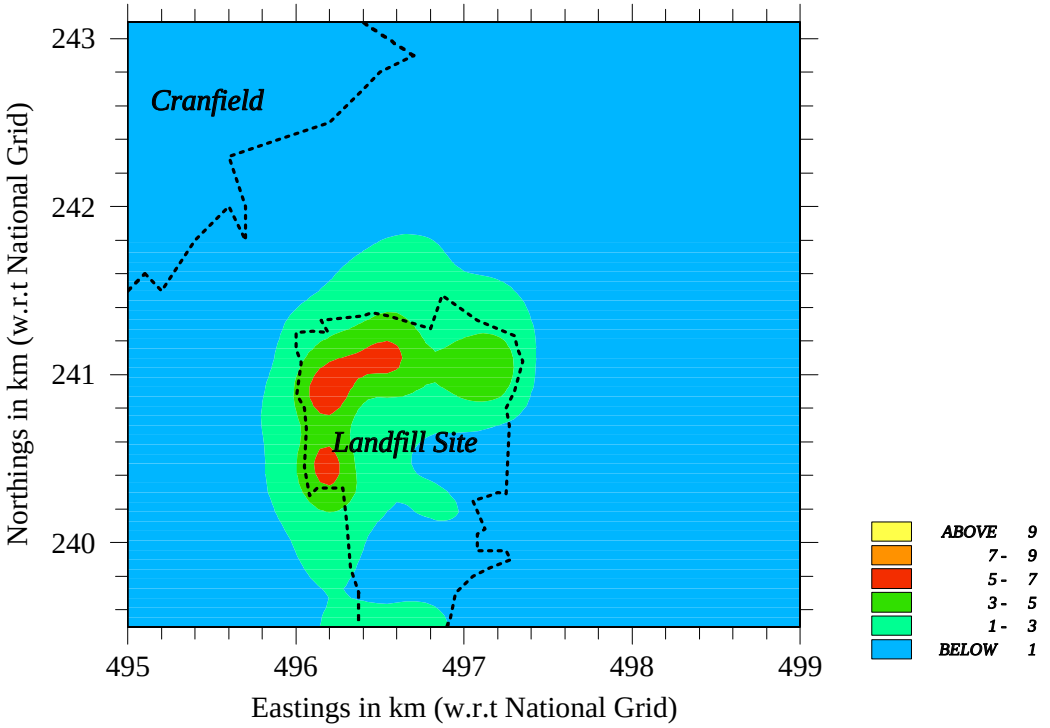


Figure 6.21 A contour plot of percentage frequency of odour levels *(hourly average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

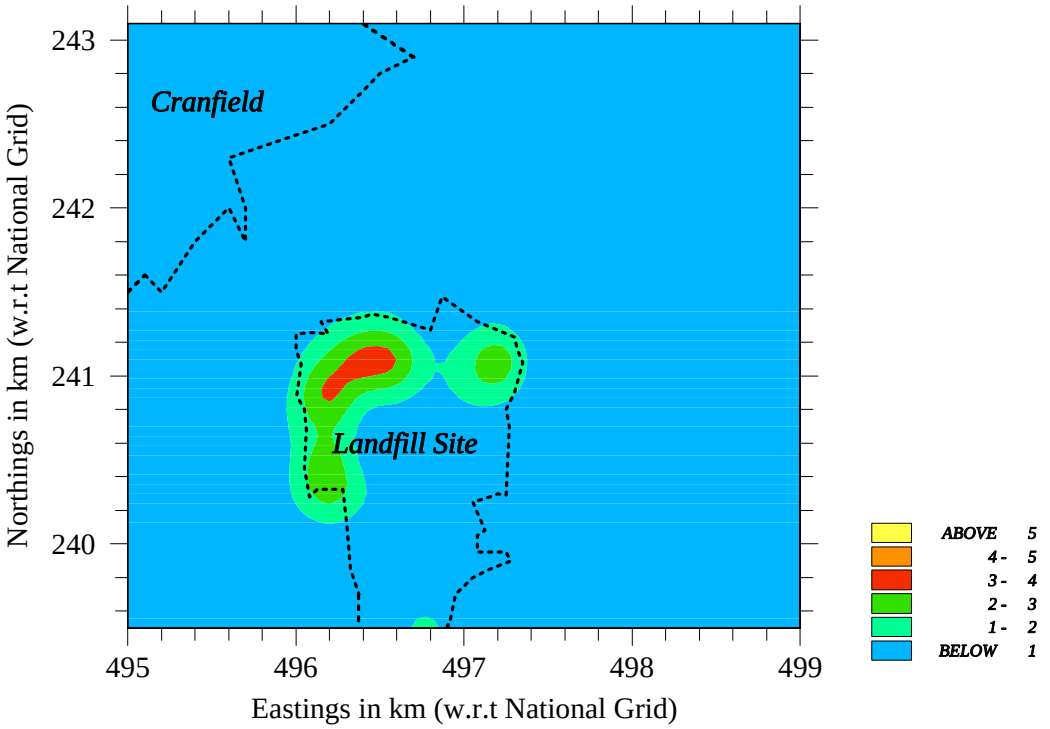


Figure 6.22 A contour plot of percentage frequency of odour levels *(hourly average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

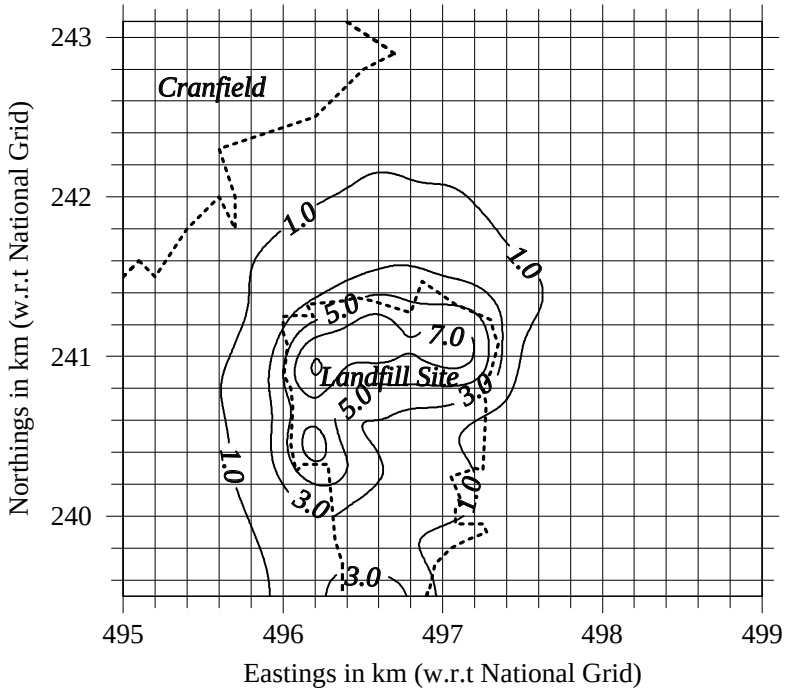


Figure 6.23 A contour plot of percentage frequency of odour levels *(10 minutes average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

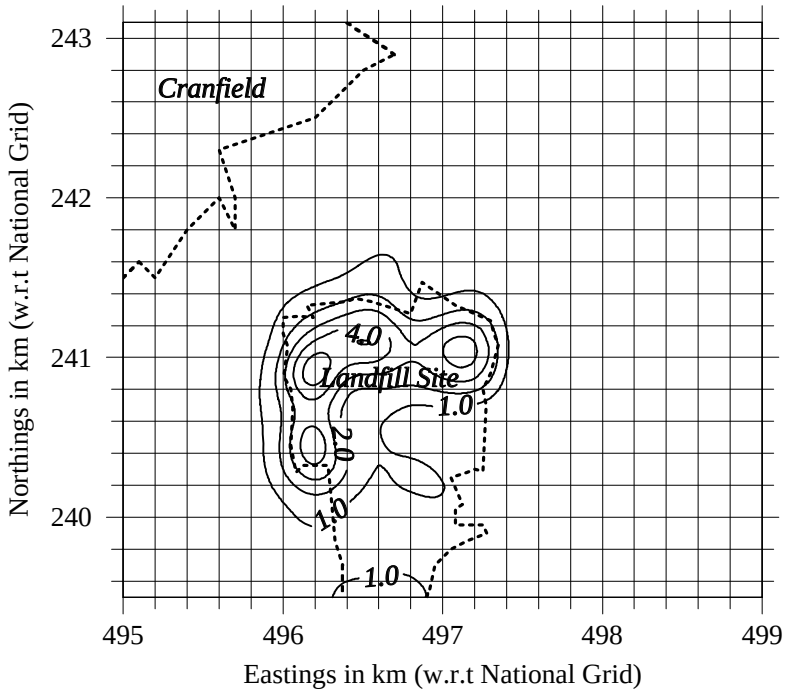


Figure 6.24 A contour plot of percentage frequency of odour levels *(10 minutes average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

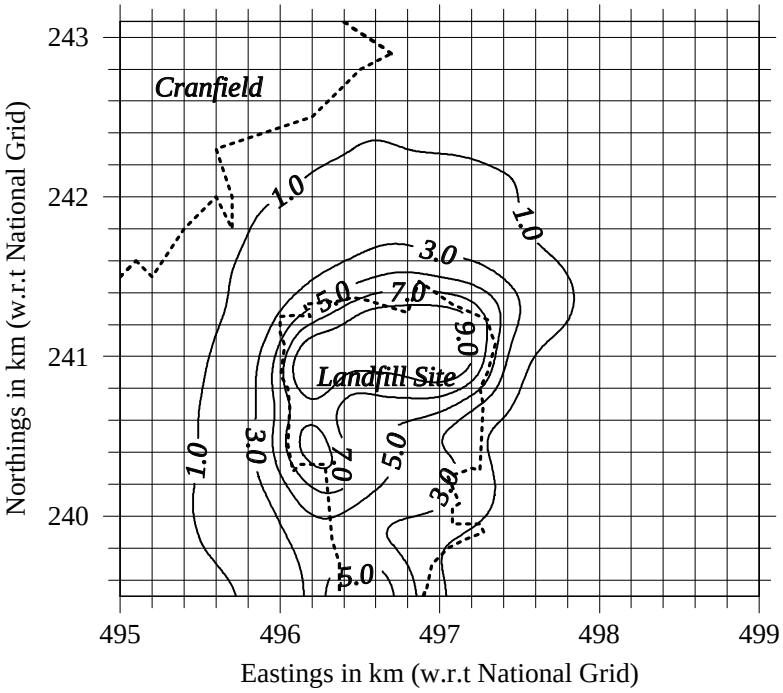


Figure 6.25 A contour plot of percentage frequency of odour levels *(3 minutes average)* crossing an optimum threshold of **3.0 ou/m^3** in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

