ODOUR MANAGEMENT AT LANDFILLS

By

Duncan Roebuck
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ABSTRACT

Landfill sites that are situated near residential zones pose significant management challenges. One of the key issues concerns odour emissions; they can be a major cause of public opposition to the existence of landfills. Mounting opposition can result in costly and premature closure of waste management facilities.

The Bisasar Road landfill in Durban is one of the largest general waste landfills in South Africa, and is surrounded by residential areas on three sides. Odour emissions are therefore of primary concern. The situation at Bisasar provided an opportunity to involve the surrounding residents as odour "receptors" in order to undertake research that would provide a better understanding of odour emissions and how best to manage them. Effective management of odour emissions requires a model to accurately predict the occurrence and extent of the problem. For effective modelling and prediction of odour at a landfill, it becomes necessary to characterize the odour sources in terms of their odour emission rates and also to establish the population's response to the odour over a wide range of concentrations. This thesis describes the application of numerical dispersion modelling, coupled with interactive community involvement, in order to indirectly estimate odour emission rates, where the community acts as an odour assessment panel.

A reanalysis of data captured from a 2002 community survey was performed in order to investigate the odour emission rate from the open waste piles – transfer station and working face - at the Bisasar road Landfill site. The odour emission rate from these similar odour sources was found to lie in the range 10^2-10^3 OU/m^2/s. For the duration of the survey, the working face contributed 82% to the odour perceived at the receptors and the Transfer Station contributed 18% to the overall offsite odour. The 2002 survey required receptors to fill out a weekly diary of odour observations, but a new community survey in 2004 used direct telephonic communication with receptors to establish the odour impact. Residents were contacted telephonically at their homes on a regular basis to ascertain whether they perceived an odour at the time of call. This data, in conjunction with the concentration predictions form the odour prediction model, allowed for an emission rate for the open waste piles to be inferred through backward dispersion. The emission rate from an open waste pile was estimated at being 250 OU/m^2/s. The individual response of each receptor as well as the combined response for the panel to a range of odour concentrations was assessed in terms of probability of detection and perceived odour intensity.

The odour emission rate, inferred through backward dispersion using the 2004 community survey data, was used to establish the impact of the odour from the open waste piles on the surrounding community through long term forward dispersion calculations. This provided a scientifically defensible methodology for the specification of buffer zones around sources that emit nuisance odours.

PREFACE

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

08/11/05 ....

Date

D Roebuck ....

Signature

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LIST OF SYMBOLS

A	annoyance or area
a	dimensionless constant for persistence of annoyance
A_s	surface area covered by wind tunnel
A_t	cross sectional area of wind tunnel
C	odour concentration
$C_{50\%}$	concentration that corresponds to the odour threshold
C_{5AU}	concentration that corresponds to population annoyance of 5AU
F_o	sensible heat flux
I	odour intensity
k_1 ,k_2	constants used in odour intensity analysis
n	total number of observations in bin, both negative and positive
p	dimensionless constant for odour persistence
P	probability of detection
Q	odour emission rate
Q_{OU}	odour strength
T	ensemble averaging time
t	time
T_f	fluctuations averaging time
T_R	source emission temperature
T_{STP}	temperature at standard temperature and pressure
u_{10}	average wind speed at 10m
V	volumetric flowrate
v_e	efflux velocity
v_t	wind speed indise wind tunnel
x	travel distance from source
z_o	surface roughness
σ_θ	standard deviation of wind direction
σ_{yt}	transverse spread due to turbulence

σ_{yw}	transverse spread due to variations in mean wind speed
σ_y	transverse spread parameter
σ_z	vertical spread parameter
θ	mean wind direction

LIST OF ABBREVIATIONS

ADMS	atmospheric dispersion modelling system
AU	annoyance units
BET	best estimate threshold
FWO	fresh waste odour
GC	gas chromatography
GC-MS	gas chromatography – mass spectrometry
LFG	landfill gas
Met	Meteorological
MOPD	maximum odour perception distance
MSW	municipal solid waste
OER	odour emission rate
OMS	odour management system
OU	odour unit
OU_E	odour unit (European standard)
VOC	volatile organic compounds

CHAPTER 1

1. INTRODUCTION

1.1 Motivation

The public's negative perception of land filling is largely due to the unpleasant odours which are associated with this means of waste disposal. What with the spread of urbanization and increased public awareness regarding environmental matters, public opposition to waste disposal facilities is now mounting to the point where the costly and premature closure of these facilities is being threatened. This is currently the case at the Bisasar landfill in Durban which is situated in the middle of a residential community.

Whilst the potential for odours to cause nuisance in communities is recognized, there is also increased focus on the potential health impacts of environmental odour pollution. Research by Shusterman (1999) suggests that prolonged exposure to certain odours in the environment can result in an exacerbation of underlying medical conditions and in some instances, cause stress-induced illnesses. Repetitive exposures to odour are also thought to cause changes to the reactions of the human immune system (Best et al., 2004).

Clearly there is a need to manage the odour emissions from landfills which are located near sensitive receptors. Effective management of odour emissions requires a model to accurately predict the occurrence and extent of the problem (Roebuck et al., 2004). For effective modelling and prediction of odour at a landfill, it becomes necessary characterize the odour sources in terms of their odour emission rates (OERs) and also to establish the population response over a range of odour concentrations. There is, however; no existing reliable method for characterizing odour emissions from landfill operations.

This research was motivated by the need for an effective odour prediction system at the Bisasar Landfill which can accurately predict the odour impact in the community and serve as a management tool.

1.2 Objectives

The main objective of this research was to use interactive community feedback in conjunction with numerical dispersion modeling to indirectly estimate the OER from the open waste piles – i.e. working face and transfer station - at the Bisasar landfill site.

An Odour Management System (OMS), developed by Laister (2002), is currently in operation at Bisasar Road landfill. The system uses regularly updated weather data from the site to generate real-time predictions of the odour plumes from the landfill. This thesis focuses on an attempt to calibrate and optimize this model through the specification of an accurate OER. A telephonic survey carried out in 2004 was used to achieve this objective.

An early attempt at calibrating the dispersion model using community feedback is described in Laister et al. (2002) and Laister (2003a). Community feedback was achieved through a diary type survey conducted in 2002 where receptors were required to record when they did smell ('positive' observation) and didn't smell ('negative' observation) an odour. Laister et al. (2002) and Laister (2003a) introduced a methodology, which was adapted and developed for the current research, whereby receptor observations in the community could be combined with dispersion model concentration estimates to establish an odour threshold for the community. The odour threshold is that odour concentration at which 50% of an odour panel will detect the odour and is defined as 1 odour unit (OU). The method sorts model predictions into bins (concentration ranges) with their associated receptor responses. The probability that an odour will be detected for a particular concentration range is then calculated from the number of positive and negative odour detections associated with that bin. A dose response histogram, where the probability of detection is plotted on the vertical axis and the odour concentration range on the horizontal axis, is then generated. This plot allows for an estimate of the odour threshold to be made by identifying the bin which corresponds to the 50^{th} percentile of detection. Through reverse dispersion it is then possible to infer the OER in $OU/m^2/s$ for the source(s) that contributed to the odour.

In this dissertation, the 2002 community survey data is reanalyzed together with newly generated odour predictions in order to develop and adapt the methodology for inferring emission rates using community feedback and odour predictions. The reanalysis aimed to establish an initial estimate for the OER from the open waste piles. Through reanalysing the data, it was hoped that a better understanding of the individual contributions of the transfer station and working face to the overall offsite odour problem could be gained.

A new telephonic community survey was conducted in 2004 with the intention of gathering data to help characterize the odour being emitted from the open waste piles. The new survey aimed to produce more accurate data for a more precise estimate of the OER. The response of the community to a range of odour concentrations was analyzed in terms of perceived intensity and probability of detection as part of the odour characterization. The new community survey also aimed to foster a continued and good relationship with the surrounding community.

Another objective of this research was to develop a scientific methodology for the specification of buffer zones using a numerical dispersion model and feedback from the community.

There are two main sources of odour identified at Bisasar: old waste undergoing anaerobic decomposition emits landfill gas (LFG); and new waste arriving at the landfill on a daily basis emits a distinct 'fresh waste' odour (FWO). The new waste arriving daily is dumped as open waste piles at the transfer station and the landfill working face. This research aimed to establish the odour emission rate from these open waste piles. Emissions of LFG are a very serious source of odour, however; these emissions were neglected since a planned gas to electricity project, which should be implemented at Bisasar in the near future, will involve actively drawing LFG out of the landfill and burning it to generate electricity. It is expected that this will reduce the odour from biogas emissions by up to 80%. This will leave the open waste piles as the major remaining sources of odour.

The main objectives of this research can be summarized as follows:

1) To calibrate the model by establishing the OER in OU/m^2/s from the open waste piles at the Bisasar Road landfill.

2) Investigate the relative contribution of the working face and the transfer station to the offsite odour impact.

3) To characterize the odour being emitted from the open waste piles through relating the responses of the receptor group to a range of odour concentrations. The responses were expressed in terms of probability of detection and perceived intensity.

4) Establish the best means of conducting community surveys to meet the above objectives by comparing the 2002 community survey with the telephonic community survey conducted over 2004.

5) Develop a scientific methodology for the specification of buffer zones using odour as the main criterion for defining protection distances.

1.3 Outline of dissertation

The second chapter of this dissertation contains a review of the literature and case studies covering: techniques for OER measurement; means of characterizing odour; the use of community feedback to investigate odour; buffer zone specification; and a summary of the odour research conducted at the Bisasar landfill.

Chapter three explores the challenge of modeling odour dispersion given that the methodology for odour is somewhat different from normal dispersion modeling.

Chapter four tackles the reanalysis of the data that was captured during the 2002 community survey with the intention of inferring an emission rate from an open waste pile and establishing the relative contributions from the working face and transfer station.

Chapter five introduces the new telephonic community survey which was conducted in 2004 with the intention of better characterizing the odour emissions from the open waste piles. The general response of the community as well as the individual receptor responses to a range of odour concentrations is investigated in this chapter.

Chapter six explores the application of relationships established from community feedback and numerical dispersion models to the specification of buffer zones using Bisasar as the case study site.

Chapter seven briefly summarises the research and draws conclusions. Various recommendations are also made here.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Introduction

Various techniques for characterizing odours and odour sources have been developed. Characterizing odour sources in terms of their odour emission rate (OER), which is the focus of this research, is achieved using a variety of direct and indirect measurement techniques. Various case studies involving the estimation of odour emission rates from large area sources such as landfill surfaces are discussed. To fully characterize an odour requires more than just the estimate of the odour threshold, but also a characterization of its perceived intensity and annoyance potential. The probability of response of an odour panel or community over a range of odour concentrations is also an important part of characterizing an odour and establishing its impact. Increasingly, it is becoming common to include community modelling in the characterization of odours and to establish the impact of odours in communities. The use of community input has been employed in a number of nuisance odour cases around the world and various case studies are discussed. Basic guides for specifying buffer zone distances around nuisance odour sources such as landfills exist. However, once an odour source has been characterized, its impact can be established using dispersion modelling with the intention of specifying a scientifically defensible buffer zone. A theoretical buffer zone was specified for a landfill in South Africa with this approach. Previous odour research carried out at the Bisasar landfill is briefly discussed here.

2.2 Overview of odour measurement techniques

Odour can be measured and monitored using various analytical and electronic techniques, or through the use of human sensory panels.

2.2.1 Gas chromatographic analysis

Analytical techniques have generally relied upon the application of gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS) for the analysis of odorous volatile organic compounds (VOCs) (Brewer & Cadwallader, 2004). Such techniques allow for the identification of the various VOCs that comprise the odorous gas. They also provide information regarding the proportion of each chemical constituent in VOC mixture.

2.2.2 Electronic nose

This instrument contains an array of electronic chemical receptors which respond to volatile chemicals; it then uses the information to produce sensory-like responses (Brewer & Cadwallader, 2004). Electronic noses can contain an array of sensors – metal oxides, lipid layers and conducting polymers – which respond to a wide variety of chemical classes. The sensors change resistance on exposure to odour and this change or response can be analyzed to establish the type, quantity and quality of an odour. The electronic nose can be trained to react like a human nose by discriminating between good and bad odours, but this requires that the nose be standardized by both chemical and olfactometric methods.

2.2.3 Dynamic olfactometry

Since no method exists at present to simulate and predict the responses of the human sense of smell, the human nose is the most suitable 'sensor' (Frequently@, 2004). Objective methods have been developed to establish odour concentration, using human assessors. The aim of dynamic olfactometry is to use a panel of human 'sniffers' to establish the odour threshold of an odour. The odour threshold is that concentration at which half the panel of 'sniffers' will detect an odour and the other half will not and is expressed as one odour unit, 1 OU. There is no electronic or analytical instrument available that can quickly measure the concentration of odours consisting of many compounds, so the odour unit becomes a useful means of quantifying an odour comprising many odorous chemicals (Brewer & Cadwallader, 2004).

Odour Thresholds are determined using a presentation method called the "3-alternative forced choice" or the "triangular forced-choice" method (Odour@, 2002). Each assessor of a panel of 1, 4, 6 or 8 sniffers performs the odour evaluation task by sniffing a diluted odour from an olfactometer. The assessor sniffs three sample presentations; one contains the odour while the other two are odour free. They must then choose the one that they believe is different from the other two. After the first set of three presentations, the assessor is then presented with another set of three but at the next concentration level. The next level presents the odour at a now higher concentration; usually two or three times higher than the previous set. The first concentration presented to the assessor is below the odour threshold and successive concentrations are presented to the assessor in an ascending concentration series. At some point in the concentration series, each panellist will be able to detect the odour (detection threshold). The Best Estimate Threshold (BET), the halfway point between the concentration where odour can and can not be detected, is calculated as the square root of the product of those two concentrations (ASTM, 1997). The BET value for each panellist is established. The log of each BET value is then calculated and averaged to get the geometric mean. The antilog of the BET geometric mean is the average concentration at which the group can detect the odour and this is defined as 1 OU. McGinley et al. (2000) make an important point regarding the units used for odour: "The detection threshold and recognition threshold of an odour sample are derived using dilution-ratios and the best-estimate criteria and, therefore, are dimensionless. However, the pseudo-dimensions of Odour Units (OU) or Odour Units per Unit Volume are commonly applied. For example: Odour Units per Cubic Meter". If the original sample had to be diluted by a factor of X to reach the odour threshold, then the original concentration of the sample in odour units per meter cubed is X OU/m^3.

The above methodology establishes the odour threshold in terms of the detection threshold. Sometimes the odour threshold is defined in terms of the discrimination threshold. The discrimination threshold differs from the detection threshold in that it represents the concentration at which the panellists are certain they can detect the odour. It represents the concentration at which panellists can do more than just detect the odour, but can identify it too. The discrimination threshold is sometimes referred to as the recognition threshold. Currently there are no universally agreed upon definitions that standardize the measurement techniques for thresholds (Nicell, 2003). However, the detection threshold appears to be the more common measure of the odour threshold.

An alternative used in some odour studies is the odour unit OU_E (CEN, 1999). One OU_E is the mass of pollutant that, when evaporated into $1m^3$ of odourless gas at standard conditions, has the same odour nuisance as 1 OU of a reference odourant.

Plate 2-1 shows a four-sniffing-place yes/no olfactometer used in forced choice olfactometry for the estimate of odour thresholds. Olfactometers can come in numerous designs with varying numbers of sniffing ports, but they usually adhere to the design and operating criteria as stipulated by the ASTM E679-91 and EU 13725 standards from North America and Europe respectively. Computers are used to carefully regulate the mixing of the odorous sample with clean odourless air to supply each sniffer with varying concentrations of the odour sample.

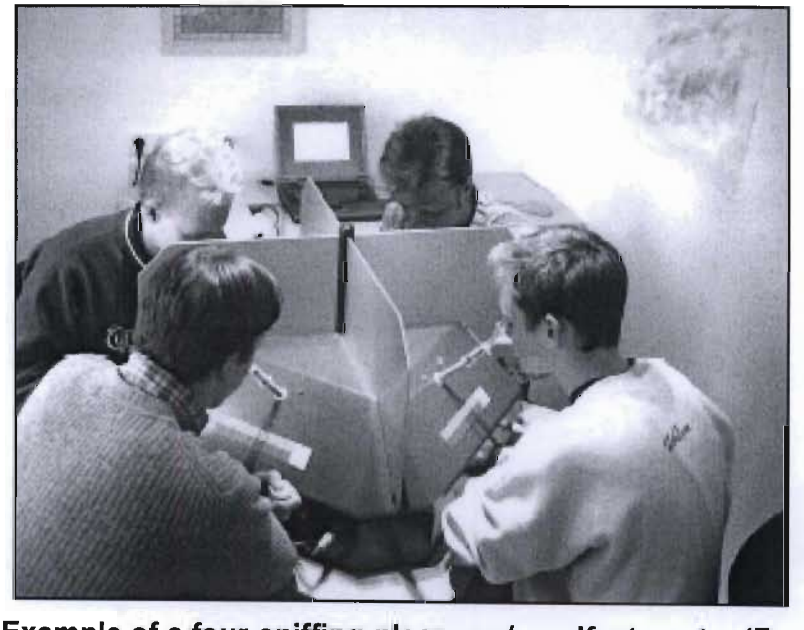


Plate 2-1: Example of a four-sniffing-place yes/no olfactometer (Frechen, 2003).

2.3 Measuring Odour Emission Rates (OERs)

It is imperative when characterizing an odour source that the odour emission rate from the source be established. Generally, the odour emission rate from a source is established as the product of the odour concentration at the source and the volumetric flow rate from the source.

The odour emission rate of a source can be established through either direct or indirect measurement techniques. Direct measurement involves the collection of odour samples at the source and the analysis thereof to establish the emission rate. Indirect measurement techniques involve the sampling of odour some distance downwind from the source and the use of a dispersion model to infer the emission rate at the source through backward dispersion. These two approaches for measuring odour emission rate are discussed in general here. Various case studies demonstrating the application of each approach are also discussed.

2.3.1 Direct Measurement

Odour emits from various source types such as stacks in industrial processes to landfill surfaces. Each source has a special requirement for sampling and measurement. Odour sources can be distinguished as being either active sources (there is a measurable outward airflow) or passive sources (there is no measurable outward airflow) (Frechen, 2003).

Active source

Sampling an active source is relatively easy and the outward airflow can either be measured by standard procedures or determined from operator documentation and process control system outputs (Frechen, 2003). Sampling of the outward airflow must ensure a representative mixture of the air being emitted in order to accurately characterize the behaviour of the odour source. This is achieved by either applying a total cover over the source, or in the case of large sources, performing incremental sampling by covering several parts of the active source. A sample is collected in a tedlar bag and sent for analysis to establish the odour concentration of the sample. In the case of a point source such as a stack in an industrial process, the odour emission rate can be calculated as follows:

$$(OER) = CV \qquad (2\text{-}1)$$

Where C is the odour concentration and V is the volumetric flow rate of gas from the stack.

Passive source

Area sources, such as landfill surfaces, are considered "passive sources" as they obviously emit odour but without a measurable outward airflow. In the case of such odour sources, it is still important to measure the odour emission rate. Typically, hood methods would be used and are commonly divided into static flux chambers, dynamic flux chambers and wind tunnels. Plate 2-2 shows an example of a wind tunnel with inlet and outlet ducts connected to the housing for the fans, one each at the inlet and outlet. On top of the tunnel is the electrical equipment. Clean air is drawn through the tunnel at a fixed rate and flows over the defined odour emitting surface where convective mass transfer takes place as it would in the natural atmosphere (How@, 2005). A Tedlar bag is placed at the outlet to collect a sample of the outflow. The concentration of the odour in the sample is then established through one of the various odour measurement techniques discussed previously. The OER in OU/m^2/s, if sampling is done using a wind tunnel and measurement through dynamic olfactometry, is calculated as follows:

$$OER = Cv_t \frac{A_t}{A_s} \qquad (2\text{-}2)$$

Where C is the concentration in OU/m^3; v_t the wind speed inside the tunnel; A_t is the cross sectional area of the tunnel; and A_s is the surface area covered by the tunnel.

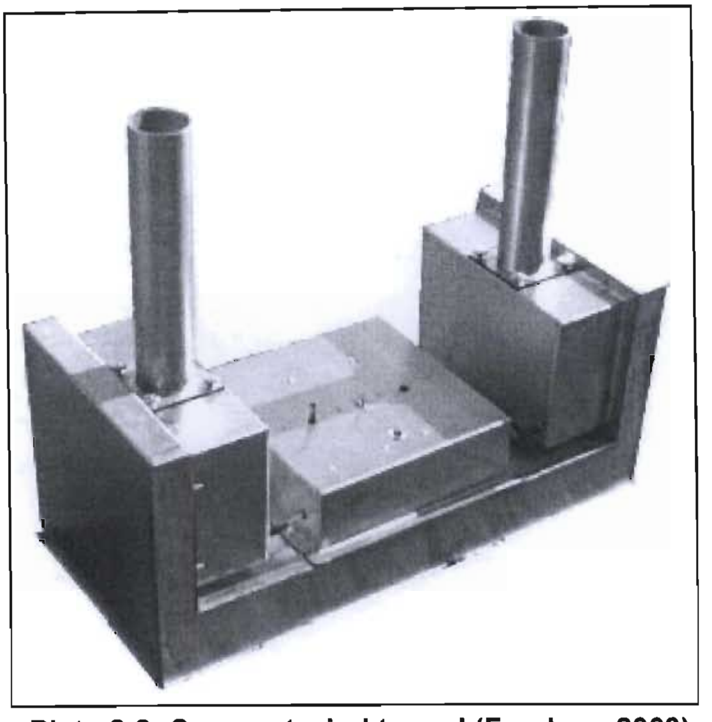


Plate 2-2: Compact wind tunnel (Frechen, 2003).