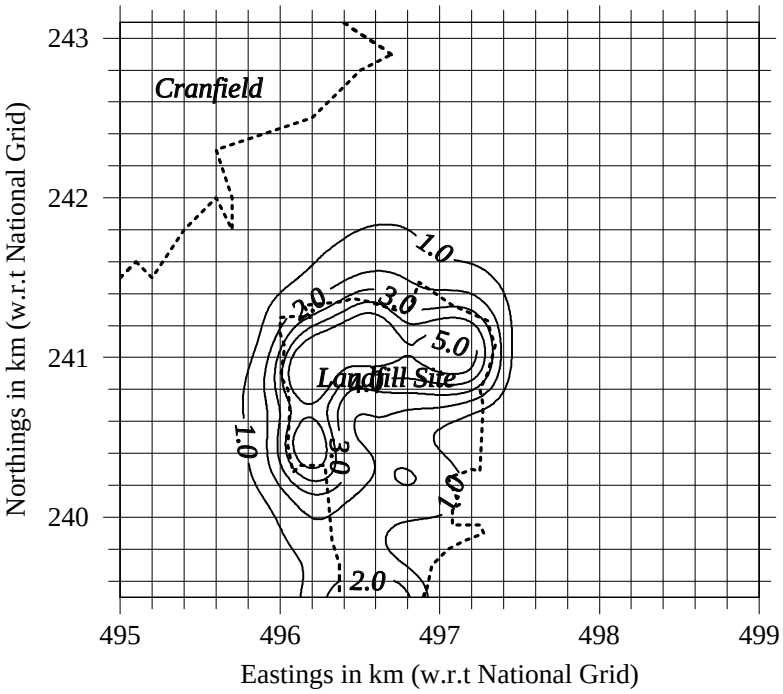


Figure 6.26 A contour plot of percentage frequency of odour levels *(3 minutes average)* crossing an optimum threshold of **5.0 ou/m^3** in and around the MSW Landfill Site in **2008**. *Meteorological data: April'1998-March'1999. Software: COMPLEX-I.*

6.5 Discussion

Both the refined modelling and the community modelling have been found useful in analysing the odour impact from the MSW landfill site. The community modelling has been partially used as a validation method of the overall OIM, while refined modelling would give us a fairly good understanding of the *separation distances* of the local community around the MSW landfill site.

In the concluding chapter (Chapter 7) the following issues will be discussed:

- The shortcomings of the various aspects of the overall approach of OIM
- Design of more powerful and appropriate experiments at the source
- Refinement of the community modelling approach, as a validation step for the OIM
- Possibility of having human receptors as well as portable odour monitoring kits (e.g. portable electronic noses)
- Correlating separation distances with dilution factors for various weather conditions from the results of refined modelling.

Chapter 7

7. Summary, Conclusion and Recommendation for Future Work

This Chapter gives a brief summary of the complete work, highlights the main and the specific conclusions and provides recommendation for future work.

7.1 Summary

The main objective of the present research has been to develop a quantitative Odour Impact Model (OIM) describing emission, dispersion and reception in order to analyse nuisance created by odour from solid wastes. The individual components of the model have been:

1. Emission assessment,
2. Odour transport and dispersion, and
3. Reception by the people within the surrounding community of the odour source.

For each of the above features, test cases related to a waste transfer depot and a Municipal Solid Waste landfill site have been analysed.

7.1.1 Emission assessment

Firstly, two approaches for measuring emission rates of odour from various areas of a municipal solid waste landfill site have been discussed.

1. The first one is a direct emission measurement approach- the enclosure approach using an emission isolation flux chamber (the Lindvall hood).
2. The second approach is based on an indirect method of emission rate measurements based on micrometeorological modelling that uses simple meteorological measurements, suitable odour sampling methods, and analysis of the odour samples based on principles of olfactometry.

Secondly, the two methods have been compared on the basis of their suitability for applying to cases of huge solid waste landfill sites.

7.1.2 Odour transport and dispersion

To estimate dispersion, existing modules (UK-ADMS, MPTER/COMPLEX-I) have been used. The study also attempted to compare the performance of the models for application specially to odour dispersal. The test cases are detailed in *section 4.6* of Chapter 4 and in Chapter 6. The model predictions have been compared with each other and with the data reported by community sniffers.

7.1.3 Analysis of Perception

The analysis of perception of odour samples from a municipal solid waste landfill site was done using various well-known *psychophysical models* and respective parameters for each of the models were estimated by a non-linear model fitting technique. The overall performance of each model was tested against sets of data from the olfactometry analysis.

7.2 Conclusion

Some of the conclusions have been very specific to the individual component of the OIM, while the rest are general in nature and relevant if we view the overall OIM in totality.

7.2.1 General conclusions

The general conclusions of the Odour Impact Model developed are:

- The micrometeorological method is better than standard Lindvall hood technique for assessing the emissions from a huge areal plot like a municipal solid waste landfill site.
- UK-ADMS predicts better than MPTER/COMPLEX-I for odour dispersion, particularly because odour impacts are predominantly at short ranges.
- The model based on Weber-Fechner law describes the relationship between odour intensity and odour concentration (ou/m^3) very well for most of the *less intense* odour samples, while the model based on Laffort's equation expresses a better relationship with comparatively *more intense* odour samples (e.g. samples from KOPW3, W1H1, W28H1 etc.).

7.2.2 Specific conclusions

Emission Assessment

- The major advantage of the micrometeorological method over the hood is that the surface under consideration is in the natural influence of the atmosphere. The methods can be automated and are useful in measurements of diurnal and seasonal variations in gas fluxes.
- The strength of micrometeorological methods is their capability to measure fluxes across a wide area with minimum disturbance to the underlying surface. The method can be applied at various spatial resolutions for experiments within the surface layer, depending on the choice of the sensor height for a particular type of surface. The footprint area contributing to a certain odour concentration can be reduced or enlarged depending on the choice of the sensor height under varied meteorological conditions and effectively a huge area of certain homogeneity could be covered within the scope of one experiment.
- Weaknesses include the need for expensive, sophisticated equipment, complex calculations and surface constraints that may limit the use.

Dispersion Modelling

- In general the concentration predicted by UK-ADMS is greater than that predicted by MPTER/COMPLEX-I especially at short ranges. ADMS uses a better representation of short range dispersion (considering plume meandering and in-plume fluctuations) and is thus likely to be more accurate close to the source.
- In view of the complaints received from the nearby *community for the case of waste transfer depot*, it could be concluded that MPTER/COMPLEX-I underpredicted the average scenario.
- The two models compare well at distances greater than 500 metres downwind from the source whereas UK-ADMS, we believe to be more reliable close to the source (less than 500 metres) as compared to MPTER/COMPLEX-I because of its better representation of the local dispersion processes (mentioned in Chapter 2 and Chapter 4).

Analysis of Perception

- The Weber-Fechner law, which is the most widely used laws when the scaling technique is *category estimation*, did not always perform the best for all types of odour samples (with various ranges of intensities) from various sources of the landfill site.
- Beidler's and Laffort's models did fit the data quite well on certain occasions (see Table 5.6), specially for more intense samples of odour.
- In order to estimate the performance of a particular model to describe the relationship between odour intensity and odour concentration for various sources within the landfill, more research and measurements are necessary.

7.3 Recommendation for future work

Successful field use of both the hood and the micrometeorological methods will require measurements which account for the extreme variations in surface conditions, cover type, waste composition, waste age, and subsidence. It is important to determine the

magnitude and distribution of such variability and the impact on gas emissions in order to design an accurate emission monitoring programme.

The major shortcomings of the various aspects of the overall approach of OIM are:

- The shortage of validated data.
- The lack of validated site sampling methods.
- The lack of calibration of the difference between the hood and the micrometeorological technique.
- The lack of data related to odour events, as reported by the community monitors.
- Range of intensity levels obtained in a sample of odorous gas from the source has been found to be quite different from the intensity ranges obtained at the monitors' locations. The same calibrations were used, however the attempt was not quite successful.

Hence, the following protocols are recommended to provide a coherent basis for odour assessment for the purpose of assessing nuisance.

- Design of more powerful and appropriate experiments at the source to validate the micrometeorological "footprint" technique using transect sampling to measure odours.
- Calibration of the difference between the Lindvall hood technique, which is the widely used standard technique for these cases, with the "footprint" method in order to judge the suitability of application.
- Refinement of the community modelling approach, as a validation step for the overall OIM.
- Possibility of having human receptors as well as portable odour monitoring kits (e.g. portable electronic noses) at the same location of the human receptors.
- Possibility of including a few more dilution levels in the olfactometric experiments particularly with the intensity-concentration calibration. This should be further down towards the strength (i.e. more diluted) of the odorous sample, to account for the concentration levels reached at the receptor sites, generally. If this is restricted by the number of dilution levels the particular olfactometer can cope with, two separate experiments can be designed with same sample, but different dilution

range, and the last level of the first experiment should really match with the first level of the second experiment.

- Correlating separation distances with dilution factors for various weather conditions from the results of refined modelling.
- Developing guidelines for calculating the ***Separation Distance*** between the Landfill Site and Residential Areas to avoid community annoyance.

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APPENDIX-I

I. Composition and characteristics of the landfill gas and leachate

Landfill gas is composed of a number of gases that are present in high proportions (principal gases) and a number of gases that are present in very small amount (the trace gases). The principal gases are produced from the decomposition of the organic fraction of the MSW. Some of the trace gases, although present in small quantities, can be toxic and could present risks to public health.

I.1 Principal landfill gas constituent

Gases found in landfills include ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulphide (H_2S), methane (CH_4), nitrogen (N_2), and oxygen (O_2). The average percentage composition of gases found in a MSW landfill is reported in

Table **I.1**. The anaerobic decomposition of the biodegradable organic waste component in MSW produces two principal gases, namely methane and carbon dioxide. Methane is an explosive gas when present in the atmosphere in the range of 5%-15%. There is not enough oxygen present within the landfill that will combine with the methane to form an explosive mixture of landfill gas. However, if the landfill gas migrates from the site and mixes with air, there are possible risks of explosion.The concentration of these gases that may be expected in the leachate will depend on their concentration in the gas phase in contact with the leachate, as estimated using Henry's law.

Table I.1 Typical constituents found in MSW landfill gas[110-112].