2.3.2 Indirect Measurement

Indirect measurement techniques are not commonly used, but are useful where direct measurements of odour are not practical. The VDI guideline (VDI, 1993) provides details of how to use field inspection of an odour plume for the purposes of estimating odour emission rates and to calibrate dispersion models. A trained test person or panel makes observations of the odour plume downwind from an odour source and these observations are then correlated and compared to predictions generated by a dispersion model. A sample can also be collected downwind of the odour source and sent off for analysis using either analytical or dynamic olfactometry techniques.

The University of Ghent (De Bruyn & Langenhove, 2003) developed a strategy for the application of field measurements carried out by panellists. This strategy has been applied since 1988 to a wide range of industrial and agricultural sources. Figure 2-1 demonstrates the strategy whereby an observer, who has been familiarized with the typical smell of the source, passes in a zigzag fashion through the plume to establish the "Maximum Odour Perception Distance" (MOPD). The concentration at MOPD is equated to 1 SU/m^3, which is the equivalent to one "sniffing unit". Short term dispersion calculations are then carried out for the meteorological data recorded at the times the observations were made. The dispersion model emission rate is adjusted so that the predicted concentration at the MOPD is represented by 1 SU/m^3. The technique suggests that at least 8 field observations be made on different days, for differing weather conditions over a period of three months. It is suggested that the emission estimate can then be used to run long term dispersion calculations for the purposes of establishing an odour impact assessment in the neighbourhood around the odour source.

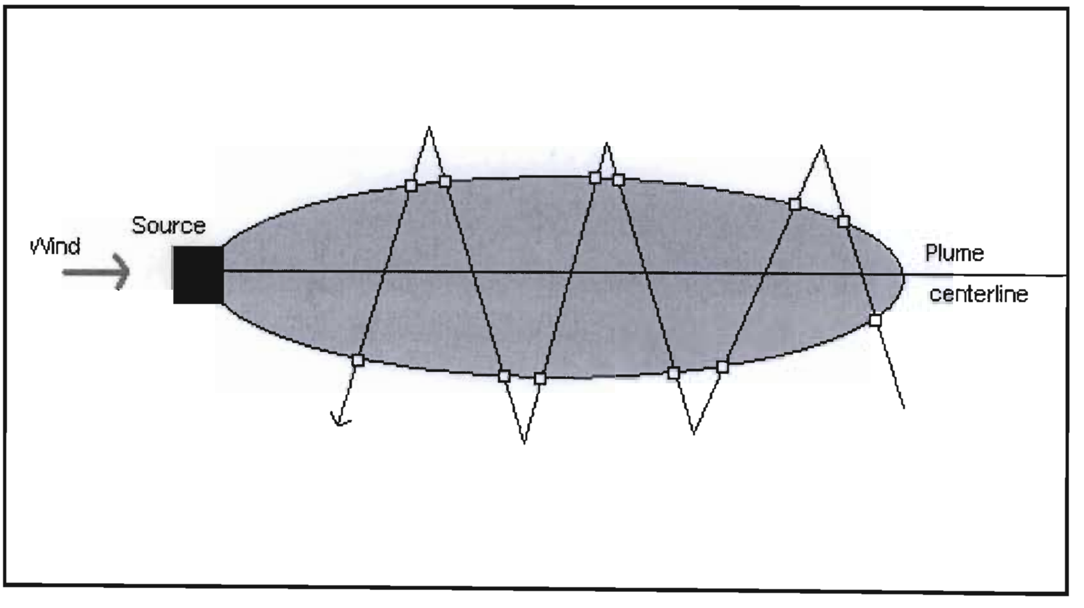


Figure 2-1: Graphical representation of technique developed by University of Ghent (adapted from De Bruyn & Langenhove, 2003)

McGinley (1998) suggests that odours from landfill sources can be modelled accurately through the use of plume profiling. Several inspectors spaced cross wind and down wind from a landfill odour source can be assigned to measure odour intensity. A dispersion model can be "calibrated" through profiling plumes under differing meteorological conditions. Model predictions can also be verified in this way.

The advantage of actually observing the odour in the field using a technique such as the one described above is that it provides results which reflect the actual perceptibility of an odour in the environment (De Bruyn & Langenhove, 2003). It is also relatively cheap when compared to standard emission measurement techniques using wind tunnels and laboratory analysis. The disadvantage, however; is trying to differentiate the odour sources when there is a cluster of odour sources at the industrial site or waste treatment works. The techniques are also less standardized and short term dispersion modelling becomes a source of uncertainty or "noise" in the method.

2.3.3 Case study review: Measuring odour emission rates

MSW landfill, Hong Kong

Research was carried out at a large landfill in Hong Kong, as reported by Xiangzhong (2003), to establish the odour emission rate from the tipping areas (working faces) at the site. This research was carried out with the intention of establishing the odour impact of the tipping areas on the surrounding community. Direct measurement of the odour emission rate was achieved by using a wind tunnel to collect samples at the three active filling locations on the site during dumping operations. About 60 L of foul gas was collected for each odour sample and analyzed using an olfactometer designed to operate in accordance with the European Standard Method EN 13725. Six panellists assessed the odour in a dynamic olfactometry laboratory on the same day that the samples were collected and the odour concentration results are displayed in Table 2-1. The OER was calculated as being 32.7 $OU/m^2/s$. This value for OER was used to run long term dispersion calculations to establish the impact of the odour from the filling locations on the surrounding community.

Table 2-1: Odour strength at the tipping areas of the landfill site (adapted from Xiangzhong, 2003)

Sample	Odour Concentration (OU/m^3)
Tipping Area 1	949
Tipping Area 2	367
Tipping Area 3	262
Geometric Mean	*450*

Anaerobic treatment ponds at piggeries, Australia

Anaerobic treatment ponds were found to be the primary source of odour at Australian piggeries and research carried out by Galvin et al. (2002) aimed to establish the odour emission rate from these large passive area sources. Five piggeries were used in their investigation and samples were collected using a wind tunnel which was supported on a specially designed gantry to allow for movement across the treatment ponds without disturbing the surface. Odour concentrations were established using a panel of eight odour assessors and a triangular, forced choice dynamic olfactometer. The odour emission rate was calculated as being in the range 10 to 35 $OU/m^2/s$ and depended on the piggery, time of year and the rate at which volatile solids were added to the anaerobic ponds. The project carried out at these piggeries is also discussed by Galvin (2004) where a cheaper alternative to estimating pond odour emission rates is suggested using indirect odour emission rate measurement. Odour emission rates were estimated by back calculating using dynamic olfactometric analysis of samples collected downwind from the ponds. A good relationship was observed between directly measured odour emission rates and those derived from back calculations.

Manure at swine farms, Canada

A study was carried out in Manitoba, as reported by Zhang (2001), to establish the odour emission rate from manure applied to land a 10 swine farms. A flux hood was applied to the passive area sources and samples collected and sent to a dynamic olfactometry lab for analysis. The amount of odour emitted from the facilities was quantified by the odour emission rate, which was calculated as the product of the odour concentration and the airflow (ventilation) rate. Farm average emission rates ranged from 12 to 39 $OU/m^2/s$.

Waste water treatment plant, Italy

An investigation was conducted in Northern Italy to indirectly establish the OER from a waste water treatment plant through backward dispersion (Centola et al., 2003). Direct sampling of the odour source was not possible in this instance, so indirect estimation of the odour emission rate was necessary. The ground level odour concentrations were measured outside the plant and a dispersion model was applied backward from the odour concentrations to the emission source using known meteorological data conditions for the hour that the downwind observations were made. Ten gas samples were collected outside the treatment works within a one hour time period. The samples were analyzed using dynamic olfactometry. The inputs used for the backward dispersion modelling were the instantaneous impact and the meteorological data at the moment of sampling. In other words, a dispersion model was run iteratively by changing the emission rates of the odour sources of the plant until the instantaneous odour impact was correctly simulated. Centola et al. (2003) found that the OERs calculated by the backward dispersion model from the measured ground level concentrations were a hundred times higher than OERs reported in scientific literature or directly measured in other plants for similar sources. The researches suggest that "noise" affected the concentration measurements and that some other source, not modelled for, may have affected the result.

2.4 Odour-concentration, dose response relationships

The odour threshold of a gas is the most popular measure of odour concentration, however; it alone does not provide a complete characterization of the odour being emitted from an odour source. In other words, the odour threshold fails to account for the range of different responses of individuals in a population as the odour is experienced over a range of concentrations above (supra-threshold) and below (sub-threshold) the odour threshold (Nicell, 2003). It is important to relate the responses of a population to odour in terms of the probability of response (detection and discrimination), degree of annoyance and perceived intensity in order to establish the odour's potential impact on people living or working around an odour source. Population dose responses in terms of these odour characterizations are typically established using dynamic olfactometry.

2.4.1 Probability of response

The odour threshold, by definition, is that odour concentration at which 50% of an odour panel will detect the odour. It can also be said that there is a 50% probability that people will detect the odour at this concentration (detection threshold). Figure 2-2 shows a theoretical dose response for probability of detection where the threshold corresponds to 1 OU. The probability of detection increases for increasing odour concentration and tends to 100% for high concentrations and tends to 0% for low concentrations. The response of a population to changes in odour concentration is not linear (Nicell, 2003). The three curves in Figure 2-2 represent different population dose responses to different odorous gases. Odour C can be said to persist more than odours A and B for sub-threshold concentration levels. A persistent odour is characterized by a shallow slope of the dose response curve. Nicell (2003) suggests that persistence is also a measure of the variability of individual thresholds in a population and proposes that persistence is a factor that will influence the magnitude and extent of an odour impact in a community.

Nicell (2003) developed mathematical expressions based on sigmoid probability curves plotted on semi-log charts to relate the probability of response to odour concentration. Sigmoid probability curves show several consistent characteristics that are advantageous for modelling dose-response trends: (1) at low concentrations the probability of response approaches 0%; (2) at high concentrations the probability of response approaches 100% and (3) on a semi-log plot, the sigmoid curve is symmetrical about the point of inflection corresponding to the threshold. The following expression is that of a sigmoid curve which relates probability of detection to concentration (Nicell 2003):

$$P = \frac{100}{1 + \left(C_{50} / C \right)^{(1-p)/p}} \tag{2-3}$$

Where P is the probability of detection (%); C is the dose concentration; $C_{50\%}$ is the concentration that corresponds to the odour threshold; and p is a dimensionless constant such that $0 \le p \le 1$. The value of $C_{50\%}$ determines the relative position of the sigmoid curve along the horizontal axis and p, the 'persistence of response', determines the slope of the curve. As p approaches 1, the odour becomes infinitely persistent and as p tends to zero, the odour is no longer perceptible below the odour threshold.

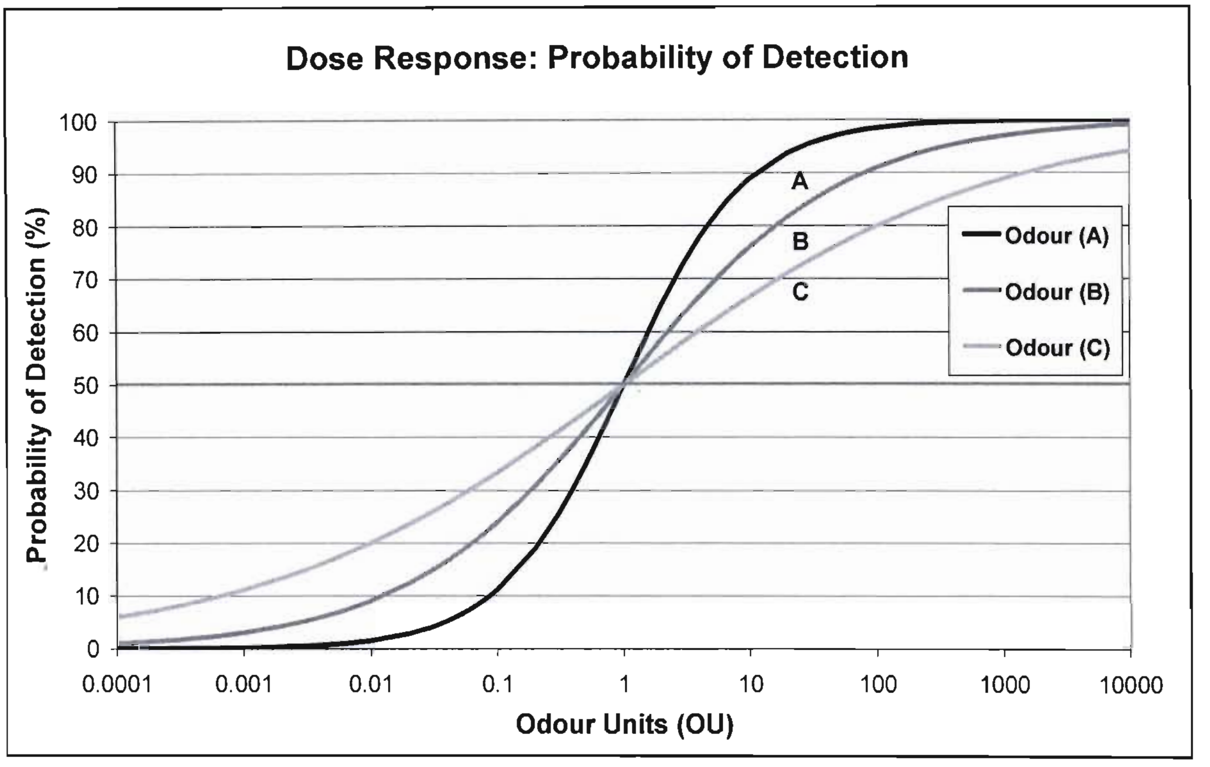


Figure 2-2: Dose Response of probability of detection (adapted from Nicell, 2003).

Probability of discrimination curves are very similar to probability of detection curves, but differ in that the threshold for a discrimination curve will occur at an odour concentration greater than 1 OU if plotted on the same axes. If a sigmoidal probability curve were plotted above, it would look similar to the detection curve except it would be shifted slightly to the right along the horizontal axis.

2.4.2 Intensity

Establishing a population's perceived intensity to a range of odour concentrations also provides an insight into the persistence of an odour once it enters the environment. Odour persistence is a term used to describe the rate at which an odour's perceived intensity decreases as the odour is diluted (Odour@, 2002). Intensity is typically measured on a 6 point, 7 point, or 10 point scale. The scales start at zero, which represents no perceived odour, and increasing intensity is represented by increasing numerical values on the scale. The German Standard (VDI, 1992) categorizes odour intensity on a numerical 7 point scale as shown in Table 2-2.

Table 2-2: German Standard for the categorization and scaling of odour intensity (adapted from VDI, 1992).

Scale (*I*)	Intensity Description
0	Not detectable
1	Very weak
2	Weak
3	Distinct
4	Strong
5	Very strong
6	Extremely strong

There are a number of psychological dose response functions to relate perceived intensity to odour concentration, but two seem have the widest acceptance namely the Weber Fechner Law and Stephen's Psychological Power Law (e.g. Hobbs, 2003).

The Weber Fechner model has the form of:

$$I = k_1 \log C + k_2 \qquad (2\text{-}4)$$

Stephen's Power Law has the form of:

$$I = k_1 (C)^{k_2} \qquad (2\text{-}5)$$

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

2.4.3 Annoyance

Annoyance is used an indicator of how a population might react to an odour over a range of concentrations. A population's response, in terms of annoyance, to a particular odour is very subjective and depends on the hedonic tone and character of the odour. The hedonic tone is the subjective measure of the odours "pleasantness"; and character is the objective description of what the odour smells like. The odours generated at a landfill, for instance, are likely to be perceived as very unpleasant when compared to the odour generated at a bakery. Consequently, the same odour concentration from each source is likely to generate greater annoyance in the case of the landfill. Annoyance is usually measured on a 5 or a 10 point scale and is measured in annoyance units (AU). Figure 2-3 gives an example of the rating and categorization of annoyance on a ten point scale (Springer, 1974).

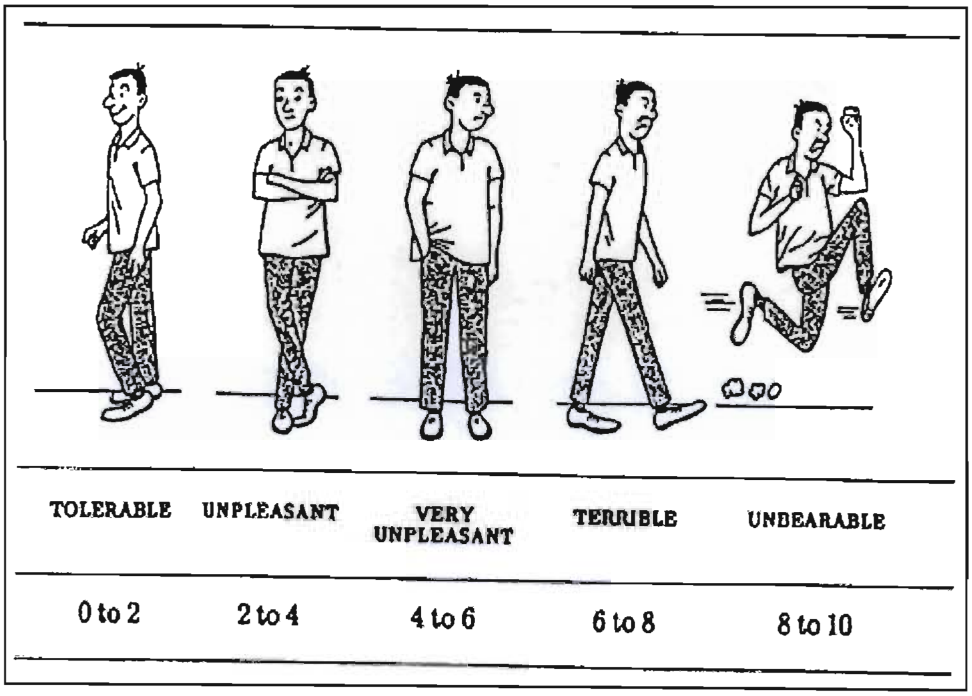


Figure 2-3: Annoyance ratings used in the evaluation of odour hedonics (Springer, 1974).

Nicell (2003), found that population dose responses in terms of annoyance could also be expressed with sigmoid curves. Equation 2-6 is a variation of the probability of detection sigmoid curve given in equation 2-3.

$$A = \frac{100}{1 + \left(\frac{C_{5AU}}{C} \right)^{\frac{(1-a)}{a}}} \qquad (2\text{-}6)$$

Where A is the degree of annoyance of the population (AU); a is the dimensionless persistence of annoyance; and C_{5AU} corresponds to the odorant concentration where the annoyance has a value of 5 AU. C_{5AU} is comparable to a threshold and a can be seen as a measure of the propensity for a population to remain annoyed with an odour as it is experienced over a range of concentrations (Nicell, 2003).

2.5 Community Modelling

It is increasingly considered good practice to involve residents and communities in the process of characterizing and managing nuisance odours. Current trends in Australia, Europe and North America show a shift towards establishing odour regulations based on input from citizen involvement (McGinley, 1995).

McGinley (1998) recommends the implementation of citizen monitoring be part of an interactive community outreach program for a landfill. A primary function of citizen monitoring is to provide accurate information that represents real conditions in the community. Feedback from residents can also help develop an understanding of the odour intensity at which complaints are likely to arise. Best et al. (2004) suggest for the characterization and assessment of odours, that observations made by people who are sensitized to an odour source due to regular exposure may have better foundations than "relatively blind adherence to poorly-generated odour exposure characteristics and response thresholds discovered by laboratory odour panels". It is also suggested that conflict resolution and community mediation become possible when the importance of community input is recognized.

Community feedback has been used in a number of cases round the world to help establish the impact of odour sources and to characterize these sources in terms of their emission rates, intensity and potential to cause complaints. Various case studies are discussed here.

2.5.1 Case study review: Community Modelling

Waste water treatment works, Minnesota

In order to establish the neighbourhood impact of waste water treatment works in Minnesota, a study was carried out to quantify the public perception of odour through a telephone survey utilizing telemarketing protocol (McGinley, 1995). An "Odour Annoyance Index" community survey was conducted over four months in the neighbourhoods surrounding the waste water treatment works. The survey provided information regarding the degree of annoyance experienced by the neighbouring citizens. McGinley (1995) discusses two techniques for carrying out odour surveys with communities: mail-in questionnaires and telephone surveys. Mention was also made of a telephonic survey that incorporated calling citizens and obtaining the immediate status of odours by asking the citizen to step outside and describe what they smell. However, no reference was given for this particular case. A sample of 196 citizens was randomly chosen from areas surrounding the treatment works and contacted over 4 months on a two week cycle. Due to the high number of participating citizens, it was not critical if a citizen was absent for a call cycle. Citizens were asked if they had smelled any odours in their neighbourhood in the two weeks since the previous call. If they replied in the negative, then the call was ended and they were contacted in the next call cycle. However; if they responded in the affirmative, then they were asked the following: what the odour smelt like; how annoying it was; and when they noticed it. An annoyance ranking was used, as shown in Table 2-3, that helped determine the annoyance index of different regions of the community by averaging each regions responses. The survey helped provide a picture of which areas around the landfill were most impacted by the treatment works in terms of an odour nuisance.