Component	**Percent (dry volume basis)**[a]
Methane	45-60
Carbon dioxide	40-60
Nitrogen	2-5
Oxygen	0.1-1.0
Sulfides, disulfides, mercaptans, etc.	0-1.0
Ammonia	0.1-1.0
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6
Characteristic	**Value**
Temperature, °F	100-120
Specific gravity	1.02-1.06
Moisture content	Saturated
High heating value, Btu/sft^3	400-550

[a] *Exact percentage distribution will vary with the age of the landfill.*

I.2 Trace landfill gas constituents

Amongst the trace gases that are generally found in a MSW landfill site are the readily volatile chlorinated hydrocarbons (VCCs), chlorinated, fluorinated hydrocarbons (CFCs), non-halogenated hydrocarbons and the BTEX aromatic substances (benzene, toluene, ethylbenzene and xylene). Trichlorofluoromethane (R11), dichlorofluoromethane (R12) and dichloromethane (R30) were the dominating halogenated trace substances detected in the MSW. The emission potential of these substances via the gas and leachate during the different biological degradation phases in the landfill phase was investigated by Deipser and Stegmann [113]. It was shown [113] that R11 degraded into dichlorofluoromethane (R21). Table I.2 gives concentrations of halogenated trace substances in six MSW sites from Hamburg, Germany. The

absorption of the VCCs/CFCs to the material "MSW" is quite high and thus it is extremely difficult to determine the total content of VCCs and CFCs with standard techniques like thermal stripping. Table I.6 gives a list of typical concentrations of trace compounds found in landfill gas at 66 California MSW landfills [114].

Table I.2 Concentrations of halogenated trace samples in six MSW[113] from Hamburg, Germany.

Component	**Concentration** $(mgkg^{-1}$ **Total Solid waste)**
Trichlorofluoromethane (R11)	Nd*-10.79
Dichlorodifluoromethane (R12)	0.01-0.22
Dichlorofluoromethane (R21)	nd-0.89
Chlorodifluoromethane (R22)	0.01-0.24
1,1,2-Trichlorotrifluoroethane (R113)	nd-0.01
Dichloromethane	0.01-2.68
Trichloromethane	nd-0.07
1,1,1-Trichloroethane	0.01-3.65
Monochloroethene (Vinylchloride)	nd-0.4
cis-1,2-Dichloroethene	nd-4.99
Trichloroethene	nd-0.59
Tetrachloroethene	nd-1.41

** nd not detectable*

I.3 Odour Marker[115]

Only a few VOCs detected by Gas chromatography/Mass spectrometry (GC/MS) can be considered as markers of the malodour.

1-Methyl-para-iso-propenyl-1 cyclohexene *(limonene)* and para-iso-ipropyltoluene *(para-cymene)* contribute to the municipal waste olfactory sensation largely [115] and can be thus used as **odour markers** in order to monitor bad odours. These compounds

have been monitored semi-continuously by means of a cold trapping gas analyser [115]. Usually these compounds are released by the biodegradation of vegetable matter in the waste. *p-cymene* has been considered as a biogas tracer whereas *limonene* indicates the fresh waste emissions. A strong correlation has been observed between the quantitative monitoring of the tracers concentration and the general olfactory perception in the environment.

I.4 Sources of Trace Gases

The major source of the trace constituents of a landfill gas is the incoming waste. Otherwise, these are produced by biotic and abiotic reactions occurring within the landfill. The tendency of these trace compounds to volatilise is proportional to the vapour pressure of the liquid, and inversely proportional to the surface area of a sphere of the volatile liquid within the landfill [116]. These trace constituents are produced or consumed by complex biochemical pathways. For example, vinyl chloride can be formed in the process of degradation of di- and trichloroethene.

Many of these trace compounds in landfill gas are recognised as potentially toxic when their concentration levels exceed toxicity threshold limit values (TLVs) or the Occupational Exposure Standards (OESs) set by the Health and Safety Executive. Table I.4 gives a list of compounds detected in landfill gas from UK sites which exceed Occupational Exposure Level (OEL 0 value in EH40 [117].

I.5 Emission of Trace Gases

Figure I.1 gives a sketch for the movement of trace landfill gases through a landfill cover [118]. The relevant equation for the diffusion of trace gases from the landfill through the cover is given by:

$$N_i = -\frac{D\alpha^{4/3}\left(C_{i_{atm}} - C_{i_s} W_i\right)}{L} \qquad \textbf{-(I.1)}$$

where

N_i = vapour flux of compound *i*, g/cm^2. s

D = diffusion coefficient, cm^2/s

α = dry soil porosity, cm^3/cm^3

$C_{i_{atm}}$ = concentration of compound *i* at the surface of the landfill cover, g/cm^3

C_{i_s} = saturation vapour concentration of compound *i* , g/cm^3

W_i = scaling factor to account for the actual fraction of trace compound *i* in the waste

$C_{i_s} W_i$ = concentration of compound *i* at bottom of the landfill cover, g/cm^3

L = depth of the landfill cover, cm

Since the concentration of the trace compounds reaching the landfill surface will be quickly diminished by the process of molecular diffusion and dispersion directed by the wind into the ambient air, $C_{i_{atm}}$ may be assumed zero. Hence, equation (I.1) takes the following conservative form:

$$N_i = \frac{D\alpha^{4/3}\left(C_{i_s} W_i\right)}{L} \qquad \textbf{-(I.2)}$$

The diffusion co-efficient D is reported in Table I.5 for twelve trace compounds for temperature ranging from 0°C to 40°C. The range of porosity for different types of clay varies from 0.010 to 0.30. If field measurements are not available, the concentration of the i^{th} trace compound just below the landfill cover, $C_{i_s} W_i$, can be estimated from the data given in Table I.6. However, Table I.6 covers only 10 trace compounds. If the compound of interest is not listed in Table I.6, a value of 0.001 can be assumed for W_i and the saturation concentration C_{i_s} can be obtained from APPENDIX H of [118].

If the term, $C_{i_s} W_i$ is to be estimated from field measurements, a gas probe should be inserted through the landfill cover, to a point immediately below the landfill cover. Then the concentration of the compound and temperature both need to be recorded. An average emission rate of a particular trace compound can then be estimated from equation (I.2).

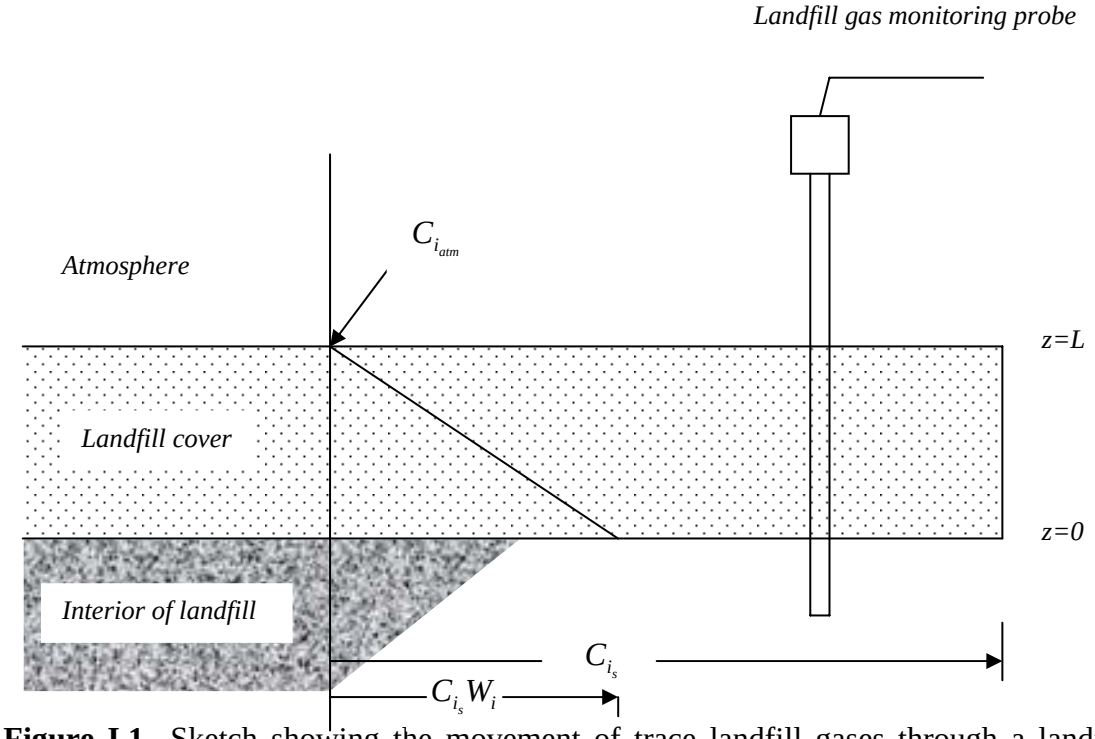

Figure I.1 Sketch showing the movement of trace landfill gases through a landfill cover[118].

Table I.3 Measured and saturation gas phase concentrations of 10 trace compounds[114].

	Concentration, mg/m^3		**Scaling factor,**
Compounds	**Maximum measured[a]**	**Saturation value**	W_i
Benzene	135.9	319,000	0.0004
Chlorobenzene	6.8	54,000	0.0001
Ethylbenzene	414.5	40,000	0.01
1,1,1-Trichloroethane	86.3	715,900	0.0001
Chloroethene	89.2	8,521,000	0.00001
Tetrachloroethene	1331.7	126,000	0.01
Trichloroethene	85.1	415,000	0.0002
Dichloromethane	871.5	1,702,000	0.0005
Trichloromethane	63.9	1,027,000	0.00001
Toluene	1150.5	110,000	0.01

a Measurements taken from 44 California landfills

Table I.4 Compounds detected in landfill gas from UK sites which exceed OEL value in EH40[117].

Compound	OEL (mg/m3)	Maximum (mg/m3)
Hexanes	360	628
Benzene	30	114
Toluene	125	460
Xylenes	125	470
Propyle Benzenes	1	292
Dchlorofluoromethane	40	93
Vinyl Chloride	3	32
1,2-Dichloroethylenes	40	302
Tetrachloroethylene	335	350
Camphor/Fenchone	12	13

Table I.5 Selected physical properties for twelve trace compounds found in landfills[119] at temperatures 0°C-40°C.

Compound	*0 ℃*			*10 ℃*			*20 ℃*			*30 ℃*			*40 ℃*		
	D^b	vp^c	$C_s{}^d$	*D*	*vp*	C_s	*D*	*vp*	C_s	*D*	*vp*	C_s	*D*	*vp*	C_s
Ethyl benzene	*.052*	*2.0*	*12.48*	*.055*	*3.9*	*23.47*	*.059*	*7.3*	*42.44*	*.062*	*13*	*73.08*	*.066*	*22*	*119.7*
Toluene	*.056*	*6.7*	*36.26*	*.060*	*12*	*62.65*	*.064*	*22*	*110.9*	*.068*	*37*	*180.4*	*.073*	*59*	*278.5*
Tetrachloro- ethene	*.053*	*4.1*	*39.95*	*.057*	*7.9*	*74.27*	*.061*	*15.6*	*127.1*	*.065*	*24*	*210.7*	*.069*	*40*	*340.0*
Benzene	*.066*	*27*	*123.9*	*.070*	*47*	*208.1*	*.075*	*76*	*325.0*	*.081*	*122*	*504.6*	*.086*	*185*	*740.7*
1,2-Dichloroethane	*.063*	*24*	*139.6*	*.068*	*41*	*230.0*	*.072*	*62*	*363.0*	*.077*	*107*	*560.7*	*.082*	*164*	*831.9*
Trichloroethene	*.059*	*20*	*154.5*	*.063*	*36*	*268.4*	*.067*	*60*	*424.8*	*.072*	*94*	*654.5*	*.077*	*146*	*984.1*
1,1,1-Trichloroethane	*.058*	*36*	*282.2*	*.062*	*61*	*461.3*	*.067*	*100*	*715.9*	*.071*	*153*	*1081*	*.076*	*231*	*1580*
Carbon tetrachloride	*.058*	*32*	*289.3*	*.062*	*54*	*470.9*	*.066*	*90*	*741.2*	*.071*	*138*	*1124*	*.075*	*209*	*1648*
Chloroform	*.065*	*61*	*427.9*	*.070*	*100*	*676.7*	*.075*	*160*	*1026*	*.080*	*240*	*1517*	*.085*	*354*	*2166*
1,2-Dichloroethene	*.077*	*110*	*626.7*	*.082*	*175*	*961.8*	*.087*	*269*	*1428*	*.092*	*399*	*2048*	*.097*	*576*	*2862*
Dichloromethane	*.074*	*155*	*773.6*	*.080*	*242*	*1165*	*.085*	*349*	*1702*	*.091*	*536*	*2410*	*.097*	*763*	*3322*
Vinyl chloride	*.080*	*1280*	*4701*	*.085*	*1810*	*6413*	*.091*	*2548*	*8521*	*.098*	*3350*	*11090*	*.104*	*4410*	*14130*

b *Diffusion coefficient, cm^2/s.*
c *Vapour pressure, mm Hg.*
d *Saturation vapour concentration, g/m^3.*

Table I.6 Typical concentrations of trace compounds found in landfill gas at 66 California MSW landfills[114].

Compound	Concentration, ppbV[b]		
	Median	**Mean**	**Maximum**
Acetone	0	6,838	240,000
Benzene	932	2,057	39,000
Chlorobenzene	0	82	1,640
Chloroform	0	245	12,000
1,1-Dichloroethane	0	2,801	36,000
Dichloromethane	1,150	25,694	620,000
1,1- Dichloroethene	0	130	4,000
Diethylene chloride	0	2,835	20,000
trans-1,2-Dichloroethane	0	36	850
2,3-Dichloropropane	0	0	0
1,2-Dichloropropane	0	0	0
Ethylene bromide	0	0	0
Ethylene dichloride	0	59	2,100
Ethylene oxide	0	0	0
Ethyl benzene	0	7,334	87,500
Methyl ethyl ketone	0	3,092	130,000
1,1,2-Trichloroethane	0	0	0
1,1,1- Trichloroethane	0	615	14,500
Trichloroethylene	0	2,079	32,000
Toluene	8,125	34,907	280,000
1,1,2,2-Tetrachloroethane	0	246	16,000
Tetrachloroethylene	260	5,244	180,000
Vinyl chloride	1,150	3,508	32,000
Styrenes	0	1,517	87,000
Vinyl acetate	0	5,663	240,000
Xylenes	0	2,651	38,000

APPENDIX-II

II. Terms and definitions in odour assessment

In order to investigate gas samples of unknown composition with regard to their property to induce odour sensations, following terms and definitions have been found quite useful. The sensory properties of odour are both qualitative and quantitative and one does not usually know the rules of interaction of an individual with the resulting odour. The types of human responses sought depend on the particular sensory property that is measured. Odour intensity, detectability, character, and hedonic tone (pleasantness and unpleasantness) are few of the representative sensory properties of odour. The combined effect of these properties may be related to particular annoyance levels that may be caused by one or more odour events.

The following terms and definitions conform to the Guideline VDI 2449 Part 2 [120] and Standard DIN 6879 [121]. *The following terms and definitions are restricted to the property "odour"*.

Odour[123]

Perception resulting from simulating the olfactory receptors; in a broader sense, the term is sometimes used to refer to the combination of sensations resulting from stimulation of the entire nasal cavity.

Odour Intensity

The strength of the perceived odour sensation is generally termed as odour intensity. It depends on the odorant concentration in a complex way, which has been discussed in Chapter 5. The intensity of an odour is perceived directly, without knowing the

concentration of the odorous gas sample or of the degree of dilution of the odorous sample needed to eliminate odour.

Odorant concentration ($c_{od,cs}$)[120]

The odorant concentration of the gas sample to be measured (single compound or mixture) is determined by dilution with neutral air down to the odour threshold. The numerical value of the odorant concentration results from the volume flows of the gas sample and the neutral air at the moment when the odour threshold is reached. The unit of the quantity "odorants concentration" is odor unit (OU) divided by volume unit (m^3), thus OU/m^3.

Odor unit (OU)

Based on the definition of the odour threshold, 1 OU is the very quantity (number of molecules) of odorants which just induces an odour sensation when dispersed in 1 m^3 of neutral air. 1 OU/m^3 is also the benchmark of the odorant concentration scale (c_{od}). This is also called D-T (dilution to threshold ratio).

Odour detection threshold

When a sample of odorous gas is progressively diluted, the concentration of odorants decreases, and the intensity of odour weakens simultaneously, but not in direct proportion to the extent of the dilution. The intensity of the gaseous sample becomes so low with any further dilution that detection or recognition of the odour is very difficult. At some statistically defined point of dilution, the *detection threshold* is reached. With little bit less dilution (i.e. higher odorant concentration) odour is recognised and the dilution is called *recognition threshold*.

The concentration of odorous substances at *detection threshold* level leads to an odour impression with 50% of the defined population. The odorant concentration at the threshold is 1 OU/m^3 by definition.

Odour recognition threshold

The lowest physical intensity at which an odour stimulus is correctly identified a specified percent of the time.

Hedonic tone

Odours of equal intensity may differ in character. Hedonic tone is a character of odour that identifies its place on a scale of pleasantness and unpleasantness. However, an otherwise pleasant odour may be considered objectionable by the exposed population in the context of industrial emission and pollution hazards.

Odour Annoyance[122]

Annoyance experienced by a population exposed to an air-pollution odour is a combined result of the intensity, character, and hedonic tone of the odour, as well as of the frequency and duration of the exposure. It is quite difficult to measure annoyance.

Odorant flow rate (q_{od})

The odorant flow rate is the quantity of odorous substances passing through a defined area at each time unit. It is the product of the odorant concentration, the outlet velocity and the outlet area or the product of the odorant concentration and the pertinent volume flow rate. Its unit is OU/s usually.

$$q_{od} = c_{od,cs} \cdot v \cdot A = c_{od,cs} \cdot \dot{V} \qquad \textbf{-(II.1)}$$

The odorant emission flowrate is the quantity equivalent to the emission mass flow rate, for example in dispersion models.

Olfactometer

Olfactometers are instruments in which a gas sample (odorous sample) is diluted with neutral air in a defined ratio. This dilution is presented to test subjects (panellists) as a smell sample. The panellists are offered several dilution steps.

Neutral air

Neutral air is air in a defined thermodynamic state (*T,p,* and particularly humidity). It must not contain interfering components at concentrations which induce odour sensations or influence the sense of smell. Neutral air is used as dilution air and/or reference air.

Smell sample

The panellist is offered a smell sample for assessment. A smell sample may be

- A gas sample at defined dilution,
- neutral air (e.g. as a blank or reference air)
- an undiluted gas sample

Panellist[123]

A general term for any individual responding to stimuli in a sensory test.

Panel[123]

A group of panellists chosen to participate in a sensory test.

Perception[123]

The awareness of the effect of stimuli.

Receptor

A cellular structure mediating the physiological response to the presence of physical or chemical agents.

Repeatability *(r)*

The repeatability *r* is “the value below which the absolute difference between two single test results obtained using the same method, on identical test material, under the same conditions” may be expected to lie with 95% probability [120]. This would mean using the same panel, same apparatus, same laboratory and within a short interval of time.

Reproducibility *(R)*

The reproducibility R is “the value below which the absolute difference between two single test results on identical material obtained using the same method, on identical test material but under different conditions” may be expected to lie with 95% probability [120]. This would mean different panellists, different apparatus, different laboratories and/or different times.

Representativity

The panel selected for the olfactometric measurement has to be a representative sample of the population defined by the task. The frequency distribution of odour impressions from a given measurement object (gas sample) has to correspond to the frequency distribution of the population with a satisfactory approximation. This condition will normally be met with 8 to 15 panellists selected at random, if the statistical population is defined to be the real population.

Sensitivity

The ability to perceive, qualitatively or quantitatively, or both, one or more stimuli by means of the sense organs.

Supra-threshold

Pertaining to a stimulus above the specified threshold.

The procedure for odour measurement, sampling, principles of operation of a dynamic dilution olfactometer, presentation of odour concentrations and the triangular forced choice technique will be discussed in APPENDIX-III.

APPENDIX-III

III. Olfactometry

Olfactometry is the controlled presentation of odorants and the registration of the resulting sensations in man. It is a complete measuring method as defined by Guideline VDI 3881, Part 1 [124]. The main field of application of this guideline is the determination of odour thresholds and odorant concentrations of gas samples collected for air pollution prevention. The practical application of olfactometry is to investigate gas samples of unknown composition with regard to their property to induce odour sensations.

Possible tools for measurement of odour are :

III.1 Field Panels

Use of expert field panels that 'sniff out' the situation around a source, but cannot provide a quantitative description that could be used objectively in specific cases.

III.2 Population Panels

Panels are chosen usually from residents usually living around the source. They are asked to assess the odour intensity in the ambient air at their residence at a specific time every day. It can indicate a general trend in the annoyance but not suitable to provide a useful regulatory tool.

III.3 Chemical-Analytical Method

Gas Chromatography failed together with Mass Spectroscopy in this area as odour is rarely an additive result of the concentrations in the mixtures and are often determined in trace concentrations, even below detective threshold.

III.4 Olfactometry

All odour threshold measurements involve the determination of the number of dilutions of an odorous gas sample required to render it nonodorous. The devices designed are called **olfactometers** and are essential in studies of the contributions of odour to air pollution.

III.5 Olfactometer: Construction

An olfactometer consists of a dilution air pump, peristaltic odor pump, signal box, air rotameters, deodorizing chamber, six sets of sniffing ports, two manifolds and Teflon sample lines. This instrument provides six dilution stations each equipped with a set of three glass sniffing ports. Two of the ports emit deodorized room-air while the third discharges the odorous gas diluted with deodorized air.

III.6 Olfactometer: Response system

There are two forms of dynamic olfactometry response systems:

a) Yes/No Response

This is where each panel has only one sniffing port. They must indicate when they can detect an odour in the air stream.

b) Forced Choice Response

This is where panellists have 2 or more sniffing ports. At any one time only one port may contain an odour, the other(s) contain odour free air. The panellist must sniff each port and attempt to pick which one contains the odour. They must make a choice even if they cannot detect any odour.