Table 2-3: Scaling of degree of Annoyance (adapted from McGinley, 1995)

Scale	Degree of Annoyance
1	Not annoying
2	A little annoying
3	Annoying
4	Very annoying
5	Extremely annoying

MSW landfill, Montreal

Research was carried out at a large landfill in Montreal to identify the major odour sources at the site; to establish what management operations and weather conditions accentuated the odour; and to quantify the odour impact (Gelinas, 2001). This was achieved through garnering the participation of 43 residents in the residential area surrounding the landfill. The researchers sought to draw a representative sample of the local population that was neither insensitive nor hypersensitive to target odours. To get a sample of the population, an invitation to a general information meeting was sent to 20 000 residents living within a 1500 meter radius of the site. The objectives and the methodology of the study were clearly defined to those that attended the meeting and volunteer assessors were solicited. Training sessions were carried out with the volunteers from the community and insensitive and hypersensitive volunteers were eliminated from the survey. The remaining 43 assessors were trained to recognize certain types of odours typically associated with the landfill and were equipped with a 6 point ranking scale for measuring the intensity of the odours. A survey was carried out over a three month period. Observers were required to make odour observations twice a day - morning and late afternoon - five days a week. During both daily observation times, observers were obliged to go out of their homes to make their observations, which were made at ground level and always at the same place. Assessors had to fill out an observation card with the following information: personal details, observation date and time, weather conditions, odour intensity (on a 6 point scale), and odour character (compost, landfill gas, municipal solid waste, rotten egg, sewer, other). The observation cards were post-paid and mailed by the assessors back to the landfill on a regular basis. The community survey proved to be very effective and successful and citizens' participation rate was 97%. The survey data revealed that the composting at the landfill contributed 46% to the offsite perception of odour and the landfill gas contributed 22%. The survey also revealed a higher than anticipated contribution from odour sources other than those generated at the landfill to the odour perceived by residents. When the study was planned, dispersion modelling was used to estimate an impact radius around the site. The observations from the survey participants confirmed this impact radius.

MSW landfill, UK

Hobbs et al. (2003) used community modelling at a landfill site in the UK to find a link between dispersion and perception of odour. The community modelling also served as a validating step for the results of a predictive dispersion model. This research formed part of an environmental impact assessment which was carried out as part of an application to extend the landfill site. People within the community living round the landfill were engaged as regular odour monitors over a year. Monitors were recruited from the community using a record of citizens that had complained about odour from the landfill site in the past. The monitors were first tested to establish a minimum level of sensitivity, individual thresholds and ability to discriminate odours. Each monitor was tested using a category scaling to assess responses to differing odour intensities. The recruited monitors were then requested to report any incidence of odour detected in a day. On the occasions when they did detect an odour, they were required to describe its probable source and the intensity of the odour based on a 7 point intensity scale. Estimates of exposure using a numerical dispersion model were then correlated with the observations made by the monitors and dose response plots of intensity-concentration were generated. A natural logarithmic trend was fitted to the dose response data for each receptor. However, neither the Weber Fechner law nor Steven's law were fitted to the data from the monitors.

2.6 Buffer Zones

A buffer zone needs to be defined around an odour source to ensure sufficient dispersion and dilution of odour before it reaches sensitive receptors (Heber, 1997). The Minimum Requirements for Waste Disposal by Landfill (DWAF, 1998) defines a buffer zone as being the "separation between a landfill site boundary and the adjacent residential or sensitive development". According to the minimum requirements, this distance can vary between 500m and 1000m. The Sewerage Treatment Plant Buffer Zone Policy for Sydney (SWC, 1997) describes a buffer zone as "an area of land or water surrounding a sewerage treatment plant which is used in a way which is compatible with its operation and minimizes odour, noise, visibility or other adverse environmental impacts on the community". The distance recommended by Sydney buffer zone policy is 400m from the plant boundary.

There is a move towards specifying buffer zones around odour emitting sources using a case specific approach which includes the following considerations: the nature and size of the industry or treatment works generating the odour; the topography; microclimate and the sensitivity of the neighbouring land uses. Whilst buffer zones around waste water treatment works are recommended to be 400 m from the plant boundary in Sydney, the Buffer Zone Policy also suggests that a reduction of the buffer zone could be considered after an appropriate microclimatic odour study and risk analysis has been carried out. Piringer & Schauberger (1997) developed a technique to define set back distances (buffer zone) around swine buildings. Their technique requires a rigorous assessment of the odour source in order to accurately estimate the odour emission rate. It also takes into consideration the local topography and the prevailing wind directions.

A case where a proposed buffer zone was specified for a MSW landfill using a scientific approach is discussed below.

2.6.1 Case study review: Buffer zones

Shongweni landfill, KwaZulu Natal SA

Dispersion modelling was used to delineate odour and health impact zones for the purposes of determining a buffer zone for the Shongweni Landfill site in KwaZulu Natal (Scorgie, 2003). Originally, emission flux monitoring was undertaken using an isolated flux chamber to establish emission rates from the landfill surface for input into the dispersion model. However, it was found that the use of the emission flux measurements as input to the atmospheric dispersion model resulted in significant under predictions of ambient air pollutant concentrations. This was due to the emissions from the work surface (filling location) and leachate areas not having been quantified for inclusion. Emissions were re-estimated through "back calculating" (indirect measurement technique) based on measured air pollutant concentrations. The air pollutant concentration samples were analyzed for 30 different organic compounds. In defining the extent of the health impact zone, reference was made to the distance of exceedance of the chronic inhalation reference concentration for 1,2,4 trimethylbenzene. The extent of the odour impact zone was delineated to coincide with a 0.1% frequency of exceedance of the World Health Organization's odour guideline given for Hydrogen Sulphide. Long term dispersion modelling using two years weather data for the area was carried out to estimate the health and odour impact. The projected health and odour impact zones are shown in Figure 2-4. The outer most contour represents a possible buffer zone to ensure neighbouring communities are not affected by the odour from the landfill site. The hourly averaged hydrogen sulphide concentrations were predicted to exceed the odour recognition threshold, based on the WHO and current South African guideline, over significant distances from the landfill boundary. From a health impact perspective, exceedances were limited to the immediate vicinity of the landfill fenceline (inner contour).

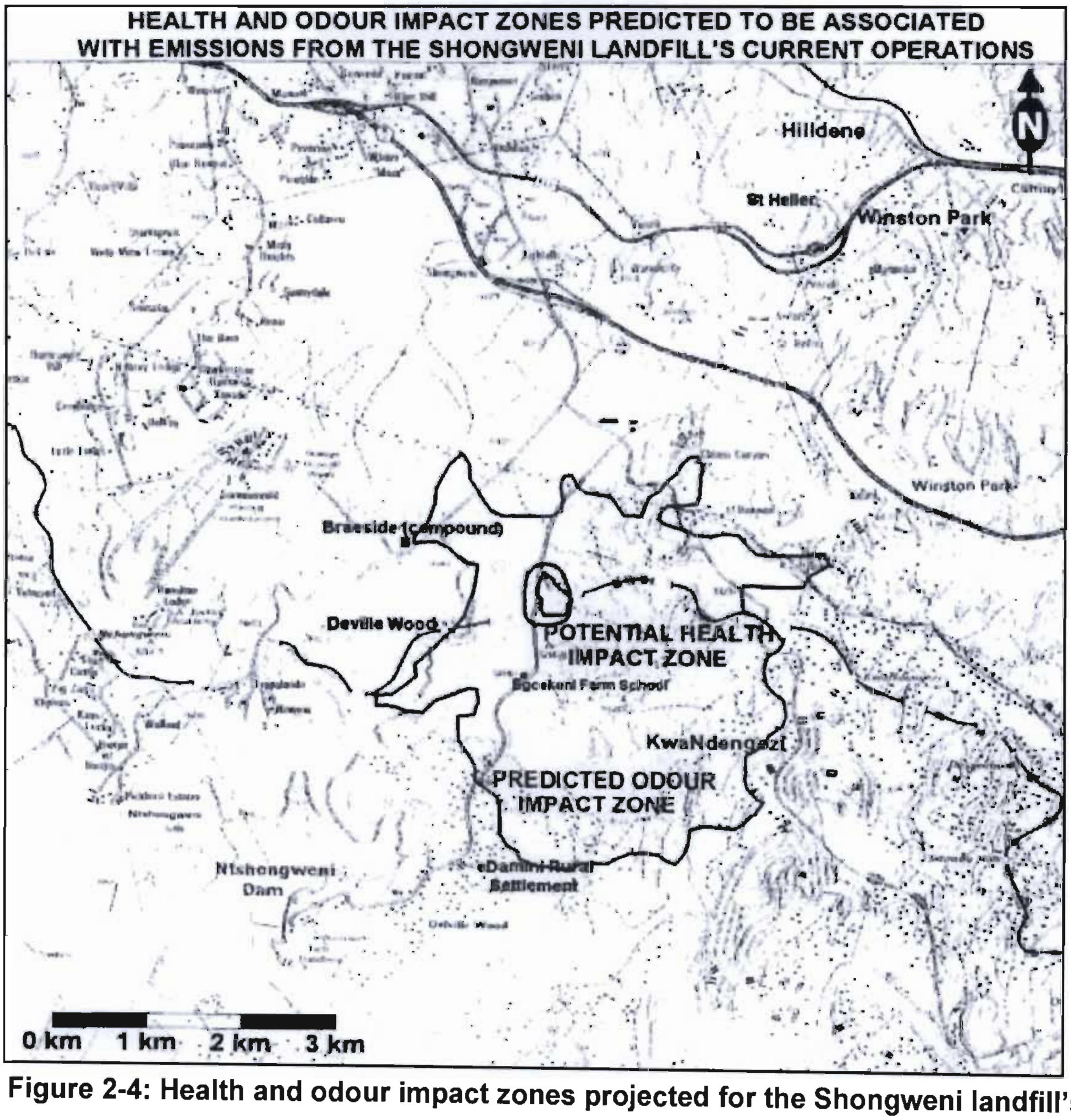


Figure 2-4: Health and odour impact zones projected for the Shongweni landfill's current operations (Scorgie, 2003).

2.7 Previous odour research at Bisasar Road landfill

Laister et al. (2002) describe an attempt to determine the emission rate and concentration of FWO from the uncovered working face at the Bisasar Road Landfill Site using dispersion modelling and community feedback. A community survey was carried out over a 10 month period from May 2002 through to February 2003. Residents who had complained about the odour in the past were contacted via mail and introduced to the fundamentals of the research project and were invited to participate in the survey. Of the 50 residents contacted, 18 residents agreed to participate and 16 of those participated through to the survey's completion. Participants were provided with survey forms on a weekly basis. They were required to make four observations daily - morning, midday, evening and night time. These survey forms were collected weekly and new ones delivered. Odour predictions were generated using a numerical dispersion model and correlated with the observations made by the receptors. Laister et al. (2002) did not establish an emission rate. However, Laister (2003a) managed to use the same community survey data to establish the dilution threshold (the number of dilutions of the source concentration necessary to reach the odour threshold). The dilution threshold for the community based odour panel was established by identifying the dilution at which 50 % of the population detected the odour. An approximate dilution factor of 150000 was estimated, which represents the number of times the source concentration has to be diluted for it to reach the odour threshold. Laister (2002) developed an Odour Management System (OMS) for the Bisasar Road landfill site. A sample of the output is shown in Figure 2-5 to illustrate how the system is used to map odour threshold concentrations around the site. The research in Laister et al. (2002) and Laister (2003a) helped calibrate the OMS so that the odour impact predictions would reflect what the community was experiencing in real-time. Laister (2003b) discussed the use of international odour guidelines together with the calibrated OMS to predict a theoretical buffer zone around the Bisasar Road landfill site. Long term dispersion simulations were carried out using historical met data from the site to predict a buffer zone contour around Bisasar.

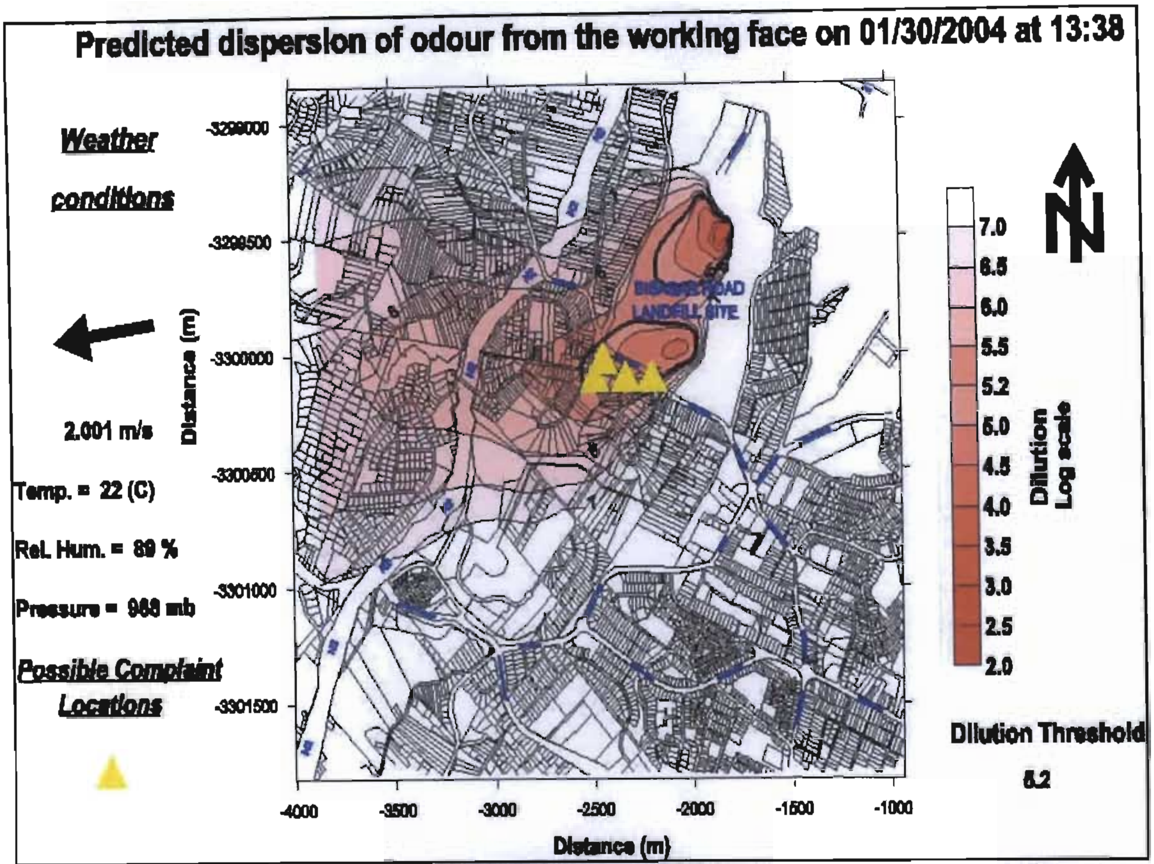


Figure 2-5: Screenshot of Odour Management System (OMS) output at Bisasar.

2.7 Summary

The odour unit is generally considered the most effective means of measuring odour. Various direct and indirect techniques have been employed globally to tackle the characterization of OERs –typically in terms of odour units- from nuisance odour sources. Comparisons between backward diffusion and direct methods to establish OERs have shown some good results, but not in all instances. To complete the characterization of an odour, its perceived intensity, potential annoyance and impact in terms of probability of response need to be investigated. Community modelling has been embraced globally in the quest to characterise odour. Buffer zones around odour sources are used to ensure that the odour is sufficiently dispersed before it reaches sensitive receptors and regulations as well as methodologies exist for their specification. An OMS - calibrated from community feedback - is the culmination of previous research conducted at the Bisasar Road landfill.

CHAPTER 3

3. ODOUR DISPERSION MODELING METHODOLOGY

3.1 Introduction

Odour dispersion modelling differs from traditional dispersion modelling in terms of the source characterization; plume transport and dispersion; and the representation of human receptors (Hobbs et al., 2000). In this chapter, modelling plume transport together with accurately representing the perception of odour amongst receptors shall be discussed. The development of a technique to characterize an odour source is the focus of this research and shall be discussed in subsequent chapters. Accurate odour dispersion modelling necessitieses the use of a numerical dispersion model that can incorporate the effects of complex terrain on plume transport (McKendry, 2002). It is also important to accurately represent the human receptor as response to an odour can occur over just a few seconds of exposure. For this reason, it is vital that small and large scale atmospheric turbulence, and the effect on odour concentration fluctuations over short time scales, be taken into consideration. The selection of the numerical dispersion model ADMS 3.1 (Atmospheric Dispersion Modelling System 3.1) (CERC, 2001a) for the purposes of this research is discussed.

3.2 Complex Terrain

Complex and diverse interactions occur between wind speed, wind direction and the underlying complex terrain (McKendry, 2002). Not only does complex terrain alter the direction of the wind flow, it also affects the average wind speed and tends to increase dispersion due to an increase in mechanical turbulence. McKendry (2002) studied the effect that complex terrain had on the dispersion of odour plumes from landfills in the UK by using ADMS to generate odour plume footprints. The importance of incorporating the effects of complex terrain in modelling odour dispersion was established. Laister (2002) studied the complex interaction between wind and terrain at the Bisasar Road landfill site by using flares which emitted plumes of visible smoke from various locations around the site. The movement and dispersion of the plumes was captured on a digital camera and revealed the complex nature of wind flow over the landfill surface. This emphasized the importance of including the effects of complex terrain when modelling odour dispersion over the landfill surface.

When the influence of the surrounding terrain and its interaction with wind direction is taken into consideration, significant changes to the predicted odour impact zone are observed. To demonstrate this, the numerical dispersion model ADMS was used to generate contours of odour impact (concentration averages) for 1 year of weather data. Contours were initially generated for a hypothetical ground level area source at the Bisasar Road landfill where complex terrain was not taken into consideration as shown in Figure 3-1. Using the same theoretical odour source and the same meteorological data, contours of odour impact were generated using the complex terrain of the landfill site and the surrounding community as shown in Figure 3-2. The effect of using complex terrain in the long term simulations is evident from the difference between the long term average concentration contours generated in each instance.

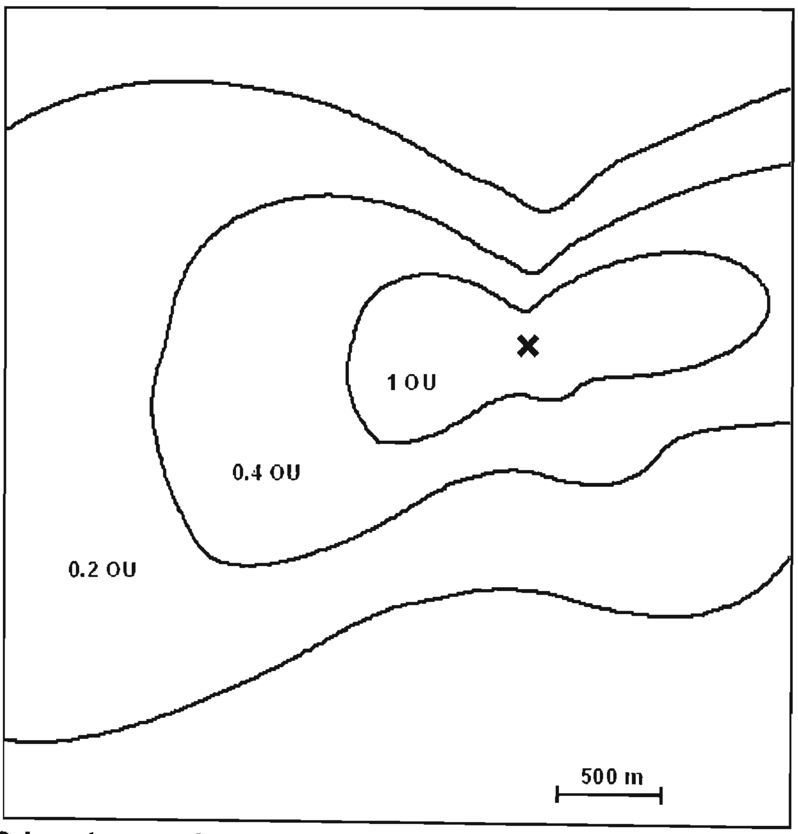


Figure 3-1: Odour impact for theoretical odour source neglecting complex terrain.

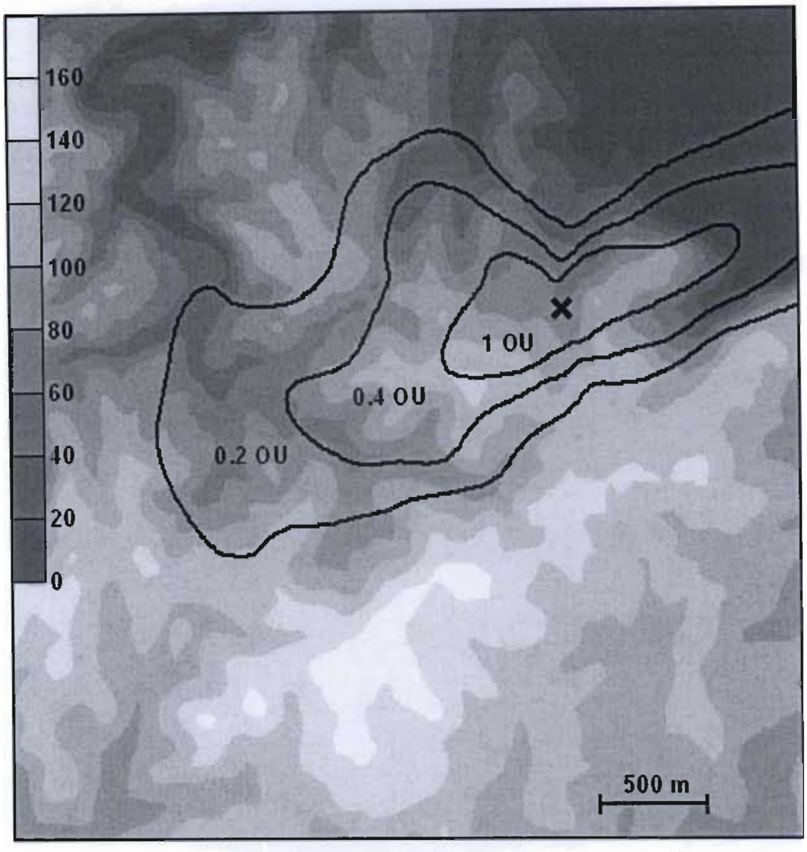


Figure 3-2: Odour impact for theoretical odour source including effects of complex terrain. Height scale in metres.