Although more complex to implement, the forced choice technique is more sensitive than the simple yes/no technique. The increased sensitivity is due to the elimination of conservative response bias in panellists [123].

III.7 Olfactometer: Principle of Operation

Ternary Forced-Choice Method

A dilute sample is presented with two odourless samples. The panelist must identify which sample contains the odorant , and signals his choice by depressing a push button

placed at the selected port. The testing continue until the subject becomes consistently correct in the identification of the odorous sample. This olfactometer operated with a ternary forced-choice principle with approximately six trained panelists is up until the best possible way of analysing odour in terms of delectability, reproducibility, reliability and repeatability of the results. However it becomes a cost effective affair in totality as the fixed cost itself includes setting up an air-conditioned laboratory, supply of dry filtered compressed air, installation of the olfactometer complete with its accessories, availability of a suitable sampling unit and a panel of minimum 4-6 trained odour sniffers. Over and above there is a running cost of supply of special plastic sampling bags, activated carbon filters etc.

Calculation of odour threshold values

There are two main methods for calculating odour thershold values from olfactometer response data. Both assume that the odour detection thresholds of the individual panellists are log-normally distributed. The two methods are:

Percent Correct Method

The percentage correct response for each dilution is converted to a Z value (Normal Distribution) and plotted against the logarithm of dilution. The dilution corresponding to a Z value of 0 (50% correct) is found using regression analysis. A correction must be applied to the percent correct data when forced choice is used. This correction is:

$$P_{corrected} = \frac{P_{observed} - P_{chance}}{100 - P_{chance}} \times 100(\%) \qquad \textbf{-(III.1)}$$

where

$P_{observed}$ is the percentage of panel who respond correctly; and

P_{chance} is the probability % of panellists guessing the correct port (33.3% for a 3-way forced choice).

III.8 Individual Thresholds Method by Dravnieks[71]

The simplest form of this method involves estimating the threshold dilution for each individual panellist. The logarithms of these individual thresholds are averaged. The odour threshold is equal to the antilogarithm of this average.

Dynamic olfactometry methodology can differ in the following ways:

- Type of response system;
- Number of panellists;
- Selection and screening of panellists;
- Flow rate of dilution air;
- Number of sniffing ports (if forced choice);
- Dilution range and number of replicates;
- Data collection analysis technique;
- Quality control.

Figure II.1 gives a schematic of Dynamic Dilution Olfactometry.

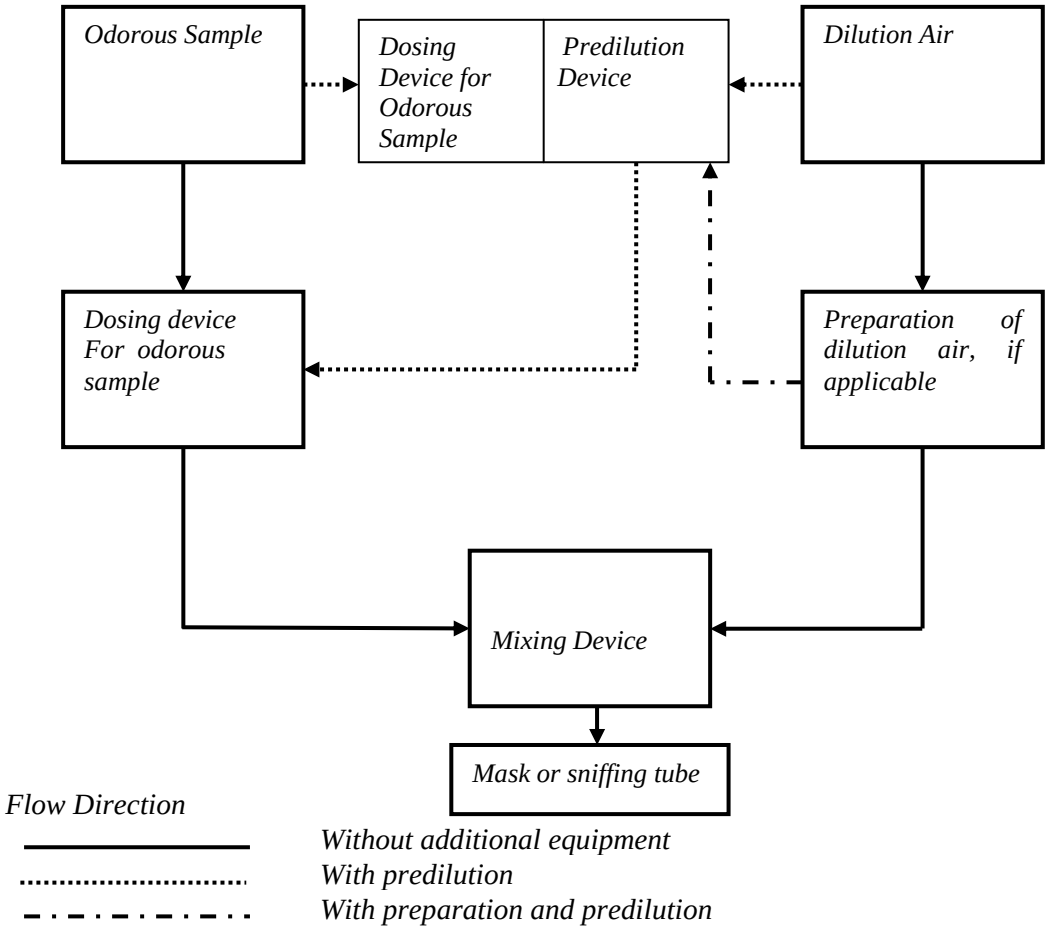

Figure III.1 Schematic diagram of dynamic dilution olfactometry.

APPENDIX-IV

IV. Ventilation exhaust rates to prevent air escape from the waste transfer building

In this appendix, ventilation exhaust rates will be calculated based on the natural ventilation physics, as described in Valentine et. al [69].

IV.1 Method

i. Specify design wind speed for the region ;

ii. Determine the ventilation coefficient from locality, nature of site, design speed and height;

iii. Calculate minimum rate of extract, below;

$$V = C \times A \qquad \text{-(IV.1)}$$

where V = ventilation rate (m^3/sec)

C = ventilation coefficient (from tables)

A = infiltration area (m^2)

In case of the transfer station an estimate of these factors is as follows:

i. Design speed for this region = 10m/sec
ii. Ventilation coefficient = 4.1
iii. Ventilation rate, $V = C \times A$

Where leakage from two sides is to be considered,

the infiltration area (A) = Leakage areas / aspect ratio (taken as 1.4)

In such cases the following formula is applied for sides a) and c),

$$\mathbf{A^1} = \frac{A_a + A_c}{1.4} \qquad \textbf{-(IV.2)}$$

In the case of the transfer station an estimate of the areas for the two adjacent sides of the building: a) and c) is:

Side a) 2 doors of 4 x 4m

Side c) 0.01 per m of wall & roof x 40m

IV.2 Calculation of the leakage for the waste trasfer station

Design wind speed = 10.0 m/sec

Ventilation coefficient = 4.1

Wall a) doors (2 nos) = 32.0

Adjacent wall c) cladding = 0.4

Combined losses from a) and c) = A^1 = (32.0+0.4) / 1.4 = 23.0

Leakage from side a) alone = 32.0 is taken,

thus, V = C x A = 4.1 x 32.0 = 131.2 m^3/sec.

The leakage from side a) is significantly greater than the additional allowance for leakage on the adjacent side c), therefore:

The higher calculation of leakage from side a) is taken giving an estimated extract value of:

131.2 m^3/sec when both doors are open,

65.6 m^3/sec with one door closed.

APPENDIX-V

V.Computation of surface layer scaling factors

In this appendix, various surface layer scaling parameters necessary to describe vertical diffusion in the atmospheric surface layer from ground level will be discussed. These include mean transport velocity, shape parameter and mean height of the plume. The use of Monin-Obukhov length and its importance in the surface layer scaling will be briefly discussed. All the expressions are specific to surface layer emissions and dispersion.

V.1 Computation of the mean height of the plume $\bar{z}$ [44,73]

The wind shear and the radiational heating of the surface plays an important role for determining the turbulence within the surface layer. Monin-Obukhov similarity theory [125] describes the effect of stability on the turbulence structure quite efficiently.

According to the Monin-Obukhov similarity theory[1] the profiles of wind speed and eddy diffusivity can be written as universal functions of z_0, L and u_*. The non-dimensional functions $\left(\Psi(z/L), \phi_m\right)$ are given below:

$$u = u_*/k\left\{\ln(z/z_0) - \Psi(z/L)\right\} \qquad \textbf{-(V.1)}$$

The von Karman constant k is 0.41.

The eddy diffusivity K is assumed equal to the diffusivity for heat.

---

[1] Monin Obukhov Similarity Theory: In a stratified surface layer any dimensionless characteristic of the turbulence can depend only upon u_*, z_0 and z/L.

$$K = ku_* z/\phi_m(z/L) \qquad \textbf{-(V.2)}$$

The general expressions for the Ψ and ϕ functions for the surface layer scaling are given below [44].

For L < 0

$$\Psi(z/L) = \phi_m^{-1} - 1 \qquad \textbf{-(V.3)}$$

$$\phi_m(z/L) = (1 - a_2 z/L)^{-1/4} \qquad \textbf{-(V.4)}$$

For L > 0

$$\Psi(z/L) = -b_2 z/L \qquad \textbf{-(V.5)}$$

$$\phi_m(z/L) = 1 + b_2 z/L \qquad \textbf{-(V.6)}$$

Nieuwstadt and van Ulden [127] have shown that *K*-models can describe the vertical dispersion from a ground level source in the surface layer quite adequately. The vertical diffusion of a passive pollutant released from a continuous crosswind line source near the ground can be expressed as:

$$u\frac{\partial c}{\partial x} = \partial(K\partial c/\partial z)/\partial z \qquad \textbf{-(V.7)}$$

where *c* is concentration at height *z*. Here horizontal diffusion is neglected. The expressions for *u* and *K*, as given in equations (V.1) and (V.2) respectively are by Businger [128]. Using the above profiles an analytical solution of equation (V.7) is quite difficult. We have approximate solutions [73] where wind speed and eddy diffusivities are expressed by power laws.

$$u(z) = u_1 z^m \qquad \textbf{-(V.8)}$$

$$K(z) = K_1 z^n \qquad \textbf{-(V.9)}$$

where u_1, K_1, m and *n* are constants.