It is also important to specify the 'roughness' of the terrain when modelling the dispersion of an odour plume. The surface roughness is measured in meters (m) and some suggested values for roughness are shown in Table 3-1. The roughness of the terrain influences the dispersion of an odour plume as it affects the generation of mechanical turbulence in the boundary layer. Greater mechanical turbulence is generated over a large urban area (roughness equal to 1.5 m) than is generated over open grassland (0.02 m) for the same meteorological conditions. A greater level of boundary layer turbulence gives rise to a more rapid dispersion of odour.

Table 3-1: Surface roughness (adapted from CERC, 2001a)

Terrain description	Roughness (m)
Large urban area	1.5
Woodlands	1
Parkland and open suburbia	0.5
Agricultural area (max)	0.3
Agricultural area (min)	0.2
Root crops	0.1
Open grassland	0.02
Short grass	0.0005
sea	0.0001

3.3 Modelling short time scale variations

Human perception of odour is both a physiological and psychological process. Odour molecules enter the nasal passages and are detected by olfactory receptors embedded in the tissue lining these passages. Signals are then relayed via neurons to the brain, where the odour is registered and perceived. Conscious perception only requires around 0.5 seconds of neural signals from sensory cells (Best et al., 2004). Given the short time scale over which perception of odour occurs, It may be inadequate to formulate predictions of downwind odour concentrations on the basis of mean concentration levels averaged over one hour (Laister, 2002). Consequently, the use of an appropriate averaging time becomes one of the primary considerations for modifying standard dispersion modelling methods for use in odour assessment (Hobbs et al., 2000).

The turbulent atmospheric boundary layer causes fluctuations in concentration due to meander of the plume as well as small scale mixing within the plume. The different scales of turbulence – different eddy sizes – result in the observed fluctuations. Large eddies (larger than the plume) tend to cause the plume to meander, whilst smaller eddies (smaller than the plume) result in mixing and widening of the plume, as demonstrated in Figure 3-3. Taking these fluctuations due to turbulence into consideration is of great importance given the short time scale over which humans can perceive odours.

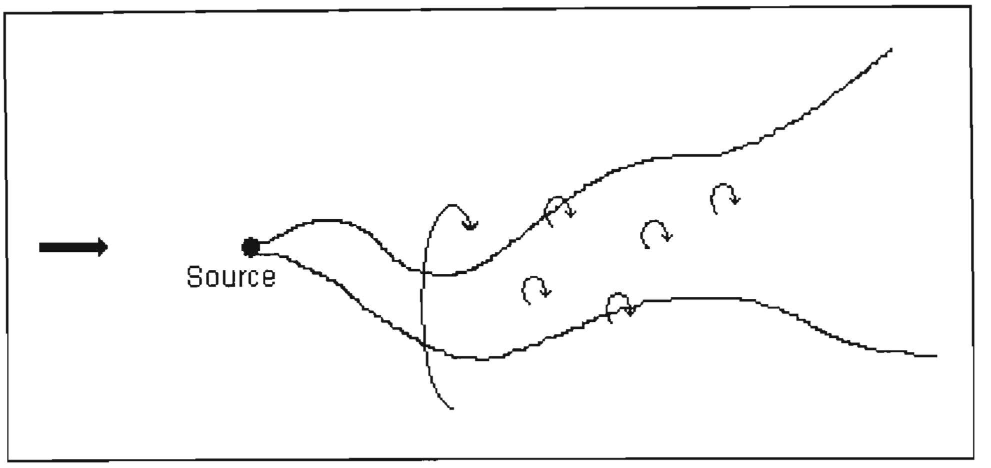


Figure 3-3: Plume moving and widening due to large and small turbulent eddies (adapted from McHugh, 2001).

Concentration fluctuations are most evident over short time scales. One might have a case where the mean odour concentration lies below the threshold detection level over a given time period. However; there may well be several intervals within that time period, where the instantaneous concentration is above the threshold value. Figure 3-4 demonstrates the mean concentration over a time period lying below the detection threshold, whilst concentrations over short time scales exceed the threshold.

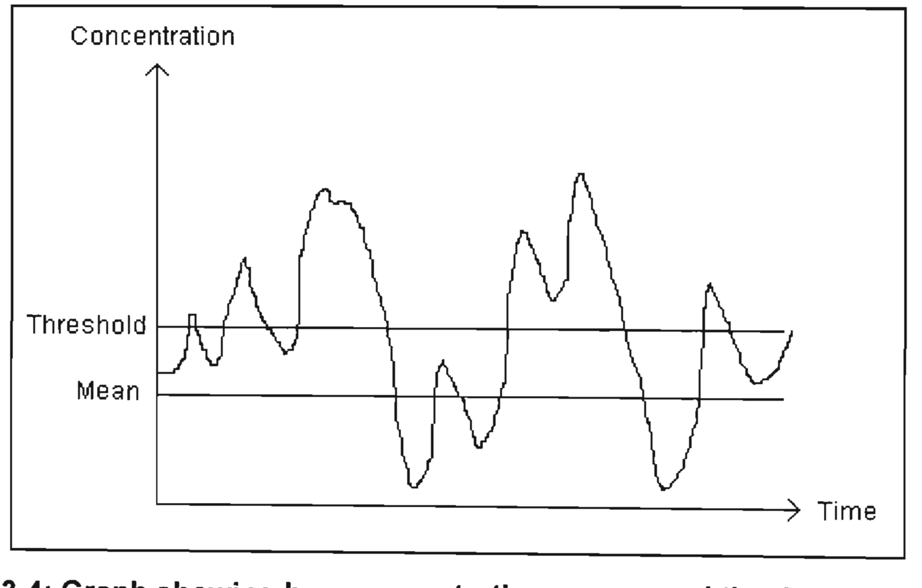


Figure 3-4: Graph showing how concentration can exceed the threshold several times during a time period while the mean is below the threshold (adapted from laister, 2002).

Whilst human response to odour can occur over a very short period of time (a matter of a few seconds and less), it still remains unclear what period of exposure will result in a perceived nuisance. Simms et al. (2000) suggest that the effects of very short-term fluctuations (over a matter of seconds) can probably be adequately modelled by considering an averaging period of approximately 3 minutes. However, they also point out that it likely that odour only becomes a concern when it is detectable for significant periods of time, well in excess of three minutes.

Generally, most dispersion models used for regulatory purposes assume that the meteorological conditions are constant over the averaging period and calculate ensemble concentrations averaged over 1 hour. In reality, although the meteorological conditions may be constant, during the averaging period there will be short time scale variations due to boundary layer turbulence. Recognizing this dilemma, modellers have adopted a variety of approaches to account for variations in short term concentration caused by turbulent fluctuations. Sometimes factors are used to convert between different averaging times. For instance, if odour predictions are generated using a conventional model adjustment factors may be used to give the characteristics of short-term exposure (Best et al., 2004). However, this is generally considered a crude approach as factors are usually derived for specific scenarios and aren't necessarily applicable to all cases. Other modellers account for a decreased averaging time by adjusting the amount of meandering of the wind direction (Dyster et al., 1999). However, the above approaches to modelling odour fluctuations tend to neglect the contribution of small scale turbulence to fluctuating odour concentrations. The fluctuations module in ADMS 3.1, however; takes both wind meander as well as fluctuations due to boundary layer turbulence into consideration.

3.3.1 ADMS fluctuations module

The ADMS fluctuations module generates statistics of fluctuations in concentration (CERC, 2002b). Both turbulence and meandering cause variations in concentration from the mean value. The fluctuations module takes both causes into account, i.e. it calculates statistics of concentration fluctuation due to boundary layer turbulence and plume meandering (Dyster et al., 1999).

The module is based on a 'two particle dispersion' concept and uses an approximation developed by Sawford (Sawford, 1983). Sawford argued that if one followed pairs of fluid particles backwards in time from time t to time zero - where particles were released from a source at time zero - the displacement of the centre of mass of the particle pairs would be close to Gaussian and independent of the particle separation. The ensemble mean concentration field is calculated as usual by the model and the concentration variance is estimated by the fluctuations module using the Sawford approximation. This allows for various statistics of exceedance to be generated. For long term calculations, the model estimates a probability exceedance and the expected number of exceedances, i.e. the model predicts the probability that a concentration (C), as stipulated by the user, will be exceeded; and the number of times per year that C would be exceeded.

The user enters an averaging time or sampling time T for ensemble mean concentration calculations and a fluctuations averaging time T_f (CERC, 2001b). T determines the lateral spread (σ_θ) of the release due to changes in the mean wind direction (θ), unless σ_θ is supplied to the model by the user. The results from the fluctuations module depend on T, T_f and the type of release specified. In the case of a continuous release, the model estimates the probability that the concentration averaged over the period T_f exceeds a particular value C. According to the user guide, the results are equivalent to those obtained by making many measurements over the period T_f, during the sampling time T, where the meteorology remains constant but the boundary layer turbulence varies.

An important feature of the fluctuations module in ADMS is that it allows the effect of fluctuations over short time scales to be included in long term average calculations (CERC, 2001a). For instance, this allows the user to compare modelled long term 15 minute average concentrations (T_f set equal 15 minutes) with odour regulations that require the 15 minute mean concentration not to exceed a certain concentration for a certain number of hours per year.

The ADMS user guide (CERC, 2001b) manual suggests that the ensemble mean averaging time T can be set to a time period shorter than one hour for comparison with an air quality standard which has an averaging time of shorter than one hour. However, the guide recommends that a better approach is to set T = 1 hour and to use the fluctuations module with a fluctuations averaging time (T_f) of shorter than an hour. To simply reduce the value of T to account for fluctuations over short time scales is to only take into consideration the effect that plume meandering has on concentration fluctuations. To model for short time scales using the fluctuations module means that both turbulence and wind meander are taken into account. The difference between using and not using the fluctuations module to generate contours of impact for averaging times less than an hour is shown in Figure 3-5 and Figure 3-6 respectively. Contours representing the number of 3 minute mean exceedances of 10 OU around a theoretical ground level area source were generated by first setting T_f to 3 minutes and then T to 3 minutes. The odour impact contours using the fluctuations module are greater than when it is not used. Dyster at al. (1999) performed an analysis to compare the results of using and not using the fluctuations module for modelling averaging times less than an hour. They concluded that neglecting fluctuations can lead to the underestimation of the impact of a release.

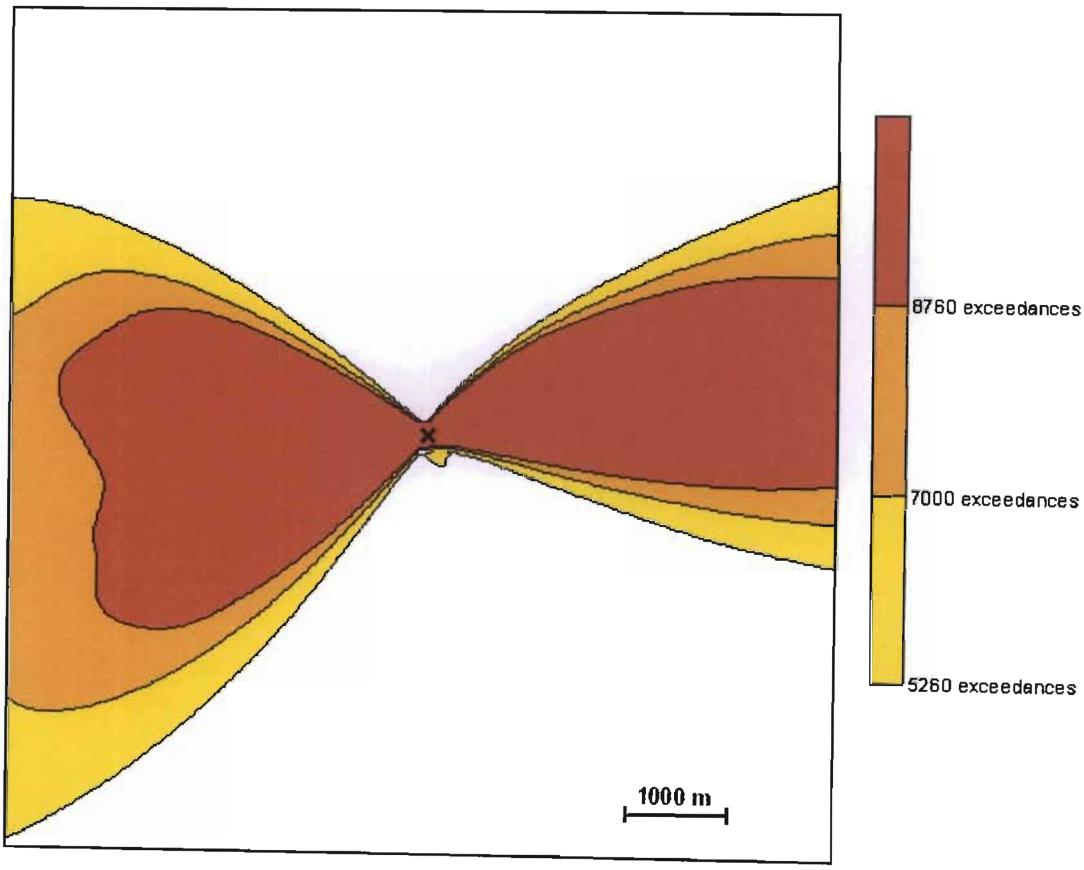


Figure 3-5: Number of occasions in a year (exceedances) that the 3 minute mean exceeds 10 OU including fluctuations.

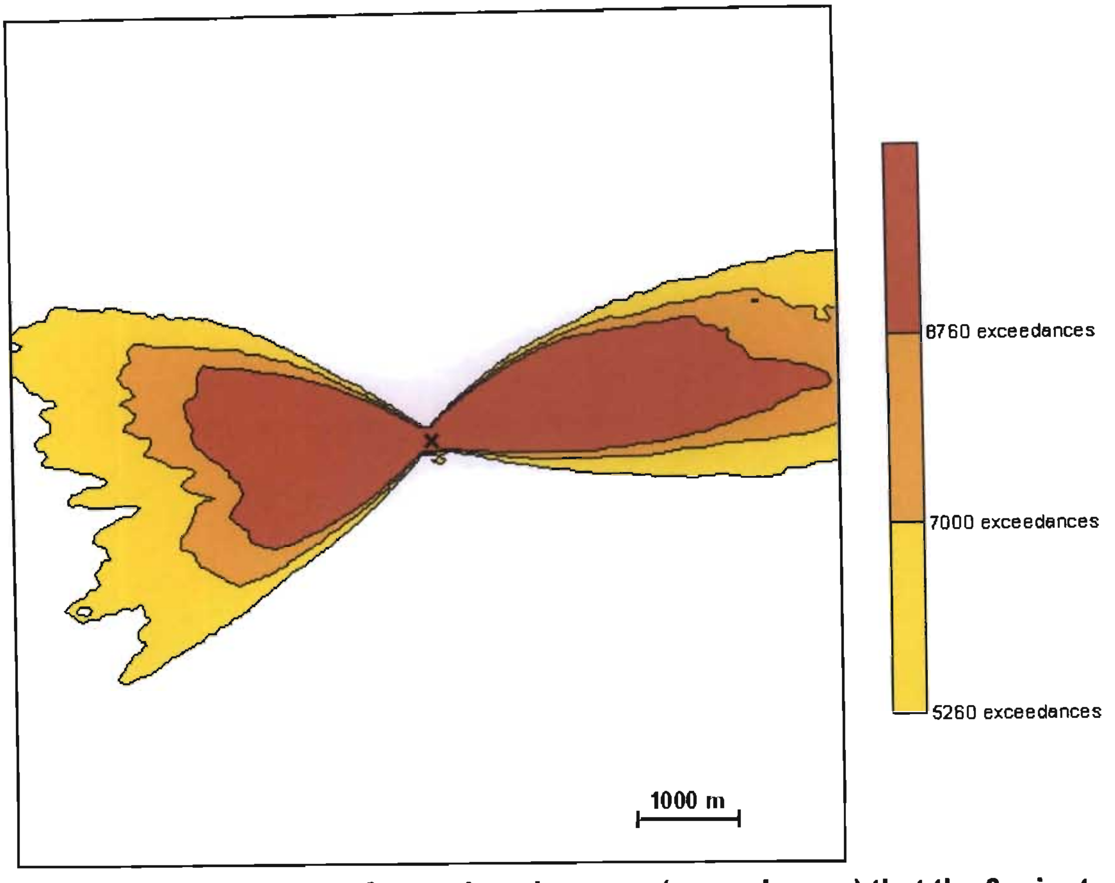


Figure 3-6: Number of occasions in a year (exceedances) that the 3 minute ensemble mean exceeds 10 OU.

3.4 Choice of dispersion model

Various dispersion models are commercially available. However, the Atmospheric Dispersion Modelling System (ADMS) appears to be the most widely used steady-state numerical dispersion model for modelling odour dispersion from MSW landfills.

Hobbs et al. (2000) concluded - after a comparison of two dispersion models, i.e. UK ADMS and MPTER - that UK ADMS was a better tool for predicting odour dispersion from landfills. They found through comparing the dispersion model outputs with observations made by citizens in the neighbouring community that UK ADMS generated better predictions of odour at short range (within 500m of the source). MPTER does not use a detailed characterisation of the boundary layer structure and does not account directly for the turbulence factors of the atmosphere. UK ADMS, on the other hand, uses a more detailed parameterisation of the local atmospheric conditions and does account for turbulence factors.

Laister (2002) did a comparison of five dispersion models and ADMS was chosen as the most accurate and most user-friendly model. Laister (2002) established the importance of including complex terrain in dispersion modelling and found that it was uncomplicated to do so with ADMS. McKendry et al. (2002) chose ADMS 3.1 for a study carried out to model the dispersion from odour sources at six landfill sites in the UK.

ADMS also allows for the specification of odour sources in terms of odour units and generates concentration predictions in odour units. The fluctuations module is also particularly useful as it generates statistics of exceedances by taking fluctuations into account.

ADMS was used for the purposes of this research given that it has been widely tested for modelling odour dispersion for scenarios similar to the one at the Bisasar Road landfill site and it has particular features relevant to odour dispersion modelling.

3.5 Steady state vs. non-steady state models

A problem with steady state numerical dispersion models, such as ADMS, is that they assume meteorological conditions (including wind direction) are constant over the time required for the plume to travel from the source to the receptor (Pope et al. 2000). Consequently, the accuracy of the odour concentration predictions will tend to decrease with distance from the odour source. Non steady state models, on the other hand, are recommended for long range transport problems (long range being over 50 km) or in situations where assumptions of straight line, steady state conditions are invalid (Calpuff@, 2005).

If the available met data for generating odour predictions is averaged over an hour, then for a minimum wind speed of 0.75 m/s (minimum wind speed that ADMS can model for), the predictions should be valid up to approximately 3km. If the met data available is averaged over ten minutes, then for the same wind speed, the predictions should be valid up to 450m.

Odour impacts are predominantly at short ranges (Hobbs et al., 2002), and provided receptors are located within a couple of kilometres of the odour source, the use of a steady state model is justified.

3.6 Summary

To accurately model the dispersion of odour requires careful consideration to be given to the transport of the plume from the source to the receptor and the response time of the receptor. The numerical dispersion model ADMS 3.1 was chosen to help meet the objectives of this research as it has been used in similar scenarios both locally and internationally. ADMS is a steady state model which should be adequate for the purposes of predicting odour concentrations at receptors within a few kilometres of the site.

CHAPTER 4

4. REANALYSIS OF THE 2002 COMMUNITY SURVEY

4.1 Introduction

A reanalysis of the 2002 community survey data was carried out in order to adapt and develop the methodology for inferring emission rates using community feedback and odour predictions. Reanalysing the survey data was also done with the intention of estimating an initial OER range from the open waste piles at the landfill.

From May 2002 until February 2003 a community survey was carried out at the Bisasar road landfill which sought to use input from the residents living around the landfill to assist with development of a long term odour mitigation strategy at the site. The data collected from this community survey was used in conjunction with odour predictions from ADMS 3.1 (CERC, 2001a). An original analysis of the survey data and the numerical model odour predictions (Laister et al., 2002; Laister, 2003a) sought to establish the odour threshold and the overall odour emission rate from the Bisasar site by correlating the observations made by the community with the odour concentrations predicted by the model.

The decision to reanalyze the data collected from the 2002 community survey and to regenerate odour predictions to correlate with these observations was motivated by a number of factors. Firstly, the relative contribution of each odour source – transfer station and working face - to the overall odour perceived at a receptor was not investigated in the original analysis of the 2002 survey. Secondly, the original analysis did not seek to establish an odour threshold and odour emission rate specifically for an open waste pile, which is an objective of the present research. Thirdly, problems with the weather station during the survey meant solar radiation readings were incorrectly recorded for the duration of the community survey which had a negative impact on the odour predictions by the numerical model. As an absolute minimum, ADMS requires wind speed, wind direction and sensible heat flux (F_o) or Monin-Obukhov length data to generate predictions (Thomson, 2003). If F_o is not supplied directly by the user, then ADMS requires values of day, time and solar radiation to make an estimate of F_o. Reanalyzing the 2002 community survey presented an opportunity to investigate different approaches to odour dispersion modelling using the numerical model, ADMS.

Through remodelling the odour predictions and reanalyzing the community survey data it was hoped that the relative contributions from the working face and transfer station to the odour perceived at the receptors could be established. Through correlating the remodelled ADMS odour predictions and the community observations, it was hoped that an odour threshold for the odour emitted from an open waste pile could be estimated. The reanalysis also aimed, through backward dispersion, to make an initial estimate of the OER in $OU/m^2/s$ from an open waste pile.

4.2 Community modelling: 2002 Survey

Potential participants for the survey were selected from on site records of previous complainants. Of the potential participants contacted, 18 agreed to take part in the community survey. Of these, only 16 actually ended up participating. The survey involved filling out a questionnaire on a daily basis, noting any odour observations. Each day was divided into four observation periods and each was assumed to correspond to the following times: morning (7:00-10:00), midday (11:00-14:00), evening (17:00-20:00) and night time (20:00-23:00). Receptors were supposed to record precise times next to their observations, but quite often they would simply record their observation next to one of the four observation periods above. Participants were supplied with a new questionnaire at the beginning of each week, a sample of which is shown in Figure A-1. Receptors that agreed to participate were asked to keep a record of when they could and could not perceive an odour from the landfill site. When a receptor confirmed perceiving an odour, it was classified as a positive observation and where the receptor indicated they had not perceived an odour, it was classified as a negative observation. When participants made a positive observation for odour, they were also required to rate the intensity of the odour they perceived as being strong, medium or weak.

A summary of the survey participants, the number of observations made by each and the breakdown of these observations are displayed in Table 4-1. Map references in the table can be used to identify the locations of each receptor on the map in Figure 4-1. This Figure provides a sense of the spatial distribution of the receptors that took part in the survey relative to the sources of odour at the landfill site.

Table 4-1: Summary of odour observations made by receptors

Receptor	Map Reference	Total Observations	Positive Observations	Negative Observations
93 Bazley	1	188	4	184
34 Burnwood	2	279	202	77
178 Clare	3	153	145	8
48 Crouch	4	284	12	272
3 Dodoma	5	138	3	135
11 Dodoma	6	112	40	72
27 Elf	7	194	49	145
186 Foreman	8	145	80	65
192 Foreman	9	108	21	87
79 Kennedy	10	98	57	27
127 Kennedy	11	261	51	210
3 Revenge	12	851	0	851
15 Rosemary	13	310	46	264
7 Vialls	14	238	208	30
27 Vialls	15	51	49	2
144 Wattle	16	737	36	701
TOTAL		*4147*	*1003*	*3130*

4.3 Odour Modelling

The Advanced Dispersion Modelling System 3.1 (ADMS) was used to generate odour predictions in Odour Units (OU) to correlate with the observations made by the receptors in the community. To effectively model the dispersion of the odour plume, it is necessary to specify certain key parameters in the model such as the source emission rate, and to supply the relevant weather and complex terrain data.

4.3.1 Source & Receptor Specification

The working face and the Transfer Station were assumed to emit odour at the same rate in odour units per square meter per second ($OU/m^2/s$). This assumption was based on the fact that both these sources receive a similar waste type. Refuse arriving on a daily basis goes to both the working face and the transfer station and is typically made up of waste from residential and commercial sources. The working face, however; is considerably larger in terms of its area and so its emission rate in odour units per second (OU/s) is proportionally larger than the emission rate from the transfer station.

In order to identify the relative contribution of both the working face and the transfer station to the odour being perceived at the receptors, the sources were specified as emitting different chemical types in the model. Specifying different chemical types has no affect on the dispersion physics and simply aids in separating the contribution of the transfer station and the working face to the odour being perceived at a given time at a particular receptor.

During the 2002 survey period, the working face migrated around the landfill site. This was taken into consideration and three locations of the working face were modelled for the period of the survey. However, no detailed record of the coordinates of the working face was kept during the 2002 survey period, so approximated locations had to be used.

ADMS 3.1 has a feature which enables the user to input emissions and calculate output in Odour Units. By specifying the Odour Strength Q_{OU} (OU/m^3); the efflux velocity from the source v_e (m/s); the source area A (m^2) and the source emission temperature T_R, it was possible to calculate the odour emission rate Q (OU/s) using the following expression (Gray & McHugh, 2004):

$$Q = Q_{OU}.A.v_e.\frac{T_{STP}}{T_R} \qquad (4\text{-}1)$$

The temperature ratio is included in *4-1* because the OU release strength is defined at standard temperature and pressure (T_{STP} = 288.15K). A summary of the source specifications is listed in the Table 4-2. The ratio T_{STP}/T_R, for an emission temperature of 23 C, is equal to 0.97. This has little effect on the OER specification and values in the table below neglect the temperature ratio contribution. There is no measurable efflux velocity from an open waste pile, so to account for this, v_e was set equal to 0.001 m/s. Specifying a low value for v_e, such that $v_e \leq 0.01u_{10}$, removed the effect of plume rise due to efflux momentum from the modelling.

Table 4-2: Summary of model source specifications

Source	v_e (m/s)	T_R (C)	A (m^2)	Q_{OU} (OU/m^3)	V (m^3/s)	Q (OU/s)	Q/A (OU/m^2/s)
Transfer Station	*0.001*	*23*	*79*	*10^6*	*0.079*	*79000*	*10^3*
Working Face	*0.001*	*23*	*1000*	*10^6*	*1*	*10^6*	*10^3*

The Cartesian coordinates of the community survey participants (receptors) were identified using a web based GIS service from Ethekwini Municipality (Ethekwini@, 2005) and entered into the model. ADMS was set up to estimate the odour concentration at each receptor for each line of met data. Figure 4-1 shows an aerial colour image of the landfill site and the adjacent residential areas with the odour sources on the site and the receptors in the community indicated.

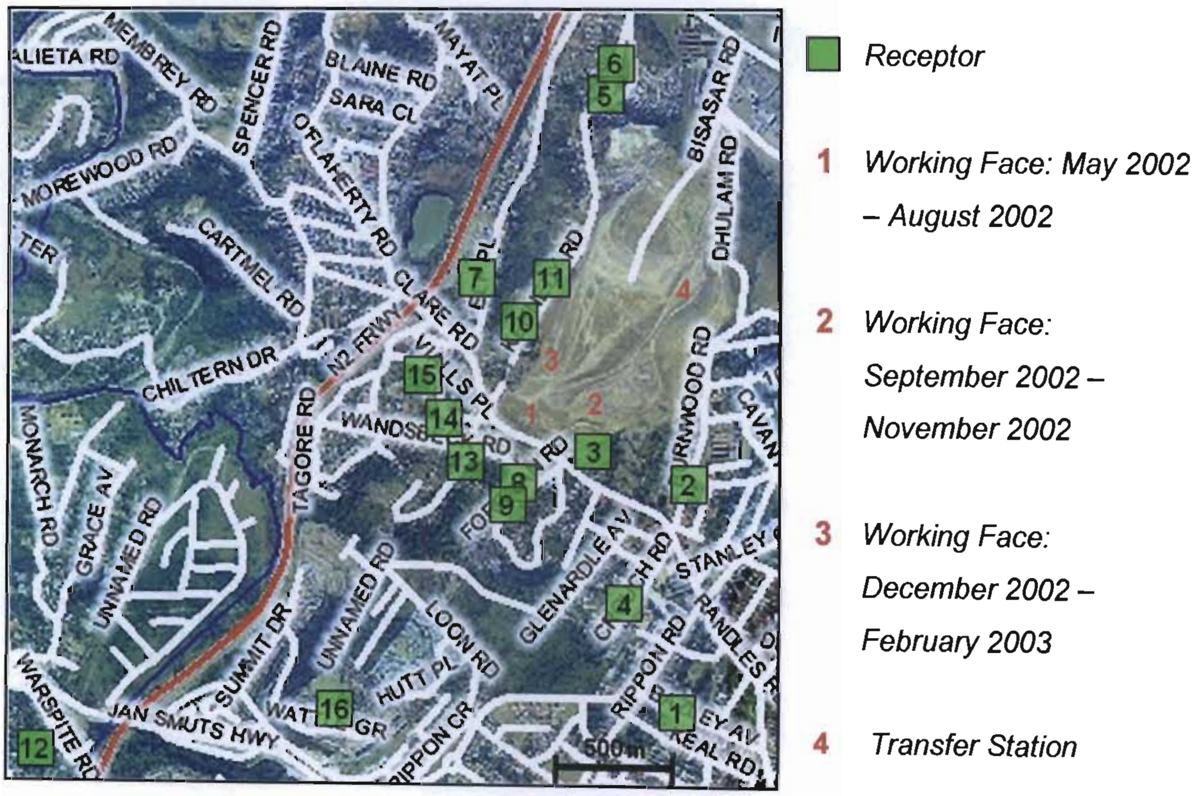


Figure 4-1: Spatial distribution of receptors and odour sources. Colour aerial photo (Ethekwini@, 2004).

4.3.2 Meteorological data

ADMS requires an input of meteorological data to make predictions of odour concentration downwind from the odour source. Meteorological (met) data is supplied to ADMS via a "met file" which can contain as many as 20 000 lines of met data. There is a weather station on site at the Bisasar road Landfill which records met data every 10 minutes and has been generating met records for the site since 2000. These met records contain the following data: date, time, wind speed, wind direction, standard deviation of wind direction, temperature, humidity, pressure, solar radiation and rainfall. While ADMS can generate predictions using only wind speed, wind direction and sensible heat flux (F_o), it was decided that the model would be supplied with most of the recorded met data at the site in order that it generate more specific predictions. Two approaches to generating odour predictions using ADMS were investigated. The first approach used the 10 minute meteorological data as it was recorded on site and the second approach used the same met data but averaged over one hour.

Ten minute averaged met data

The met data recorded by the onsite weather station was processed and prepared into an appropriate met file format for use by the dispersion model. When the ten minute met data was used for generating odour predictions, the met file was prepared with 9 of the 10 met parameters recorded by the weather station: julien day number, hour number, wind speed, wind direction , standard deviation of wind direction (σ_θ), temperature, humidity, solar radiation and precipitation.

The julien day number was calculated from the date and represents the day of the year. For instance, the 10 Feb 2004 is represented by the julien day number 41. The hour number was calculated from the time and was rounded to the nearest hour; for instance, 10:45 is represented by the hour number 11. The day number and the hour number are used by ADMS in the calculation of F_o (Thomson, 2003).

The wind speed (m/s), wind direction (degrees) and σ_θ (degrees) did not require any further preparation and were transferred directly into the met file. Temperature ($^\circ$C), humidity (%), solar radiation (W/m^2) and precipitation (mm/hr), were also transferred directly into the met file from the onsite weather record and did not require any adjustment.

Hourly averaged met data

An obvious advantage to averaging the ten minute met data over an hour is that it dramatically reduces the ADMS processing time. Typically, what would take over a week of continuous computations, would take just over a day. Another advantage to using hourly averaged weather data is that it allows one to use the "met data hourly sequential" option in ADMS which provides better estimates of boundary layer height if the met data supplied to ADMS is averaged over the hour (Thomson, 2003).

When the hourly averaged met data was used for generating odour predictions, the met file was prepared with 8 of the 10 met parameters recorded by the weather station: julien day number, hour number, wind speed, wind direction, temperature, humidity, solar radiation and precipitation.

The hourly wind speed and wind direction values were prepared by expressing the ten minute wind speed and wind direction quantities as wind vectors and then vector averaging over one hour. Temperature, humidity, solar radiation and precipitation were averaged over one hour by simply summing the ten minute values over the previous hour and dividing by six.

Standard deviation of wind direction (σ_θ)

Vertical (σ_z) and transverse (σ_y) spread parameters are estimated and used by ADMS to calculate the dispersion of the plume (CERC, 2001b). The transverse dispersion parameter is given by:

$$\sigma_y = \sigma_{yt}^{\ 2} + \sigma_{yw}^{\ 2} \qquad (4\text{-}2)$$

Where σ_{yt} is the spreading due to turbulence and σ_{yw} is the spreading due to variations in mean wind direction. The spread due to variations in mean wind direction is given by:

$$\sigma_{yw} = \sigma_\theta . x \qquad (4\text{-}3)$$

Where x is the travel distance from the source. The standard deviation of the mean wind direction (σ_θ) is either specified as a measured met input parameter in degrees, or an effective σ_θ is calculated by ADMS using the following expression developed by Moore (1976):

$$\sigma_\theta^{rad} = 0.065\left(\frac{7T}{u_{10}}\right)^{1/2} \qquad (4\text{-}4)$$

Where T is the averaging time in hours (as specified by the user) and u_{10} is the mean wind speed at a height of 10m.

Initially, simulation runs were carried out by allowing ADMS to make its own estimates for σ_θ using equation 4-4. Where ten minute met data was used, the averaging time T was set to three minutes. This choice of averaging time was based on an initial understanding that fluctuations and short term peak concentrations could be accounted for by adjusting the averaging time. It was later decided that the σ_θ recorded from the site should be used directly. The weather station samples every 30 seconds. These samples are then averaged and recorded every ten minutes by the data logger. The σ_θ is calculated by the logger using the 30 second samples that are received during the ten minute interval.

However, recent testing of the ADMS has revealed that even when σ_θ is specified directly by the user via the met file, the model output still changes with varying averaging time specification. This is not congruent with the technical reference for ADMS 3.1 which suggests that the averaging time is only used when σ_θ is not specified directly (Carruthers et al., 2003). This anomaly was brought to the attention of the developers of the dispersion model. It was later revealed that there was an error in the ADMS code which resulted in σ_{yw} being factored by the square root of the averaging time even when σ_θ was specified by the user. Subsequent versions of the model will be corrected. It was suggested by the developers that to avoid this problem, T should be set to 1 hour as the square root of 1 hour is 1. However, the averaging time specification was never altered from 3 minutes for all runs of the dispersion model using 10 minute met data. This meant that in all instances where σ_θ was used directly from the Bisasar landfill weather record, σ_{yw} was reduced by a factor of approximately 5 (the square root of 3 minutes expressed in hours).

When simulations were carried out using the hourly averaged weather data, ADMS was allowed to make its own estimate of σ_θ according to Moore (1976). T in this instance was set to 1 hour to correspond with the period over which the met data was averaged. Further investigation into the Moore technique for estimating σ_θ, revealed that the parameters in equation 4-4 were derived from experiments conducted in the U.K.. Consequently, the expression is likely only suitable for application in U.K.. Carruthers et al. (2003) suggest that local data should be used to define the model constants. Parameters could probably be derived for the expression that better reflect the relationship between wind speed and σ_θ in a South African context or even for a site specific context at Bisasar. However; this was not investigated and simulations carried out using hourly averaged weather data, were done with ADMS making its own predictions of σ_θ based on a T = 1 hour.

Solar Radiation

During the very early stages of the 2002 community survey, the pyrometer for measuring the solar radiation malfunctioned at the Bisasar Road landfill site and was not repaired for 8 of the 10 months that the survey was carried out. From the end of May 2002 through to the beginning of January 2003, the weather logger recorded the equivalent of zero readings for solar radiation for all hours of the day. ADMS odour predictions were initially made using these erroneous solar radiation readings and these predictions were then correlated with the observations made by the community. For the purposes of the reanalysis, these incorrect solar radiation readings were replaced with incoming solar radiation data from the Durban International Airport for the same period. The data from the airport are reported as Global Radiation, measured in KW/m^2, and are recorded on the hour as the sum of the global radiation from the previous hour. In order to convert the data to a format that could be used by ADMS, the values of global radiation were divided by 3.6 and multiplied by a factor. Solar radiation units are W/m^2, so to convert the global radiation readings supplied to these units, the data was multiplied by a thousand joules and divided by 3600 seconds. On inspection of the data, it became apparent that it required further adjustment. This was achieved through the use of a factor which was established by correlating a months worth of solar radiation readings at Bisasar with the same months readings from the airport. A factor of 10 – an approximation of the slope 9.56 shown in Figure 4-2 - was used to adjust the airport data for use by ADMS. The cause of this discrepancy has not yet been determined.

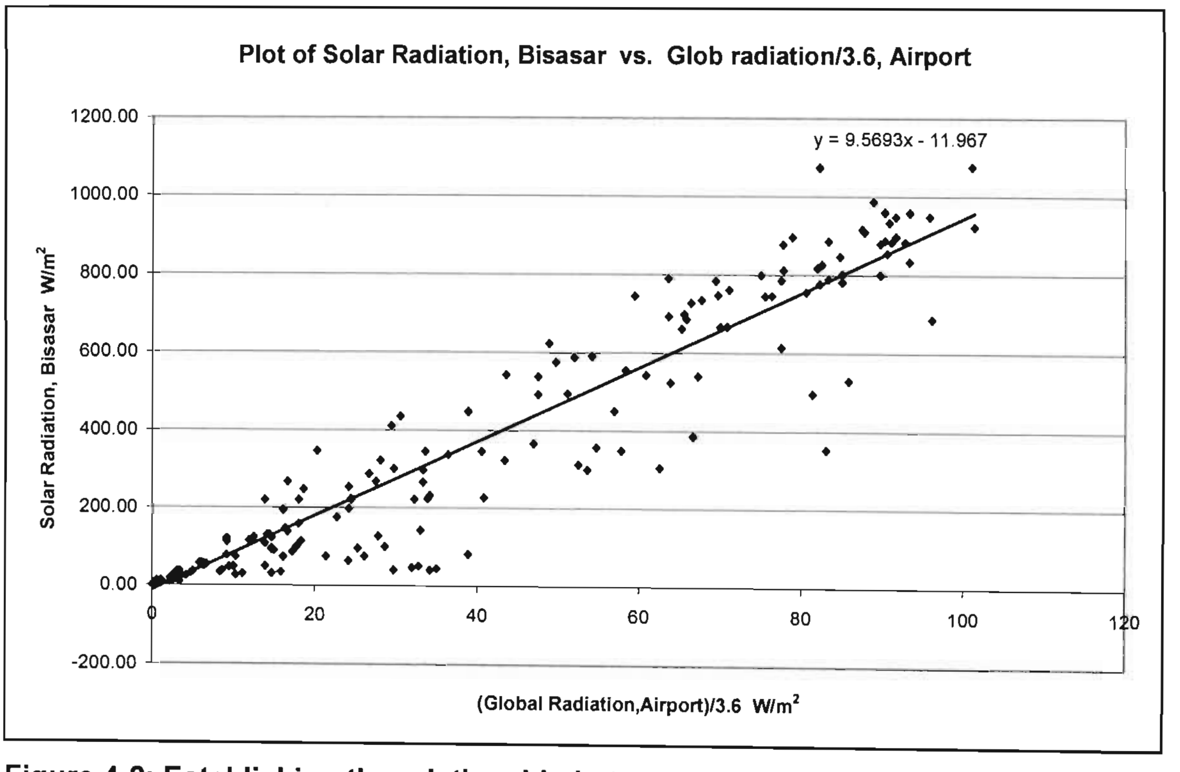


Figure 4-2: Establishing the relationship between solar radiations readings (Bisasar) and global radiation readings (Airport)

4.3.3 Complex Terrain

For the purposes of rerunning the simulations for the period of the 2002 community survey, terrain data of the landfill site from 2002 as well as terrain data for the surrounding residential areas were combined. Given that the topography of the landfill site is constantly changing and over a few years can change quite dramatically, elevation surveys are carried out on an annual basis at Bisasar. The terrain data of the Bisasar landfill site recorded in 2002 as well as the terrain data for the wider residential areas surrounding the landfill site were combined to form a 3850 m by 3850 m grid with 55 m grid spacing. Figure 4-3 shows a 3-dimensional representation of the terrain file used for the simulations with the odour sources shown by red numbers and receptors as blue numbers. Numbers correspond to receptors in Figure 4-1 and Table 4-1. The scales along the x, y and z axis are in meters.

Defining the surface roughness (z_0) is relevant as it has a direct impact on the calculation of the wind turbulence. The surface roughness was specified using a roughness file which defined the roughness over the landfill site and the community with two different roughness values. The roughness file contains coordinates which correspond to the terrain file grid coordinates. For the coordinates over the landfill, the roughness was set to 0.02m (corresponding to an open grassland) and over the surrounding community the roughness was specified as 0.5m (corresponding to parkland or suburbia) (ADMS, 2001a).