Assuming these profiles, equation (V.7) can be written as [72]:

$$c/Q = \left(A/\bar{z}\bar{u}\right)\exp\left[-\left(Bz/\bar{z}\right)^{s}\right] \qquad \textbf{-(V.10)}$$

where Q is the source strength and A and B depend on the shape factor, s, as explained below.

$$\bar{z} \equiv \int_0^\infty zc \cdot dz \Big/ \int_0^\infty c \cdot dz\,, \qquad \textbf{-(V.11)}$$

Here $\bar{z}$ is the mean height of particles that have travelled a distance x [73], and the main horizontal velocity, $\bar{u}$, is expressed as:

$$\bar{u} \equiv \int_0^\infty uc \cdot dz \Big/ \int_0^\infty c \cdot dz\,, \qquad \textbf{-(V.12)}$$

The shape factor, s, is mainly determined by the growth of the vertical spread of the plume with distance. This is related to the powers m and n as follows:

$s = 2 + m - n$

We have,

$$A \equiv s\Gamma\left(2/s\right)/\left[\Gamma 1/s\right]^2 \qquad \textbf{-(V.13)}$$

$$B \equiv \Gamma\left(2/s\right)/\Gamma\left(1/s\right) \qquad \textbf{-(V.14)}$$

where Γ is the gamma function.

We now see that the concentration profile is determined by the mean plume height, $\bar{z}$, the mean horizontal plume velocity, $\bar{u}$ and the shape factor, s.

Firstly, we will derive expressions for the *mean plume height* $\left(\bar{z}\right)$. We can write, following equation (V.11),

$$d\bar{z}/dx = \int_0^\infty \left(z - \bar{z}\right)\left(\partial c/\partial x\right) \cdot dz \Big/ \int_0^\infty c \cdot dz \qquad \textbf{-(V.15)}$$

Equation (V.15) can be solved using equations (V.7) to (V.10) and we get:

$$d\bar{z}/dx = s\left[\Gamma\left(2/s\right)/\Gamma\left(1/s\right)\right]^{s}\left(K_1/u_1\right) \cdot z^{-1-s} \qquad \textbf{-(V.16)}$$

This form can be again written as (in terms of u and K)

$$d\bar{z}/dx = K\left(p\bar{z}\right)/u\left(p\bar{z}\right)p\bar{z} \qquad \textbf{-(V.17)}$$

where

$$p = \left[s\left\{ \Gamma\left(2/s\right)/\Gamma\left(1/s\right)\right\}^{s} \right]^{1/(1-s)} \qquad \textbf{-(V.18)}$$

We must note that equations (V.17) and (V.18) depend only on the profiles for u and K and on the shape factor, s.

An estimate of the shape factor, as given by Gryning *et al.* [129] is as follows:

V.2 Computation of the shape parameter s[44,73]

$$s = \frac{1 - a_1 c\bar{z}/(2L)}{1 - a_1 c\bar{z}/L} + \frac{\left(1 - a_2 c\bar{z}/L\right)^{-1/4}}{\ln\left(c\bar{z}/z_0\right) - \Psi\left(c\bar{z}/L\right)} \qquad \text{for L < 0} \qquad \textbf{-(V.19)}$$

$$s = \frac{1 + 2b_1 c\bar{z}/L}{1 + b_1 c\bar{z}/L} + \frac{1 + b_2 c\bar{z}/L}{\ln\left(c\bar{z}/z_0\right) + b_2 c\bar{z}/L} \qquad \text{for L > 0} \qquad \textbf{-(V.20)}$$

where

L = *Monin-Obhukov length (m)*

z_0 = *Surface aerodynamic roughness length*

k = *von karman constant* ~ 0.41

x_0 = 0 (For ground level sources)

p = 1.55

c = 0.6

$a_1 = a_2 = 16$

$b_1 = b_2 = 5$

We find that s is a function of $\bar{z}, z_0$ and L.

Now, substituting (V.1) and (V.2) into equation (V.17) we get:

$$\frac{d\bar{z}}{dx} = \frac{k^2}{\left[\ln\left(p\bar{z}/z_0\right) - \psi\left(p\bar{z}/L\right)\right] \cdot \phi_h\left(p\bar{z}/L\right)} \qquad \textbf{-(V.21)}$$

In order to obtain $\bar{z}$, as a function of *x*, equation (V.21) has to be integrated with respect to $\bar{z}$.

In the neutral and stable conditions, with functions (V.5) and (V.6) the integration gives the following result:

$$x + x_0 = \left(\bar{z}/\kappa^2\right)\cdot\left[\left\{\ln\left(c\bar{z}/z_0\right) + 2b_2\, p\bar{z}/(3L)\right\}\times\left\{1 + b_1\, p\bar{z}/(2L)\right\} + \left(b_1/4 - b_2/6\right) p\bar{z}/(L)\right]$$

for L > 0 **-(V.22)**

Here x_0 is a constant of integration, determined by the source height and it also corresponds to the upwind distance of a virtual surface source. $x_0 = 0$ for ground level sources.

In the case of an unstable atmosphere, using the functions in equations (V.3) and (V.4), we get the following approximate solution:

$$x + x_0 = \left(\bar{z}/k^2\right)\left[\ln\left(c\bar{z}/z_0\right) - \Psi\left(c\bar{z}/L\right)\right]\times\left[1 - pa_1\,\bar{z}/4L\right]^{-1/2} \qquad \text{for L} < 0 \qquad \textbf{-(V.23)}$$

The variation of $\bar{z}$ with distance and stability is shown in Figure V.1(*van Ulden's results have been verified*). In neutral conditions, $\bar{z}$ is approximately proportional to $x^{0.8}$. In moderately stable conditions, the power is about 0.5 and for the unstable conditions the power of *x* is about 1.5.

Equations (V.22) together with (V.5) and (V.6) or Equations (V.23) together with (V.3) and (V.4) are solved *iteratively* for $\bar{z}$.

Lastly, the mean horizontal velocity, $\bar{u}$ is another important factor for determining the concentration profile.

V.3 Computation of the mean transport velocity of the plume $\bar{u}$ [44,73]

Van Ulden [73] evaluated $\bar{u}$ using the concentration profile given in equation (V.6) for s varying in between 1 and 2. The percentage variation was quite low and hence we use Chatwins's [130] solution for the neutral condition.

$$\bar{u} = \left(u_*/\kappa\right)\cdot\ln\left(c\bar{z}/z_0\right) \qquad \text{for } L=0 \qquad \textbf{-(V.24)}$$

For the unstable condition, it is difficult to perform the integration in equation (V.12) analytically and we end up with the following approximate solution, that could be used for all practical purposes.

$$\bar{u} = u_*/k\left\{\ln\left(c\bar{z}/z_0\right) - \Psi\left(c\bar{z}/z_0\right)\right\} \qquad \text{for } L < 0 \qquad \textbf{-(V.25)}$$

This form is exact for $\bar{z}/L \to 0$ and $-\infty$. For any other intermediate value, the error is within 10%.

In case of stable conditions, the stability correction is linear in *z*, as given in equation (V.5) and we get the following expression for $\bar{u}$.

$$\bar{u} = u^*/k\left\{\ln\left(c\bar{z}/z_0\right) + b_2\bar{z}/L\right\} \qquad \text{for } L > 0 \qquad \textbf{-(V.26)}$$

Knowing u^*, $\bar{z}$ and z_0 $\bar{u}$ is calculated.

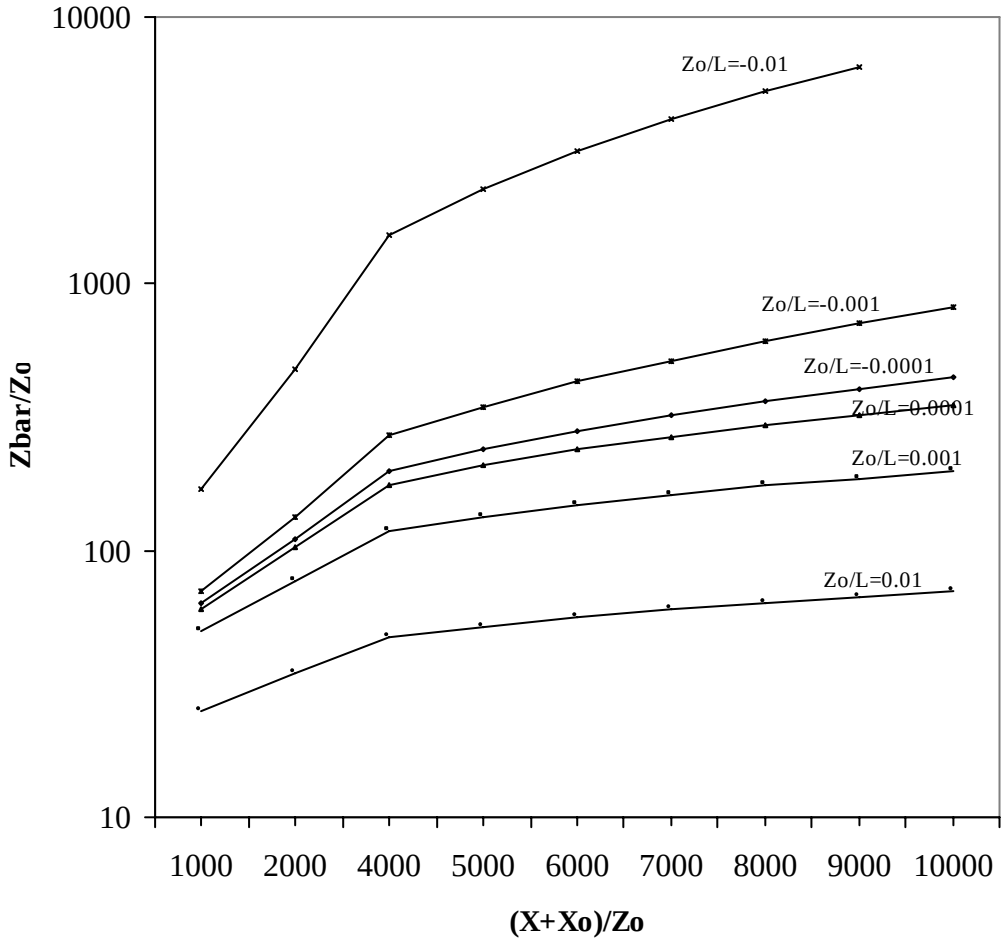

Figure V.1 The increase of the vertical dispersion with distance for several values of z_0/L.

V.4 Computation of the Monin-Obukhov Length from the meteorological observations of the experiment

Let us recall the expression for the **Turbulent Kinetic Energy** (**TKE)** [126] for a steady-state surface layer.

$$-\overline{u'w'}\cdot\partial\bar{u}/\partial z+\left(g/\overline{\theta_v}\right)\overline{w'\theta_v'}-\partial\left(\overline{w'e}+\overline{w'p'}/\rho\right)/\partial z-\varepsilon=0 \qquad \textbf{-(V.27)}$$

The term 1 is for shear production, term 2 represents the buoyant production or destruction term of the vertical component, term 3 represents the vertical transport within the ABL and term 5 is a pressure-velocity correlation term.