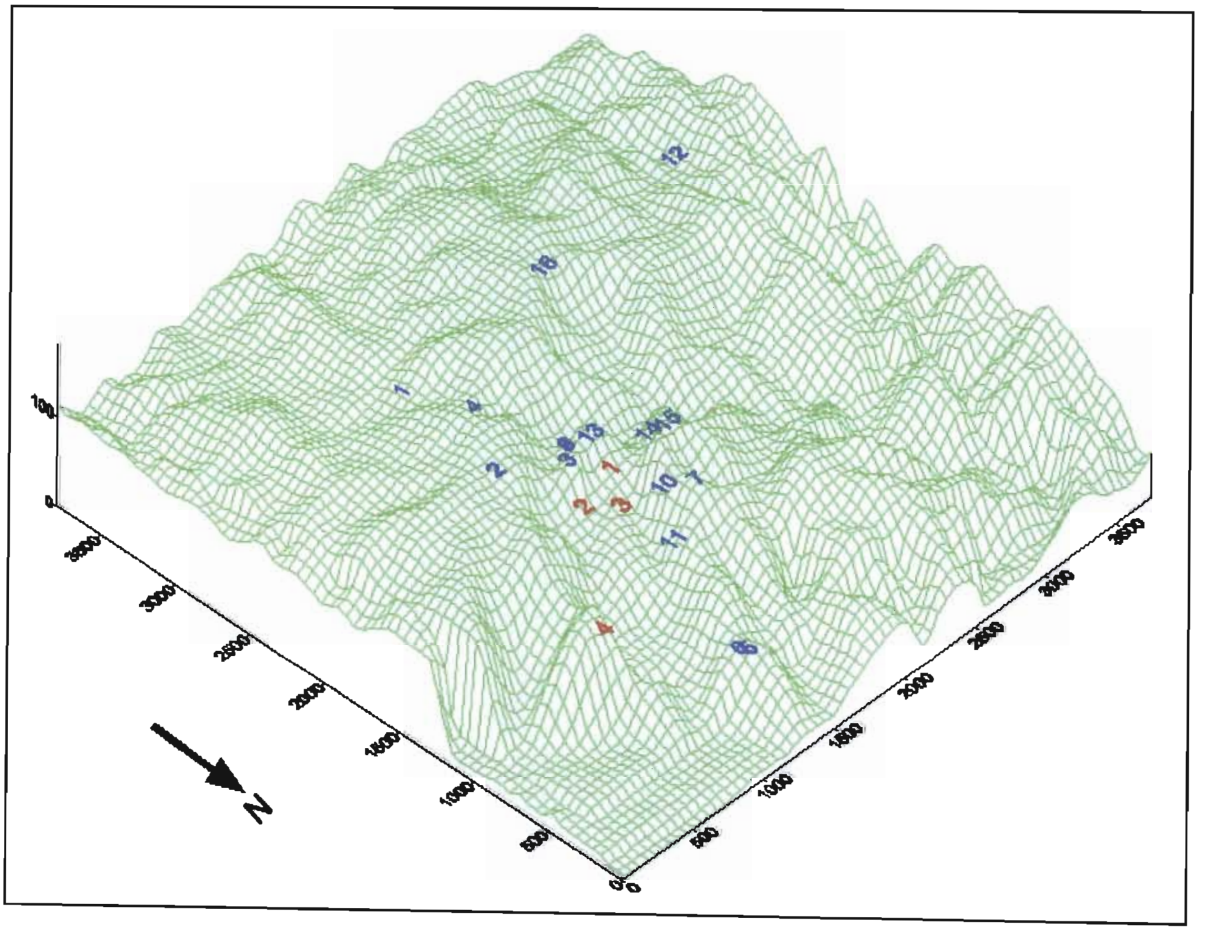


Figure 4-3: 3-dimensional representation of terrain file used in dispersion modelling with ADMS 3.1.

4.4 Analysis

4.4.1 General methodology

The observations made by the receptors during the 2002 community survey were archived together with corresponding concentration predictions made using ADMS. The model predictions for all cases were then sorted into bins with their associated receptor responses. The probability of odour detection for each bin was then established based on the number of positive and negative odour detections associated with that bin. A dose response histogram, where the probability of detection was plotted on the vertical axis and the odour concentration range on the horizontal axis, was generated. This plot allowed an estimate of the odour threshold to be made which is the concentration value at which 50% of the receptors detected an odour. The odour threshold is defined as 1 OU. Through reverse dispersion it was possible to infer the emission rate for the source(s) that contributed to the odour.

4.4.2 Analysis approach

The reanalysis of the 2002 community survey data and the corresponding odour predictions occurred in three stages corresponding to three runs of the dispersion model (Run 1, Run 2 and Run 3). The three runs of the model were based on differing model specifications and differing met data preparation. The three runs provided thousands of odour predictions which were then correlated with the odour observations made by each receptor. The results of each run of the model were analyzed in conjunction with the corresponding odour observations using various analysis techniques. Dose response histograms combining all the receptor observations and their corresponding odour predictions were generated for each analysis technique.

Various techniques for analysing the odour predictions and corresponding odour observations were tested. This was necessary in order to determine how best to interpret the data from the 2002 community survey. For instance, receptors didn't always include precise times next to their odour observations, but often would simply record their observation next to one of the four observation periods, i.e. morning, midday, evening and night time. As a result, it was unclear whether the average concentration or peak concentration over a period should be correlated with the observation. Analysis techniques using both average and peak concentrations over observation periods were tested. The different analysis techniques also aimed to establish the best approach for preparing met data, i.e. using 10 minute average met data or using hourly averaged met data. An analysis technique was considered effective if the resulting dose response histogram demonstrated a strong correlation between odour concentration and its probability of detection. Receptors indicated their perception of the intensity of the odour on a three point scale, i.e. weak, medium and strong. These intensity scales have not been analysed but do appear on the histograms for each analysis to indicate the intensity perception breakdown in each concentration bin.

Three analysis techniques were tested using the results of run 1 of the model and two analysis techniques were tested using the results of run 2 of the model. A further two analysis techniques were investigated using the results of run 3. A summary of each analysis technique for all three runs of the model is provided in Table 4-3. A detailed description of each analysis is given in Appendix B-1.

Table 4-3: Summary of approach to data analysis.

Simulation Run	Analysis	Summary
Run 1 (10 min met data)	1	Blank fields included as negative observations.
	2	Blank fields excluded from analysis.
	3	Only observations during morning and midday periods used. Blank fields excluded.
Run 2 (Hourly met data)	1	Average concentration over morning & midday periods.
	2	Peak concentration over morning and midday periods used.
Run 3 (10 min met data)	1	Average concentration over time period.
	2	Peak concentration over time period.

4.4.3 Analysis results

Dose response histograms were plotted for the combined receptor responses and corresponding model predictions for each of the analysis techniques summarised in Table 4-3. Error bars were generated for each bin and posted on the combined dose response histograms to indicate the margin of error for each concentration range. Calculation of the error bars is discussed in Appendix A-2.

Analysis 1 of run 3 of the model was used to infer an OER, as the dose response histogram generated in this instance appeared to demonstrate the strongest correlation between probability of detection and odour concentration. A summary of the number of positive and negative observations used for each receptor in the analysis 1 of run 3 is shown in Table 4-4. The total number of observations used in the analysis is less than the total number of observations recorded, as reported in Table 4-1. This is due to periods of calm conditions – wind speeds less than 0.75 m/s – where the model was unable to generate predictions. In some instances, the weather station did not record met data and so odour predictions could not be generated. The results of the analysis for run1 and run 2 are given in Appendix B-2. The histogram generated from analysis 2 of run 3 is also given in Appendix B-2.

Table 4-4: Summary of observations used for each receptor in Run 3, Analysis 1.

Receptor	Total Observations Used	Positive Observations Used	Negative Observations Used
93 Bazley	159	3	156
34 Burnwood	245	194	51
178 Clare	136	126	10
48 Crouch	140	4	136
3 Dodoma	70	1	69
11 Dodoma	56	19	37
27 Elf	91	18	73
186 Foreman	90	53	37
192 Foreman	76	19	57
79 Kennedy	55	43	12
127 Kennedy	129	23	106
3 Revenge	432	0	432
15 Rosemary	164	29	135
7 Vialls	86	69	17
27 Vialls	31	29	2
144 Wattle	375	32	343
Total	*2335*	*662*	*1673*

Odour Threshold and odour emission rate

The histogram generated from analysis 1 of run 3 of the model, shown in Figure 4-4, was used to estimate the odour threshold for the community panel. The waste piles were specified in the model as having an emission rate of 10^3 OU/m^2/s. With predictions based on this emission rate, the 50th percentile appears to correspond to the bin 1-10 OU, which implies that the odour threshold lies in this range. The model output in ADMS scales linearly with the emission rate specification. In other words, if the emission rate is reduced by a factor of ten, then the model output will reduce by a factor of ten. Consequently, the emission rate can be adjusted such that an output of 1 OU from the model will correspond to a 50% probability of detection amongst the odour panel. By inspection of the histogram in Figure 4-4 we infer that the emission rate lies in the range 10^2 -10^3 OU/m^2/s.

Resolving the concentration range 1-19 OU in order to more precisely identify the threshold did not yield a better result as shown in Figure 4-5. When resolving in the range 1-19 OU, there is no clear trend of Probability of detection increasing with increasing odour concentration, so there is no distinct concentration range which corresponds to the 50th percentile in Figure 4-5.

One could assume that the odour threshold lies at the midpoint of the range 1-10 OU, i.e. 5 OU. In this case, the odour emission rate specification should be reduced by a factor of 5. This would ensure that odour predictions of 1 OU, generated by an emission rate of 200 OU/m^2/s, represent the 50th percentile of detection (odour threshold of the community odour panel).

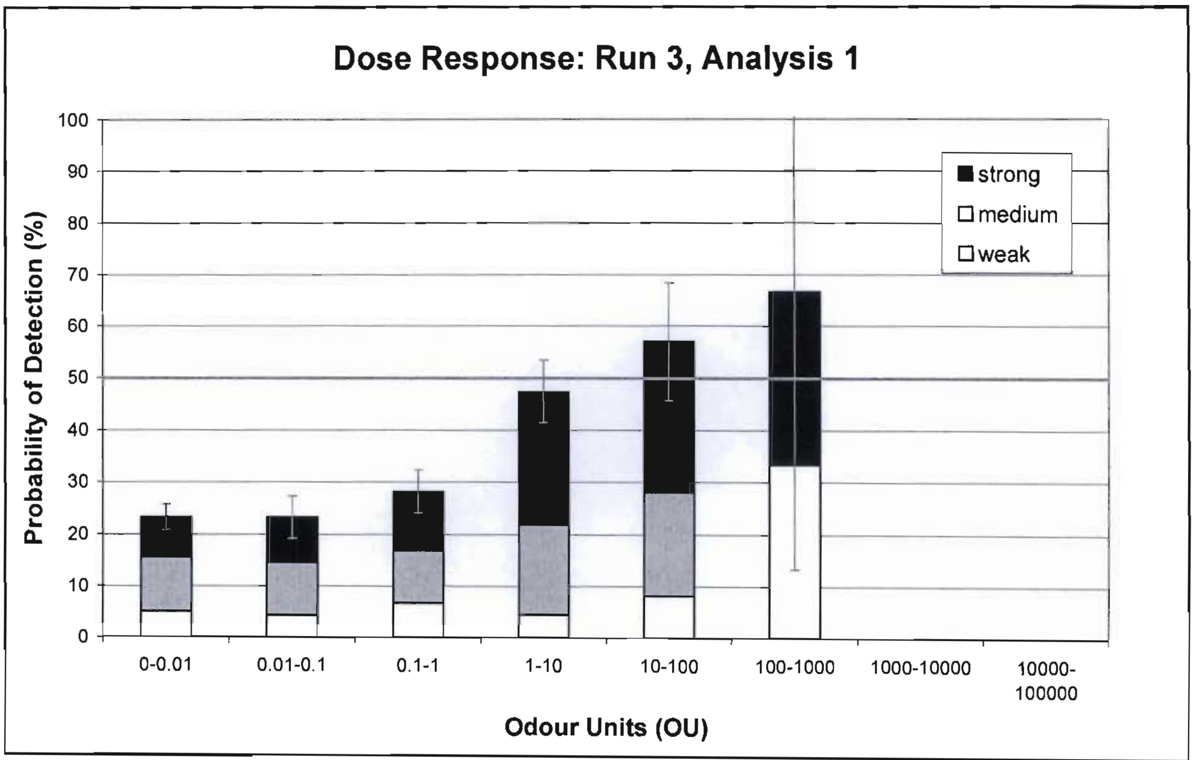


Figure 4-4: Histogram showing combined dose response: Run 3, Analysis 1

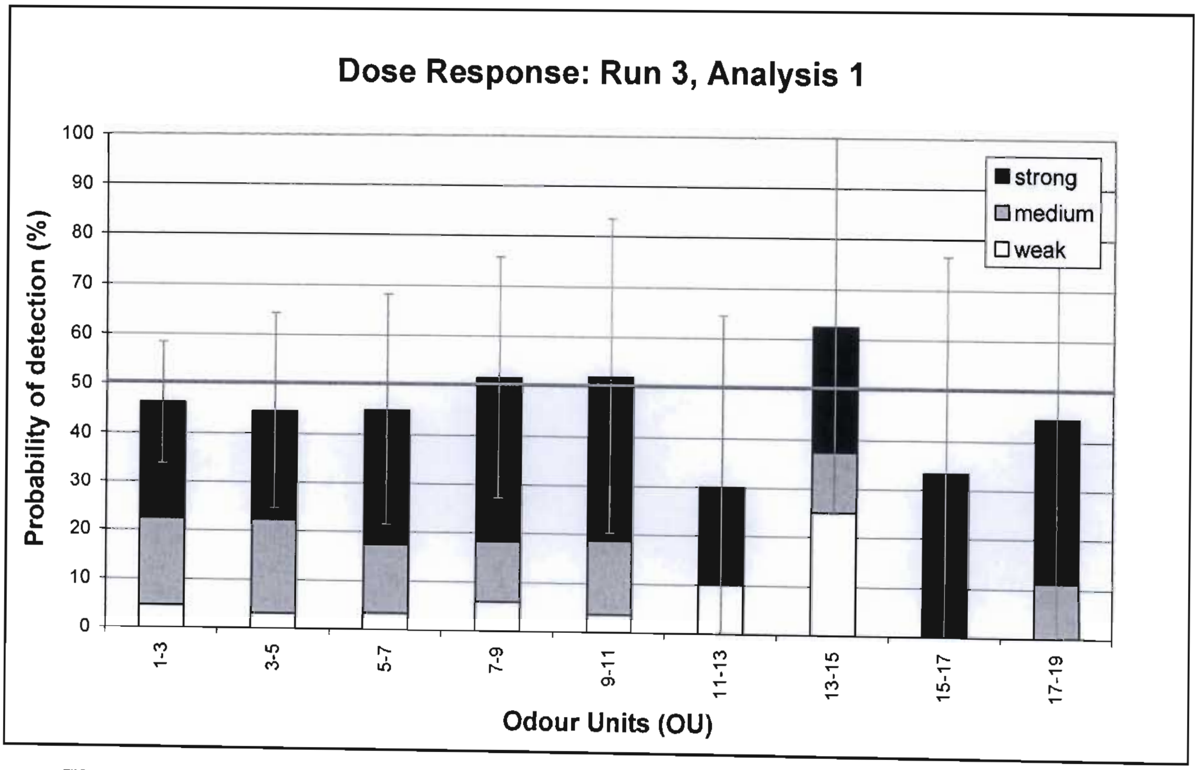


Figure 4-5: Histogram showing combined dose response: Run 3, Analysis 1. Resolved for 1 to 19 OU.

Individual Receptor Dose Responses

Appendix B-3 contains histograms showing the dose-response in terms of probability of detection for each receptor that took part in the survey. These dose response histograms are based on the 1st analysis technique used on the odour predictions of the 3rd run of the model. One expects the probability of detection to increase for increasing odour concentrations, but this is not the case for some of the receptors as demonstrated by the dose response for the receptor in Figure 4-6. This could be an indication of the unreliability of certain receptors. It could also indicate that receptors were perceiving odours from other sources - on or off the site - which resulted in high probabilities of detection for the lower concentration ranges. Given that the aim here is to establish the emission rate from an open waste pile, only the working face and the transfer station were modelled as odour sources. Consequently, other onsite sources such as sources of biogas were neglected. Receptors did not describe the character of odours they were perceiving when they filled out the weekly diary, making it difficult to confirm that the odour they were perceiving did indeed come from an open waste pile on the site.

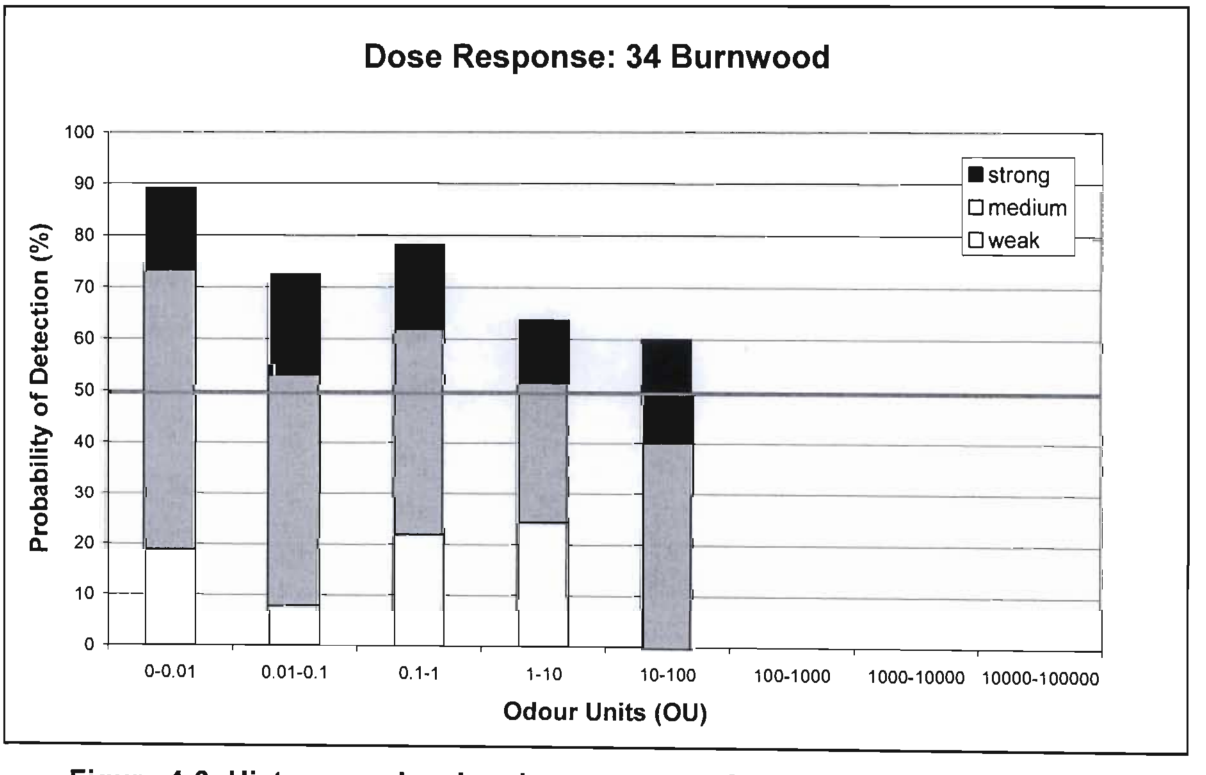


Figure 4-6: Histogram showing dose response for receptor at 34 Burnwood

Contribution of working face and transfer station

The results from analysis 1 of ADMS run 3 were used to establish the proportional contribution of the Transfer Station and the Working Face to the overall odour perceived at the receptors during the survey. Positive observations where the corresponding odour predictions were above 0.1 OU were used. A lower limit of 0.1 OU was chosen to exclude positive observations for odour that may have been recorded when another source, not modelled, was dominant. Table 4-5 shows a summary of the percentage contribution of Working Face and the Transfer Station to the overall odour perceived by each receptor during the survey period. The relative contributions from the working face and the transfer station during the 2002 community survey were 82% and 18 % respectively (see Table 4-5). Clearly the working face was the main contributor to the odour perceived off site during the survey.

Table 4-5: Percentage odour contributions from the working face and the transfer station at each receptor during the course of the survey.

Receptor	**Working Face (%)**	**Transfer Station (%)**
Bazley 93	97	3
Burnwood 34	84	16
Clare 178	63	37
Crouch 48	96	4
Dodoma 3	-	-
Dodoma 11	98	2
Elf 27	60	40
Foreman 186	88	12
Foreman 192	68	32
Kennedy 79	59	41
Kennedy 127	62	38
Revenge 3	-	-
Rosemary 15	90	10
Vialls 7	96	4
Vialls 27	93	7
Wattle 144	92	8
Average	*82*	*18*

4.5 Discussion

Two main problems exist with the 2002 community survey data. Firstly, receptors would often not record precise times next to their observations. This made it difficult to link an odour prediction with these observations during analysis. It was unclear whether the average concentration or the peak concentration over a time period should be used in an instance where an exact observation time was not provided. Secondly, the survey did not require receptors to provide a description of the character of the odour. Consequently, there was uncertainty regarding the source of the odour.

There were problems with the weather data recorded onsite during the survey. Periods of weather station downtime and a faulty pyrometer resulted in problems trying to generate odour predictions to correlate with the receptor odour observations.

The reanalysis of the 2002 community survey data revealed a need to conduct a new more direct survey to alleviate the above problems. A more direct survey would use precise observation times so that a better correlation between odour observations and odour predictions could be achieved. A new survey would also seek to establish a distinction between the different types of odours perceived by the receptors. This would aid in identifying the source of the odour.

4.6 Summary

A reanalysis of the data captured from the 2002 community survey was performed in order to investigate the odour emission rate from the open waste piles – transfer station and working face - at the Bisasar road Landfill site. The odour emission rate from an open waste pile was found to lie in the range 100-1000 $OU/m^2/s$. For the duration of the survey, the working face contributed 82% to the odour perceived at the receptors and the Transfer Station contributed 18% during operating hours when the working face was uncovered. An insight into modelling the dispersion of odour from a landfill site using ADMS was gained. The appropriate approach to analyzing receptor observations and their corresponding odour concentration predictions was established as well as an understanding of how best to interpret the weekly survey forms.

CHAPTER 5

5. 2004 TELEPHONIC COMMUNITY SURVEY

5.1 Introduction

The results of the 2002 survey provided an estimated range for the emission rate from an open waste pile. It was hoped that a new community survey, that sought to gather accurate odour observations from the community, could provide a more precise estimate of the emission rate. To this end, a new survey approach using direct telephonic communication with residents to collect data was explored.

The analysis of the 2002 survey data did not provide a clear picture of the dose-response for each receptor that took part in the survey. The new survey aimed to provide a clearer picture of how individuals in the community respond to the odour coming from the landfill. Previously, only dose-responses in terms of probability of detection were investigated. It was hoped that a new survey could provide dose-response relationships in terms of perceived intensity and probability of detection.

The 2002 survey had proven to be an effective public relations exercise and this also became one of the motivating factors for reinitiating community participation through a new community survey in 2004.

5.2 Community modelling: 2005 Survey

A new community survey was initiated at the beginning of 2004 with the intention of attaining accurate observations of odour from residents using direct telephonic communication. The idea was to get a similar number of observations from each receptor across a range of odour concentrations as predicted by the model. However, this was difficult to achieve given that some receptors were less likely to experience odour within certain concentration ranges than others due to their location and the prevailing wind patterns at the site.

5.2.1 Choice of Survey Technique

During the 2002 survey, participants recorded their odour observations in a diary type format. The major problem with using diaries is that it is very difficult to obtain any independent verification of what is recorded in the diary; only the respondent knows whether or not it is accurate (Goodman, 1998). More often than not, receptors during the 2002 survey would not record a specific time of observation, but would simply indicate whether an observations was made in the morning, midday, afternoon, evening or night time. The 2002 survey also did not seek to differentiate between odour being emitted from FWO sources and odour being emitted from LFG sources.

Instead of using a diary technique to record odour observations, the 2004 survey sought to use direct telephonic communication with residents to establish the sensitivity of the community to the odour from the landfill. This meant that an odour observation at the time of the call could be recorded and be correlated with an odour prediction from the model for a specific time, giving a more explicit relationship between odour observation and odour prediction. The telephone survey approach also allowed for verification of the odour observations made by the receptors. Independent verification was conducted by the author travelling to the receptor locations soon after a call was made and rating his own odour perception. The community feedback was also verified by checking it against the predictions of the odour management system at the landfill which generated real time predictions of the odour impact.

However, telephonic survey techniques also have their disadvantages. Not everybody has a telephone, and the disparities are not random, but associated with variation in economic and social status (Marks, 1989).Typically, using a telephone survey technique results in under-representation of the economically disempowered members of the community. Another disadvantage to the telephone survey technique is that contact is not always guaranteed; people are not always at home when a call is made. Another obvious disadvantage of such a survey approach is its potential intrusiveness.

5.2.2 Survey Sample

The survey was conducted with the intention of estimating the odour threshold and the emission rate of the odour from the landfill site. This required the participation of a representative cross section of the community living around the landfill. The sample did not need to be large, provided it was a representative sample (Stone, 1986). However; this proved very difficult to achieve.

Potential survey participants were contacted from a historical record of former odour complainants. Participants of the 2002 survey were also contacted. In total, 30 community members were contacted, of which 26 showed an interest in participating. By the end of the survey, 19 of the original 26 residents that showed an interest in the survey were still participating.

The sixteen residents from the 2002 survey were contacted, thirteen of which showed an initial interest in participating in the 2004 community survey. Four of the thirteen residents that originally showed an interest dropped out of the survey during the first few months of telephonic communication due largely to their unavailability during the hours of the day when the data was to be collected.

The fact that potential participants were not selected at random from the community is likely to introduce some bias as only those residents that had complained about the landfill odour in the past were approached. However, as discussed previously, one of the aims of the survey was also to establish and maintain good relations with the community by cooperating with some of the landfills biggest critics in the community. In this respect, approaching complainants to participate in the community survey was justified.

Bias was also introduced due to the exclusionary nature of a telephonic survey; people who did not own a telephone could not participate. There is an informal settlement situated immediately to the North of the landfill and another situated about a kilometre south of the site. Nobody from these informal settlements could participate in the telephonic survey. The community around the landfill is made up mostly of Indian and African residents. However; of the 26 residents that originally agreed to take part, all were Indian except for one, a white resident located about 1.5 kilometres to the South of the landfill site.

Phone calls to residents were made during working hours which meant that of the 19 households that participated in the survey, it was the member of the family that stayed at home during the day that contributed to the survey. Of the 19 participants that stayed with the survey through to its conclusion, 16 were female and 3 were male. One of those men included the author.

5.2.3 Telephonic Survey Questions

After potential survey participants were identified from the complaints file, they were then contacted via telephone. A script was compiled beforehand for introducing the survey concept to the resident via the phone. The script was necessary to make sure the salient points were covered with each resident. The script was not read out verbatim, but rather was used as guide to ensure the same meaning was conveyed during each call (Marks, 1989). The concept of the telephonic survey was briefly introduced and the interest of the resident gauged. If the resident was interested in participating, then a series of questions was asked to get a profile of the receptor. If the resident was not interested in participating, they were politely thanked for their time and the conversation ended.

If the resident was interested, they were then asked to confirm their full name, address and contact numbers. The resident was also asked to identify the times of day that would be convenient for them to receive a call and how many calls a week they were prepared to take. Finally, receptors were asked if they had identified different types of odour coming from the landfill. This was with the intention of establishing if the resident could discriminate between LFG odours and FWO coming from the open waste piles.

Once a sample of volunteer citizens was identified, the survey was initiated. The participants were referred to as odour receptors during the run of the survey. Receptors were contacted on a regular basis throughout 2004. Each phone call to a receptor would last around 5 to 10 minutes, but could go on for much longer if the receptor wanted to discuss other issues regarding the landfill. Given that one of the objectives of the telephonic survey was to serve as a form of public relations exercise, if a receptor wanted to vent their frustrations about the landfill, they were given the freedom to do so. On these occasions, the phone call was only terminated once the receptor had finished expressing him or herself.

The receptors were required to answer a list of simple questions during each call. The questions were kept simple and short in order to keep the duration of the calling period under ten minutes which is a common guideline in telemarketing (McGinley, 1995). Receptors were asked if they could perceive an odour from the landfill at the time of the call (direct observations). If the receptor was indoors and away from the outside air, they were asked to go outside and make a direct observation. Receptors were also asked to make indirect observations by recalling stand-out odour events over the past week (indirect observations).

Direct Observations:

- Are you detecting an odour from the landfill at this time?
- What does the odour smell like (Character)?
- How strong is the odour (Intensity): Weak, Medium or Strong?

Indirect Observations:

- Have you detected any odours in the past week?
- Date and Time odour was detected?
- Character? Intensity?

The receptor's description of the character of the odour aided with identifying which source the odour likely came from. Firstly, a description of the odour helped establish if the odour was indeed coming from the landfill site. If the receptor described the odour as being 'Smokey',' burning', 'sewerage' like in nature, then there was a very real possibility that what they were smelling was not coming from the landfill. Secondly, it aided with differentiating between the various odours coming from the landfill itself. The receptors were generally familiar with the two distinct odours that dominate the odour being emitted from the landfill, namely LFG emissions and FWO from exposed waste. Receptors would typically describe the LFG odour as being 'gassy' and would refer to the FWO as being comparable to 'rotting', 'garbage', 'decay', 'urine' and 'faeces'. Character observations for odour were coded as follows:

- Landfill gas: *0*
- Fresh waste odour: *1*
- Combination: *2*
- No odour: -

The odour that dominated during the day, however; was generally from fresh waste at the working face. Receptors were also asked to identify the intensity of the odour. Typically intensity is defined on a seven point scale, from zero to 6, but to keep matters simple and given that the receptors were not a trained odour panel, the scale was on a four point scale:

- Weak: *1*
- Medium: *2*
- Strong: *3*
- No odour: *0*

A 'Call Summary' database was used to store the data collected from each telephonic interview. Data was recorded directly into the computer database during each call; the final result was a database containing all the direct and indirect observations for all the receptors during the run of the survey. Plate A-2 in Appendix A shows a screenshot for a day's observations made during the survey.

5.2.4 Survey Results Summary

As was the case with the reanalysis of the 2002 survey, any direct or indirect observation that confirmed an odour from the landfill was described as a positive observation and any observation that confirmed no odour perceived from the landfill was termed a negative observation. During the survey, a total of 702 direct observations and a total of 245 indirect observations were recorded. Table 5-1 shows a breakdown of observations for each receptor. A detailed record of the direct observations made by each receptor during the

2004 survey and corresponding odour predictions is located in Appendix G. The receptor on Wattle Road lived the furthest from the landfill, therefore it was difficult to collect positive odour observations from this receptor. The receptor handily kept a precise record of most positive observations made which were then used as direct observations in the analysis. A couple of other receptors also wrote down observations, with precise observations times, and these were used in the analysis. Details from receptors phoning in to make odour complaints were also used as direct observations.

Table 5-1: Summary of observations reported by receptors during survey.

Receptor	Map Ref. #	Total Indirect Observations	Total Direct Observations	Positive Direct Observations	Negative Direct Observations
Burnwood 60	*1*	10	33	10	23
Burnwood 34	*2*	8	43	8	35
Burnwood 125	*3*	35	63	24	39
Dodoma 11	*4*	20	39	7	32
Foreman 192	*5*	2	30	2	28
Kennedy 79	*6*	10	20	8	12
Kennedy 105	*7*	40	39	20	19
Kennedy 131	*8*	8	40	24	16
Kennedy 93	*9*	11	42	17	25
Kennedy 127	*10*	14	37	13	24
Kennedy 159	*11*	9	27	5	22
Rosemary 15	*12*	2	31	6	25
Site Office	*13*	7	67	31	36
Vialls 5	*14*	18	32	11	21
Vialls 27	*15*	10	29	5	24
Vialls 33	*16*	13	38	10	28
Vialls 7	*17*	11	29	3	26
Wandsbeck 78	*18*	9	24	6	18
Wattle 144	*19*	8	39	6	33
Total		*245*	*702*	*216*	486

5.3 Odour modelling

The Atmospheric Dispersion Modelling System (ADMS) was used to generate odour predictions at the various receptor locations. To ensure the generation of accurate predictions, certain key parameters in ADMS were specified and the appropriate meteorological and 3-dimensional terrain data supplied to the model. Many of the model specifications; met data preparations and 3-D terrain were the same as for the simulations carried out on the 2002 data. Any differences are discussed here.

5.3.1 Source and receptor specification

Filling occurred at two main cells during the 2004 survey, the Randles cell and the Benoni Cell. The general location of these cells is noted in Figure 5-1. The Randles cell was located at the South Eastern corner of the landfill and the Benoni cell was situated adjacent to Kennedy Rd to the West. Filling occurred as a series of terraces at the Benoni cell. Each terrace started from the southern end of the cell and worked its way North, parallel to Kennedy Rd. The filling location at the Benoni Cell was specified according to one of four coordinates as shown in Figure 5-2, depending on where filling was taking place at the time of the receptor observation. The Randles cell was specified in a similar fashion, using one of two sets of coordinates at that cell.

A detailed record of the migration of the working face around the landfill was not kept during the 2002 community survey. The reanalysis of the 2002 survey data used approximate locations of the working face over the period of the survey for the purposes of running simulations and generating odour predictions. Keeping an accurate record of the location of the working face became especially important when the working face was located near a group of receptors during the 2004 survey. This was the case when filling occurred parallel and adjacent to Kennedy Road where six of the nineteen 2004 surveys receptors were located. Not knowing the exact location of the working face during the 2002 survey for the purposes of running simulations may have resulted in inaccurate odour predictions at receptors at certain times. To ensure accurate odour predictions, a detailed record of the working face was maintained during the 2004 survey when filling was taking place at the Benoni cell. Walk-by observations of the odour plume made along Kennedy Rd when the working face was migrating up and down the Benoni Cell confirmed the need to correctly specify the coordinates of the working face in the model. The location of the working face is recorded – using the codes in Figures 5-1 and 5-2 - next to each receptor observation in Appendix D

The transfer station was once again identified as a source of odour and a break down of the relative emission rate specifications are shown in Table 5-2. The results of reanalysis of the 2002 survey suggested that the emission rate from an open waste pile lay in the range 100-1000 OU/m^2/s. The emission rate was specified as 1000 OU/m^2/s for the initial analysis of the 2004 data.

Table 5-2: Summary of model source specifications 2004.

Source	v_e (m/s)	T_R (C)	A (m^2)	Q_{OU} (OU/m^3)	V (m^3/s)	Q (OU/s)	Q/A (OU/m^2/s)
Transfer Station	*0.001*	*23*	*79*	*10^6*	*0.079*	*79000*	*10^3*
Working Face	*0.001*	*23*	*1000*	*10^6*	*1*	*10^6*	*10^3*

The Cartesian coordinates for the receptors were identified using a web based GIS service (Ethekwini@, 2004). The spatial distribution of the receptors surrounding the landfill is shown in Figure 5-1.

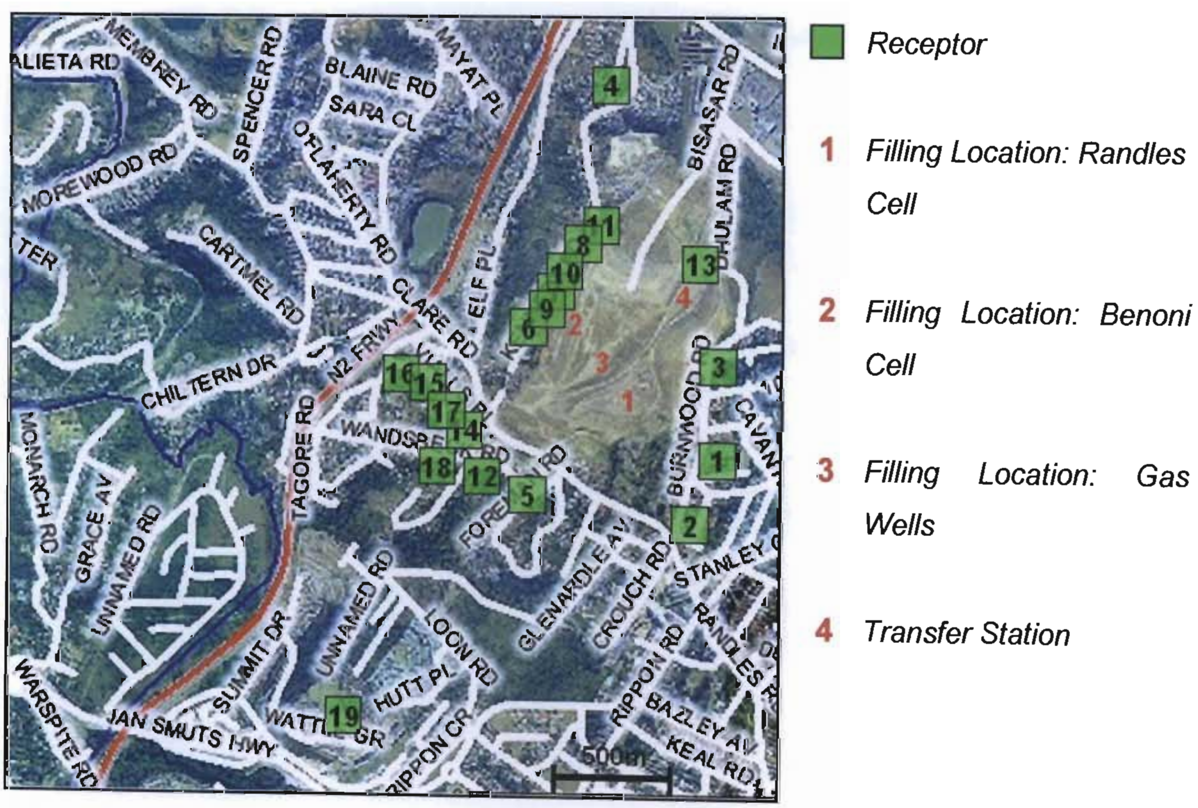


Figure 5-1: Spatial distribution of receptors and odour sources. Colour aerial photo (Ethekwini@, 2004)

1a, 1b *Filling locations: Randles Cell*

2a, 2b, 2c, 2d *Filling Locations: Benoni Cell*

3 *Filling Location: Gas Wells*

4 *Transfer Station*

Figure 5-2: Odour source specifications. Colour aerial photo (Ethekwini@, 2004)

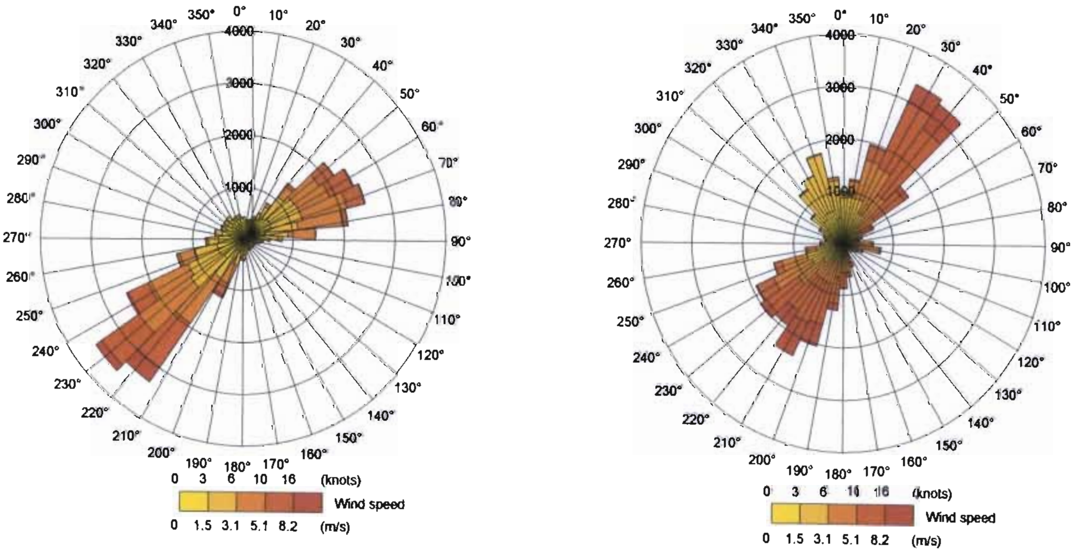
5.3.2 Meteorological Data

The ten minute meteorological data recorded by the onsite weather station was used directly to compile a met file for ADMS to generate odour predictions. The met file contained many lines of met data corresponding to dates and times of receptor odour observations. Each line contained 9 met parameters: day, hour, wind speed, wind direction, standard deviation of wind direction (σ_θ), temperature, humidity, solar radiation and precipitation. As with the analysis of the 2002 data, runs of the model were conducted initially with an averaging time set equal to 3 minutes to estimate σ_θ. When the σ_θ values recorded at the site were used in the modelling, the averaging time was not adjusted. Consequently, the previously discussed anomaly in the ADMS 3.1 code resulted in σ_{yw} (spreading due to variations in mean wind direction) being reduced by a factor of 5 (the square root of 3 minutes expressed in hours) *.

* The odour predications have since been regenerated by rerunning the simulations with the model averaging time set to 1 hour. This did not significantly alter the dose response histograms or the inferred emission rate.

Infilling Missing Weather Data

As with the 2002 survey, met data for the 2004 survey was gathered from an on site weather station at the Bisasar landfill. However, there were periods when the weather station was offline for various technical reasons and it became necessary to infill the missing weather data using data from the Durban International Airport. Wind patterns were slightly different at the two sites as demonstrated by the wind roses in Figure 5-3. However, a correlation between the two does exist and using a regression model derived from sets of wind vector data from both sites, it was possible to infill the missing data. Linear regression techniques combined with the Expectation Maximization Algorithm (EM) (Dempster et al., 1977) were used for the model to infill the missing wind vector data at Bisasar with corresponding data from Durban International was derived. The derivation of this model and its parameters are given in Appendix E.



(a) (b)

Figure 5-3: (a) Wind rose compiled from a years weather data Bisasar Landfill (b) Wind rose compiled for the same years weather data Durban International. Generated using ADMS wind rose generator (CERC, 2001a).

Met data such as temperature, humidity, solar radiation and precipitation were used directly from Durban International with no alteration. The similarity between the data from the landfill site and Durban International with regards to these meteorological parameters were such that no adjustment was deemed necessary.

5.3.3 Terrain Data

The complex terrain file used by ADMS to generate odour predictions for the 2004 survey was updated with the latest land survey of the landfill site at the end of 2003. The same terrain data as was used for the 2002 survey for the surrounding community was reused and combined with the latest terrain data for the site. The terrain file used was a 3850 m by 3850 m grid with a 55 m resolution. The same roughness file, as was used for the 2002 analysis, was used once again in the 2003 analysis.

5.4 Analysis

5.4.1 General Methodology

The analysis sought to relate the responses of the receptor group to a range of odour concentrations. The responses were expressed in terms of probability of detection and perceived intensity.

Dose-response histograms to relate probability of detection to the predicted odour concentration were generated by grouping the odour observations made by the receptors and their associated odour predictions into bins (concentration ranges). The probability of detection was then calculated for each bin using the number of negative and positive observations for odour associated with that bin. Receptors also provided information regarding the intensity of the odour during the telephonic survey which allowed dose-response curves of perceived odour intensity to be generated.