Near the surface, the turbulent transport is quite significant. There is a net intake of TKE into the upper atmosphere from the lower atmosphere.

In determining the intensity of turbulence, terms describing the shear production and buoyant production or destruction in the expression for the TKE [125] are quite important. The *flux Richardson number*, R_f, is defined as the ratio of the buoyant production (or destruction) and shear production terms, as they appear in the TKE. The dimensionless number, as given in equation (V.26) below, is a characteristic of the thermal stability of the flow field and as such an important parameter to define the local turbulence structure.

$$R_f=\left(\left(g/\bar{\theta}_v\right)\cdot\overline{w'\theta_v'}\Big/\overline{u'w'}\,\partial u'/\partial z+\overline{v'w'}\,\partial v'/\partial z\right) \qquad \textbf{-(V.28)}$$

The terms in equation (V.26) are clearly explained in chapter 2 of [125].

A *gradient Richardson number*, R_i, can be similarly defined using the flux-gradient relations of some of the turbulent terms concerned with the vertical transfer in the Atmospheric Boundary Layer (ABL).

$$R_i=\left(g/\overline{\theta_v}\right)\cdot\partial\overline{\theta_v}/\partial z\Big/\left[\left(\partial\bar{u}/\partial z\right)^2+\left(\partial\bar{v}/\partial z\right)^2\right] \qquad \textbf{-(V.29)}$$

In unstable atmospheric conditions both shear and buoyancy terms are positive, since TKE is produced and both R_f, R_i are negative. On the other hand for a stable atmosphere buoyancy tends to destroy the TKE and R_f, R_i are positive.

In practice, the gradient Richardson number R_i is often approximated in finite difference form, a quantity easier to measure, and it is known as the *bulk Richardson number* R_b, given by

$$R_b = \frac{g}{\theta} \cdot \frac{\dfrac{\partial \theta}{\partial z} + \gamma_d}{\left(\partial \bar{u}/\partial z\right)^2} \qquad \textbf{-(V.30)}$$

which is related to R_i by

$$R_i = \frac{R_b}{r^2} \qquad \textbf{-(V.31)}$$

where *r* is the exponent of a power law fitted to the wind profile

$$u(z) = u_1\left(\frac{z}{z_1}\right)^r \qquad \textbf{-(V.32)}$$

that best fits the wind profile. The level z_1 is arbitrary. In Equation (V.28) γ_d is the dry adiabatic lapse rate and θ is the average temperature between two levels.

Since $u = 0$ at $z = 0$, equation (V.28) takes the form

$$R_b = \frac{g \cdot z^2}{\theta} \cdot \frac{\dfrac{\partial \theta}{\partial z} + \gamma_d}{\bar{u}^2} \qquad \textbf{-(V.33)}$$

Each of the quantities in equation (V.31) can be measured and we can assume a value for γ_d to obtain R_b.

Monin-Obhukov length

There is another stability parameter, historically deduced by Obukhov using the TKE. The shear term, in the TKE tends to decrease as z increases. The height at which the

buoyancy term is exactly equal to the shear term, an important length-scale is defined, called the Monin-Obukhov length L_{MO}, as given in the following equation (V.32).

$$L = -u_{*0}^3 \Big/ \left[k(g/\theta_v)\cdot \overline{w'\theta_v'}\right] = u_{*0}^2 \Big/ \left[k\left(g/\overline{\theta_v}\right)\cdot \theta_{v*0}\right] \qquad \textbf{-(V.34)}$$

The corresponding non-dimensional height is z/L and is an equivalently important thermal stability parameter. We can relate z/L to R_i through flux-gradient relationships for different stability classes.

Unstable [126]

$$R_i = z/L \qquad \textbf{-(V.35)}$$

where

R_i = Gradient Richardson Number

L = Monin-Obhukov Length

Hence, knowing R_i, L can be evaluated for any *z*.

Stable[126]

$$R_i = \frac{z/L}{1+5\,z/L} \qquad \textbf{-(V.36)}$$

or,

$$L = \frac{z(1-5R_i)}{R_i} = z\left(\frac{1}{R_i} - 5\right)$$

Similarly, knowing R_i, L can be evaluated for any *z*.

APPENDIX-VI

VI. Footprint/Source weight functions and source areas

In this Appendix the concepts of source weight functions and source areas and their suitability in the measurement of scalars will be elaborately discussed.

VI.1 Measurement of scalars and scalar fluxes

The conceptual questions of micrometeorological flux measurements over complex inhomogeneous areas will be dealt with. Three of the most common heterogeneous surface types at the meso- to micro-scale are agricultural regions with a patch of variable crops, active cells of MSW landfills and urban areas. In most cases, there is more than one method (eddy correlation, profile technique, energy/mass balance etc.) available to give an acceptable estimate of surface turbulent fluxes. It is not very important which method is used, so long the scale of the measurements match to the scale of the fluxes.

VI.2 Objective

The objective of the present concept is to demonstrate the potential for application of these models, in a context that is highly relevant for micrometeorologists dealing problems relating estimation of fluxes from agricultural field, solid waste landfill sites, composting units etc. In this Appendix it will be shown how *footprint(or source weight*

function)/source area analysis is used for point-to-area representativeness of micrometeorological measurements.

VI.3 Relative source strength distribution for a given observation

The spatial scale of a surface flux estimate depends on the method by which it is obtained. In here, the method described involves measurements of concentration (rather concentration difference between the particular location and the background). In the following derivation we assume that,

- The exchange of heat, mass or momentum within the atmospheric surface layer is dependent on the capacity of the underlying surface to act as a source or a sink.
- Thus the measured value of an atmospheric variable is characterised by those surface patches which have the strongest influence on the sensor and it varies with the position.

The scales of observations of any such exchange process is estimated by considering the relative source strength distribution for a given observation following Schmid [43]. The distribution of a diffusing quantity in the atmosphere can be described by the integral equation of diffusion:

$$\eta(r) = \iint_{\Re} Q_\eta(r') \cdot f(r - r') \cdot dr' \qquad \textbf{-(VI.1)}$$

η = Value of the measured quantity at r.

Q_η = Source strength (at r')

f = Probability transfer function between r and r'.

$\Re$ = Domain of integration.

If the source strength is confined to the surface $z = z_0$ and diffusion parallel to the mean wind direction (i.e. along the x-axis) is neglected, equation (VI.1) can be written for any observation point at (x_m, y_m, z_m) as:

$$\eta(x_m, y_m, z_m) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} Q_\eta(x', y', z_0) \cdot f(x_m - x', y_m - y', z_m - z_0) \cdot dx' \cdot dy' \qquad \textbf{-(VI.2)}$$

$f\left(x_m - x^{'}, y_m - y^{'}, z_m - z_0\right)$ is the *footprint or source distribution function* and relates the value of η at $\left(x_m, y_m, z_m\right)$ to the source distribution on the ground and would accordingly be defined as the *source weight function [41,42] or the footprint function [66,67]*. The functional value of a source weight can be interpreted as the relative weight of a given source, say at $\left(x, y\right)$, to contribute to the value of η at an observation or reference point. The source weight is therefore dependent on the separation distance between the source and the reference point. The functional form of the source weight is determined by the diffusion characteristics and transport properties relevant for the distribution of η and on the nature of η itself.

VI.4 Use of relative source weights

The functional form of the source weight distribution, $f\left(x_m - x^{'}, y_m - y^{'}, z_m - z_0\right)$, can be evaluated by considering a point source of unit strength at $\left(x, y, z_0\right)$, so that the source strength distribution is:

$$Q_\eta\left(x^{'}, y^{'}, z_0\right) = Q_{\eta,u} \cdot \delta\left(x - x^{'}\right) \cdot \delta\left(y - y^{'}\right) \qquad \textbf{-(VI.3)}$$

Here, $Q_{n,u}$ is a constant of unit source strength to ensure dimensional consistency and δ is the Dirac-delta distribution function. Now, if we perform convolution on (VI.2) with (VI.3),

$$\Rightarrow \eta\left(x_m, y_m, z_m\right) = Q_{\eta,u} \cdot f\left(\Delta x, \Delta y, \Delta z\right) \qquad \textbf{-(VI.4)}$$

where,

$\Delta x = x_m - x$

$\Delta y = y_m - y$

$\Delta z = z_m - z_0$

and η may be any diffusing quantity, but whether it is a scalar or a scalar flux would be reflected in the functional form of *f*.

$f(\Delta x, \Delta y, \Delta z)$ depends on

- Nature of η
- Characteristics of transport between source and sensor.
- Differs highly amongst all modes of transfer.

If the diffusion of η is passive and individual sources are independent of each other, we can calculate the distribution of η at level z_m due to a surface point source with horizontal separation (x, y), in order to evaluate its source weight function. In an advective situation, most of the contributions from sources close to the sensor will not have enough time to be diffused up to z_m before being advected past the reference point. Hence, for small separation distances, the source weight is small. It would rise to a maximum with increasing distance and then fall off again to all sides as the separation distance is further increased (see Figure VI.1). Here, it is assumed that,

- Turbulence is horizontally homogeneous.
- The mean wind direction in a parallel but counter to the x-axis direction.

The source weight function provides information about the relative weights of individual point sources. In practice, it is often desirable to obtain an estimate of the particular region of the surface that is most efficiently influencing the value of η at height z_m. The smallest such area, Ω_P, was termed the *source area of level P* by Schmid and Oke [41].

VI.5 Source area

Another practical concept for the scale of an observation is based on estimating the region of the surface which is most effectively or most probably influencing the value of η at the sensor height, z_m.

A *source area* is defined by considering that source weight function describes the distribution of the probability density such that a point on the surface has an influence on the measurement. The normal projection of any closed curve (into the *x-y* plane) around the source weight function surface gives a *discrete area* on the ground. The probability, that this particular area has influenced the signal from the sensor, is

proportional to the integral over the source weight function. The closed curve around the source weight function surface serves as the integration limit.

The special scale of a given observation of η is then indicated by the smallest possible area to account for a given contribution P influencing the value of η at z_m. The smallest such area (Ω_P), was termed the *source area of level P* by Schmid and Oke [41].

The source area is analogous to the "field of view" of an instrument. The contributions of individual surface elements within the zone of influence are combined to produce a combined influence of the source area in the measured signal. Thus, the source area may be defined as the area bounded by a source weight function- isopleth $f(\Delta x, \Delta y, \Delta z_m) = f_P$, such that P is the fraction of the total integrated source weight function, φ_{tot}, contained in Ω_P:

$$P = \frac{\varphi_P}{\varphi_{tot}} = \iint_{\varphi_P} f(\Delta x, \Delta y, \Delta z\ ) \cdot d\Delta x \cdot d\Delta y \Big/ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(\Delta x, \Delta y, \Delta z\ ) \cdot d\Delta x \cdot d\Delta y \qquad \textbf{-(VI.5)}$$

where φ_P is the integral of the source weight function over Ω_P,e.g. 90% source area is the smallest area accounting for 90% of the detected signal. The source area and its relation to the source weight function is illustrated schematically in Figure VI.1. The source area fraction P is equivalent to the volume under the source weight function, bounded by the isopleth f_P, and the cylinder surface below it. Since, with a particular z_m and transfer conditions, f depends only on the horizontal separation equation (VI.5) reduces to equation (VI.6) separation with equation (VI.4),considering a measurement at point *(0,0,* z_m*)*:

$$P = \frac{\varphi_P}{\varphi_{tot}} = \int\int_{\varphi_P} \eta(x, y, z_m) \cdot dx \cdot dy \Big/ \int_{-\infty}^{\infty}\int_{0}^{\infty} \eta(x, y, z_m) \cdot dx \cdot dy \qquad \textbf{-(VI.6)}$$

and Ω_P is bounded by $\eta(x, y, z_m) = \eta_P$, where the vertical separation $(z_m - z_0)$ is denoted in simplified form as z_m.

For various types of scalars (e.g. concentration) and scalar fluxes (e.g. radiative flux), the footprint/source weight function takes different functional forms. The equivalent formulations for the source weight density, f, and the corresponding expressions for equations (VI.4) and (VI.6) will be different for each of the applications.

In case of our application for measurement of a scalar concentration, η has been substituted by the scalar concentration term, C, in all the expressions. Details of the derivations are given in *section 3.4.1* and *3.4.2* of Chapter 3.

VI.6 Relation of source weight/footprint function to the source area.

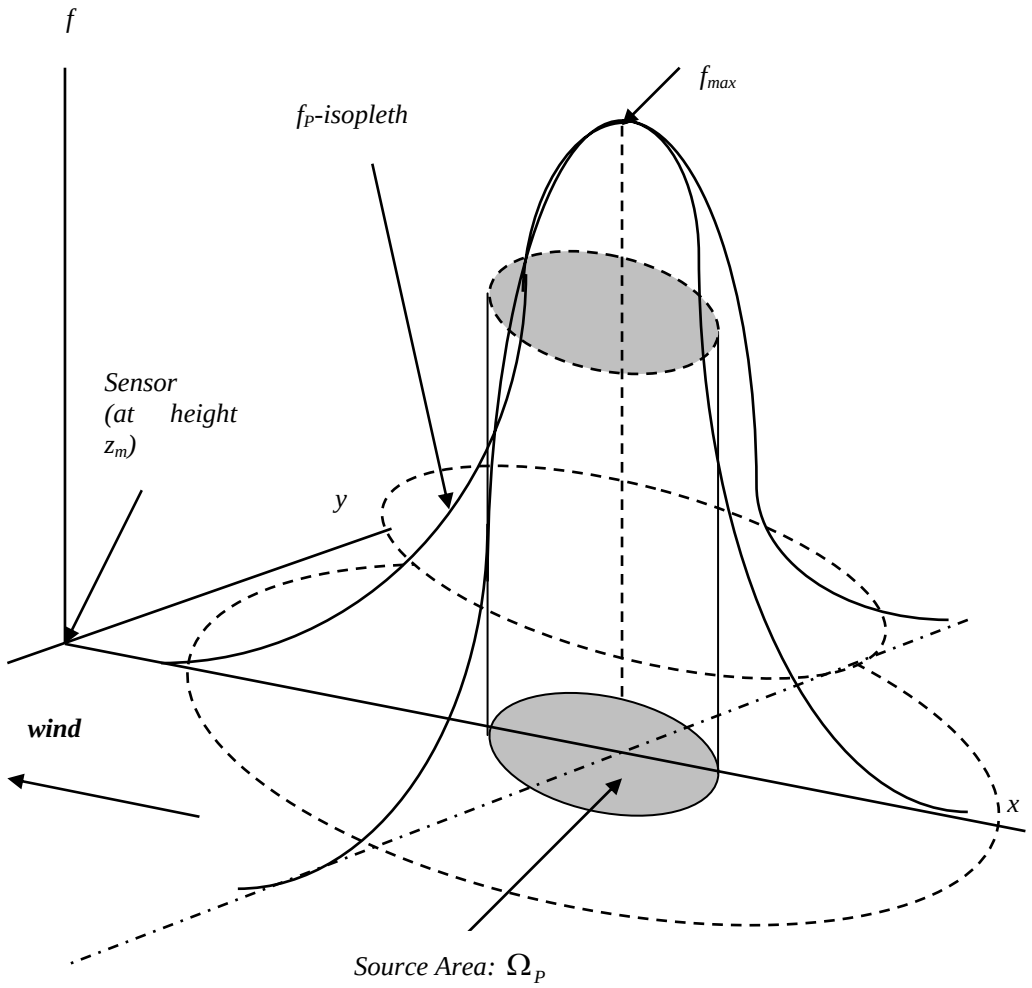

Figure VI.1 Schematic diagram showing the source area and its relation to the source weight/footprint function.

The source weight is small for small separation distances. It will rise to a maximum with increasing distance and then fall off again to all sides as the separation is further increased. The total volume under the source weight function curve is φ_{tot}. P is the fraction of this volume bounded by the isopleth f_P, and the cylinder surface below it (*grey*). The source area of level P, Ω_P, is the area bounded by the normal projection of the isopleth f_P on the *x*-*y* plane. We assume that the turbulence is horizontally homogeneous for footprints of diffusing quantities. The mean wind direction is parallel but counter to the direction of the *x*-axis.

APPENDIX-VII

VII. Requirement of data for commercial software on atmospheric dispersion modelling (specific to UK-ADMS)

In this Appendix we will discuss about requirement of various types of data for running various commercial software on atmospheric dispersion modelling. The trend will resemble the requirement for UK-ADMS.

VII.1 Input data

a) EMISSION DATA
b) METEOROLOGICAL DATA
c) LOCAL GEOGRAPHICAL DATA
d) CHEMICAL AND PHYSICAL TRANSFORMATION OF POLLUTANTS
e) DRY AND WET DEPOSITION
f) DATA FOR SPECIFIC OUTPUT (Averaging time,Receptor coordinates etc.)

VII.2 Output data

a) SOURCE CHARACTERISTICS
b) RECEPTOR COORDINATES
c) POLLUTANT CONCENTRATION (Required averages like hourly, monthly, quarterly, annual etc.)

VII.3 Emission data

1. RELEASE TYPE:
    a) CONTINUOUS
    b) FINITE DURATION
2. CONSIDERATION FOR PLUME RISE:
    c) YES
    d) NO

VII.4 Data for continuous release

FOR CONDITION **2 b)**:

PARAMETER	SYMBOL	UNITS (SI)
Source Height	h	m
Source Diameter	*D*	m
Source Strength	*Q*	Kg/s
Unit for concentration	*C*	ou/m^3

FOR CONDITION **2 a)**.

PARAMETER	SYMBOL	UNITS (SI)
Source Height	h	m
Source Diameter	*D*	m
Source Strength	*m*	Kg/s
Unit for concentration	*C*	ou/m^3
* Vertical velocity	*V*	m/s
* Volume flowrate	*Q*	m^3/s
* Specific Heat Capacity	C_p	J/Kg.$^{\circ}$C
* Molar Volume	M_v	m^3/mole
* Density	ρ	Kg/ m^3

* *Represents parameters to be calculated with respect to release conditions.*

RELEASE CONDITIONS

1) Values at release temperature
2) Values at NTP

VII.5 Additional data for finite duration release

Total Emissions	q	Kg
Duration	*t*	s

VII.6 Meteorological data (presented as a sequence of records)

1. Boundary Layer Height provided. (*data required are marked by ** in* Table VII.1)
2. Boundary Layer Height *not* provided. (*Full set of data required*)

If the meteorological data is **not** representative of the site, then following techniques are used for calculating the meteorology at source.

Simple Technique: Data Required (For Meteorological Site)

a) Surface Roughness
b) Latitude

VII.7 Local geographical data

1. Latitude
2. Surface Roughness

VII.8 Data specifically required for various complex effects

1. Effect of buildings (Data required):

a) Building Coordinates
b) Length, Side and Height of the building
c) Angle of the building *with respect to* the reference coordinate
d) Surface Elevation data file
e) Surface roughness data file

2. *Effect of coastline:*
    a) Coast-Source distance
    b) Coast-Source angle
3. *Effect of hills:*

Hill parameters:

    a) Source co-ordinates
    b) Grid size
    c) Surface elevation data file
    d) Surface roughness data file

VII.9 Survey data

    a) East co-ordinate of the receptor
    b) North co-ordinate of the receptor
    c) Receptor height above local ground level
    d) Receptor ground-level elevation

VII.10 Data for chemical and physical transformation of pollutants

1. Data for Chemical Transformation:
2. Rate constants
3. Temperature of reaction
4. Order of the reaction

VII.11 Data for dispersion of *radioactive* pollutants

1. Name of the isotope
2. Strength of emission
3. Half-life
4. Isotope data file could be used

Special calculations are necessary for Gamma-Radiation.

VII.12 Data for dry deposition

Particulate:

1. Deposition velocity
2. Terminal velocity:
    a) Particle diameter
    b) Particle density

Gases:

    a) Gas deposition velocity

VII.13 Data for wet deposition

1. Washout coefficients.

VII.14 Data for specific outputs

1. Receptor co-ordinates
    a) No. of grid points in X,Y & Z directions
    b) Spacing between X,Y,& Z grid points
2. Averaging time
3. Lateral dispersion due to changes in mean wind direction: -wind direction
4. For finite duration releases we need to specify whether we want an output for
    a) Instantaneous concentration profile (***or***)
    b) Time integrated concentration profile

Table VII.1 Requirement of meteorological data for UK-ADMS.

Symbol	Case	Parameter	Units (SI)
U	**	wind speed	m/s
UGSTAR		geostrophic wind speed normalised by the friction velocity	
PHI	**	wind direction (angle wind is coming from in degrees clockwise from north)	degrees C
DELTAPHI		geostrophic wind direction minus surface wind direction	degrees C
FTHETA0		surface sensible heat flux	$J/m^2.s$
RECIPLMO		reciprocal of the Monin-Obukhov length	
H	**	boundary layer depth	m
NU		buoyancy frequency above the boundary layer	
DELTATHETA		temperature jump across the boundary layer top	
T0C	**	near surface temperature	degrees C
P	**	precipitation rate	mm/hour
CL	**	cloud amount	oktas
R		surface albedo	
ALPHA		modified Priestley-Taylor parameter [10]	
TSEA		sea surface temperature	degrees C
DELTAT		near surface temperature over land minus sea surface temperature	degrees C
TDAY	**	Julian day number	
THOUR	**	local time	hours
FR		frequency of occasions when these conditions occur	

Specify height of recorded wind.