Where a dose response for probability of detection for the whole odour panel was to be generated, all the receptor responses and associated predictions were grouped together. In this instance, the original aim was to have a similar number of observations from each receptor contribute to the calculation of the detection probability in each bin. This, however; was difficult to achieve as some receptors rarely experienced odour within certain concentration ranges due to their geographic location and the prevailing wind directions at the site. This meant that the probability of detection for certain concentration ranges was calculated in some instances with observations from only a few of the receptors that made up the odour panel. In some cases, the contribution of a particular receptor to a bin was greater than that of another receptor. This may introduce a bias. However, the decision was taken not to normalise the contributions from each receptor to each bin. The reason being, one receptor may only have made 2 observations in a particular concentration range whilst another may have made 10 observations for the same range. The error associated with the receptor that made 2 observations is greater than for the one that made 10 observations.

5.4.2 Dose Response: Probability of Detection

The positive and negative observations reported by the receptors were combined to generate a dose response for the whole receptor group. Dose responses for each receptor were also investigated. By establishing the relationship between the probability of an odour being detected and the concentration of the odour, it was possible to identify the odour threshold and thus infer the emission rate from the odour source. Relating the probability of detection to odour concentration provided an insight into the persistency of the odour once it entered the surrounding community.

Odour Threshold and odour emission rate

As with the analysis of the 2002 survey, the analysis of the 2004 survey sought to bring together the odour observations reported by the receptors and the corresponding odour predictions made by the model in order to identify the community odour threshold and so infer, through backward dispersion, the odour emission rate at the source.

Only the direct observations made by the receptors during the telephonic interviews were used in the generation of dose-response relationships. On the occasions when a receptor confirmed the detection of an odour, but was unable to distinguish the source of the odour, the corresponding odour prediction was used to establish what the likely source was. If the odour prediction showed a high odour contribution from the working face and/or the transfer station, then the observation was assumed to be associated with an open waste pile and was then used in the analysis.

The appropriate ten minute met data recorded onsite was correlated with the observations made by the various receptors. If a receptor made an observation at say 7:35am, both the met data for 7:40am and 7:30am were used to generate odour predictions for that observation time. The two ADMS odour predictions generated for that single observation were then averaged to produce a single odour prediction.

It was previously mentioned that a detailed record of the location of the working face was kept, especially when it was close to a group of receptors. Odour emission predictions were generated for all the working face locations on site. The date of a receptor's observation determined the appropriate working face odour prediction to be associated with that odour observation. The working face location was recorded with each receptor observation as shown in Appendix D.

Only the met data corresponding to the exact times of the receptor observations were used in generating odour predictions. This helped to significantly reduce the simulation time when compared with the time necessary to process the odour predictions for the 2002 community survey reanalysis.

The model is assumed to generate accurate predictions of odour exposure at each receptor. For instance, if 1OU is predicted at receptor A and 1OU is predicted at receptor B – on separate occasions and under different weather conditions – it is assumed that both receptors experienced the same level of odour exposure. After grouping all observations from all receptors and their corresponding odour predictions into bins, a dose-response histogram for the probability of detection was plotted as shown in Figure 5-4. The bin 1-10 OU corresponds to the 50^{th} percentile for probability of detection, which suggests the odour threshold lies somewhere in the range 1 to 10 OU. By resolving a 1-11 OU concentration range in Figure 5-5, it becomes evident that the odour threshold lies somewhere between 3 and 5 OU, as the 3-5 OU bin in this instance corresponds to the 50^{th} percentile. The odour threshold was assumed to be 4 OU, which is the halfway point of the 3-5 OU bin. In other words, for a specified emission rate of 1000 $OU/m^2/s$, the odour threshold corresponds to 4 OU.

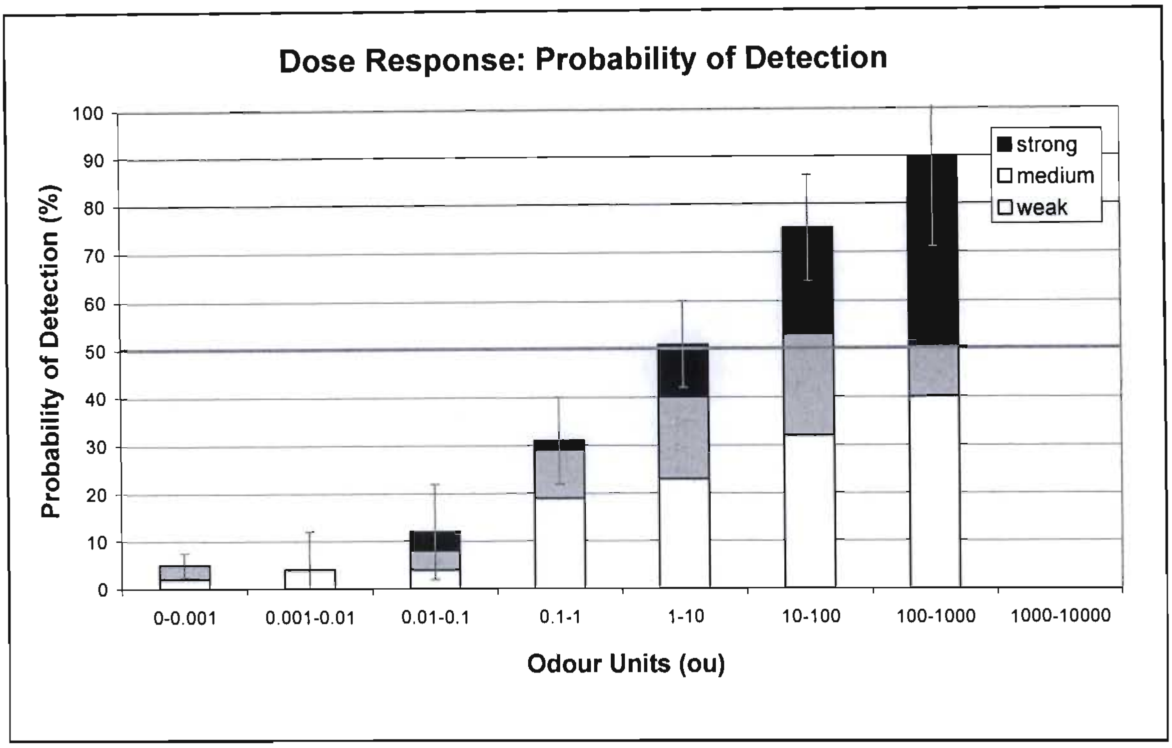


Figure 5-4: Histogram showing combined dose response.

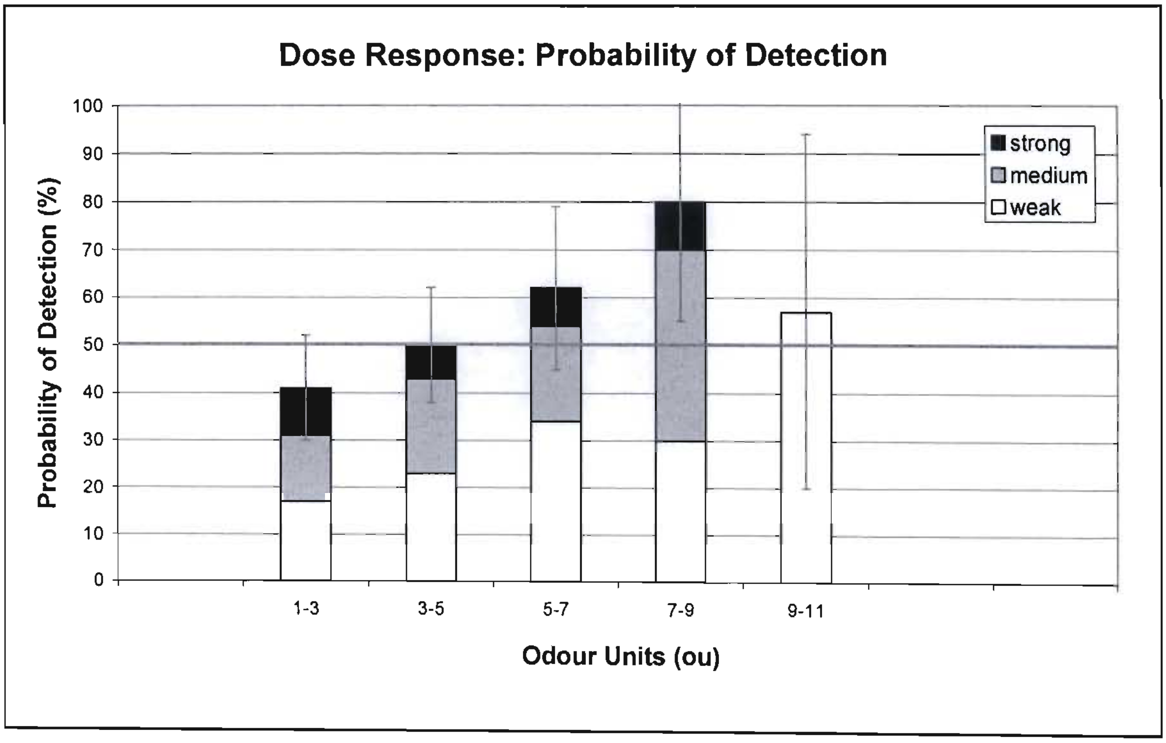


Figure 5-5: Histogram showing combined dose response for concentration range 1-11 OU.

By definition, the odour threshold is the concentration at which half the odour panel will perceive the odour and is represented by 1 OU. It was possible, by respecifying the value of the emission rate in the model, to shift the threshold so that the 50th percentile corresponded with 1OU instead of 4 OU. Since the model predictions scale linearly with emission rate, by reducing the specified emission rate by a factor of 4, from 1000 OU/m^2/s to 250 OU/m^2/s, the odour threshold was then represented by a 1OU prediction generated by the model.

This is an important result as it provides a real physical estimate of the odour emission rate from an open waste pile. It suggests that approximately 250 OU/m^2/s are emitted from the type of waste that is dumped at the Bisasar Road Landfill on a daily basis. To differentiate the odour threshold established from data gathered in the field from a possible threshold established in a laboratory, the Bisasar threshold will be identified as being measured in 'community odour units' (COU) instead of conventional odour units (OU). In other words, the emission rate from an open waste pile at Bisasar Road Landfill site is, more correctly, 250 COU/m^2/s.

The emission rate from an open waste pile at a Hong Kong landfill using direct measurement techniques was approximately 32 OU/m^2/s (Xiangzhong, 2003). This is almost a factor of ten less than the emission rate estimated for the Bisasar landfill. Centola (2003) found that the estimated emission rate from a waste water treatment pond using backward dispersion techniques was almost hundred times greater than the emission rate for similar odour sources reported in the literature. It was suggested that other odour sources, not accounted for, could have contributed to the exaggerated emission rate. Odour sources, other than the working face, likely contributed to the perceived odour offsite at Bisasar. Receptors were asked to characterize the odour in order to identify the likely source of the odour. However; biogas also emits from the working face area, so the odour perceived by the receptors was not necessarily that from exposed waste alone, but rather a mixture of FWO and LFG. In the case of the Benoni cell, where filling occurred as long parallel terraces, positive observations of odour may have been the result of "young waste" decaying under recently covered sections of the cell as opposed to resulting from the uncovered waste at the working face alone. This would result in positive observations for low estimates of odour concentration, which in turn would lead to an exaggeration of the emission rate from the open waste pile.

In the case of the MSW landfill in Hong Kong, direct measurement was made of the emission rate using a wind tunnel and dynamic olfactometry. When using wind tunnels and lab analysis, odour samples are usually taken over a 3-10 minute sampling time at the odour source. These sampling times have a tendency to smooth out shorter-term variability (fluctuations) in the odour concentration. This may partially explain why emission rates determined by standard olfactometry techniques are usually much less than by in-field observers (Best, 2004). This could account for why the emission rate of 250 COU/m^2/s at Bisasar using indirect measurement techniques is somewhat higher than is reported in the literature.

It is also important to note that the source concentration cannot be established from the inferred emission rate as the values for the actual efflux velocity from the source and the actual source concentration are unknown. The only thing known about the source is the area. Consequently, we cannot decouple the source concentration and the efflux velocity. However we do know the emission rate in COU/s and in OU/m^2/s, i.e. 250 000 COU/s and 250 OU/m^2/s respectively.

Dose Response Function

As noted in section 2.4.1, Nicell (2003) developed mathematical expressions based on sigmoid probability curves plotted on semi-log charts to relate the probability of response to odour concentration. The following expression relating probability of response to concentration was proposed:

$$P = \frac{100}{1 + \left(C_{50}/C \right)^{(1-p)/p}} \qquad (5\text{-}1)$$

This sigmoidal probability expression was fitted to the combined probability of detection dose response for the community. Using the new emission rate of 250 COU/m^2/s and scaling the odour predictions accordingly, a dose response histogram was plotted by dividing the combined community odour observations into 10 bins along a logarithmic horizontal axis as is shown in Figure 5-6. The probability of detection in each bin was then plotted against the mean odour concentration for each bin and the sigmoid probability function fitted to the data as is shown in Figure 5-7. $C_{50\%}$ was set equal to 1 COU and the parameter p was solved for by finding the least squares best fit of the curve through the data points. It was found that the combined dose response of the community could be expressed by the following dose response function:

$$P = \frac{100}{1+\left(\frac{1}{C}\right)^{(1-0.7)/0.7}} \qquad (5\text{-}2)$$

The parameter p = 0.7, implies that the odour being emitted from an open waste pile is quite persistent and that for concentrations below the odour threshold, it will remain distinct for some members in the community. This implies that the effects of the odour are likely far reaching and that residents some distance away may be affected. Nicell (2003) reported values for p ranging from 0.39 to 0.52 for pure substances analyzed in a controlled dynamic olfactometry environment.

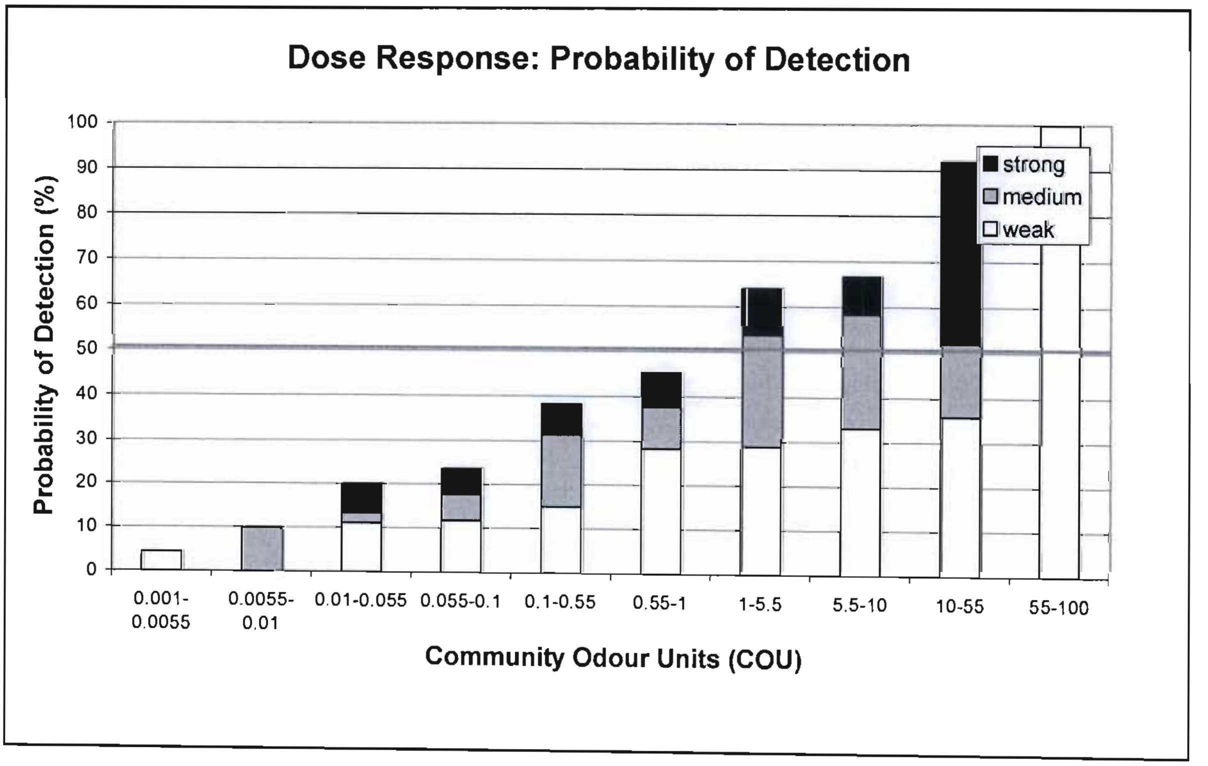


Figure 5-6: Histogram showing combined dose response for all the receptors.

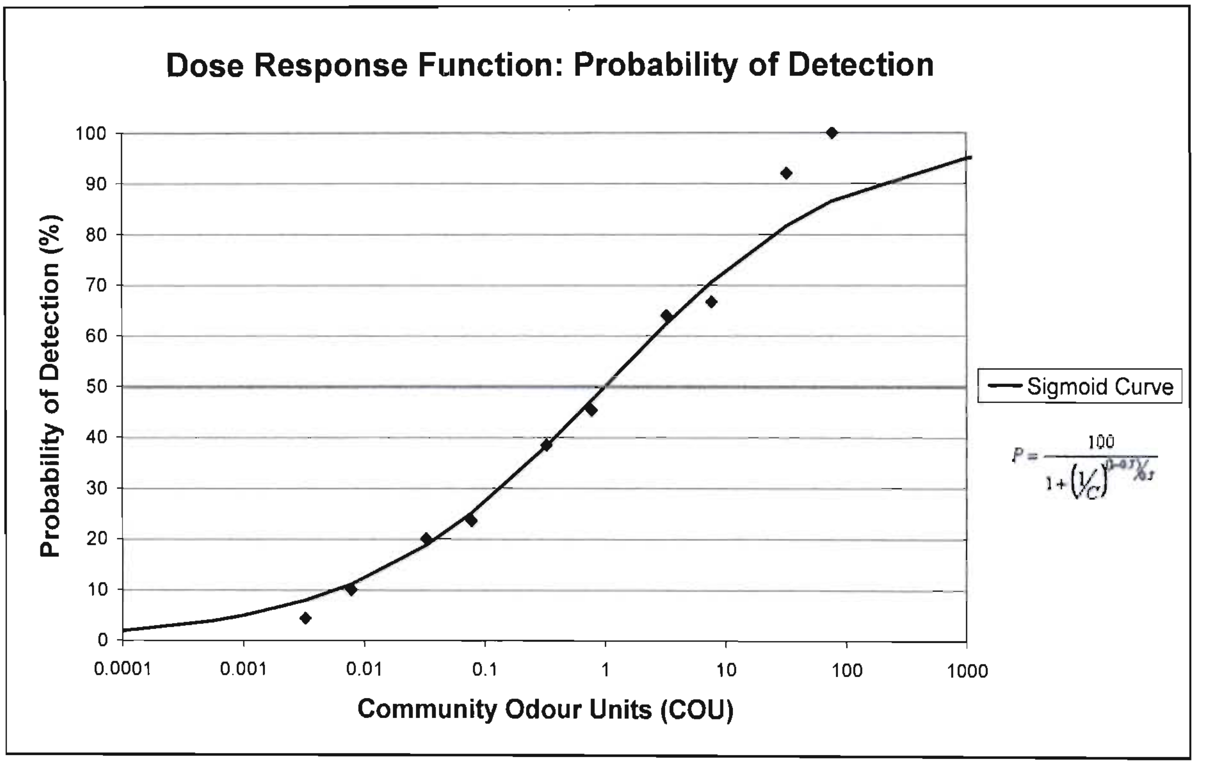


Figure 5-7: Sigmoid dose response functions fitted to combined dose response

Individual Receptor Dose Responses

The probability of an odour being detected across a range of odour concentrations was investigated for each receptor by arranging the receptor's positive and negative observations into bins and calculating the probability of detection for each bin. Probability of detection histograms were plotted for each receptor and can be found in Appendix C-3. Dose response trends were plotted using the new emission rate established previously of 250 $COU/m^2/s$.

An action research approach was employed in order to validate the receptor group. Odour observations were made by the author at a static location at the Bisasar site office. These observations were then correlated with the predictions made by the model and a dose-response histogram was generated as shown in Figure 5-8. The histogram demonstrated an increase in the likelihood of detection as the odour concentration increased from left to right along the horizontal axis. The odour threshold appeared to correspond with the concentration range 0.1-1COU on the histogram, suggesting that the odour threshold lay in this range. The probability of detection versus concentration histogram for the site office was assumed to represent a logical dose-response trend. Two criteria were defined for the identification of logical dose-response trends, as established by the analysis of the author's odour observations. The criteria were: (1) the probability of detection should increase moving from left to right along the horizontal axis; (2) the 50th percentile should be met or exceeded at some point whilst moving from left to right along the horizontal axis (provided sufficient observations in the higher concentrations ranges for a receptor had been collected).

The dose-response plots for the receptors along Kennedy road demonstrated strong correlations between the probability of an odour being detected and the concentration of the odour. By inspection, the 50th percentile for detection appeared to correspond with the range 1-10 COU for 79 Kennedy, 93 Kennedy, 127 Kennedy, 131 Kennedy and 159 Kennedy. The observations made by 60 Burnwood and 125 Burnwood also generated a logical trend of increasing likelihood of detection with increasing concentration. Here too, the odour threshold appeared to fall in the range 1-10 COU, based on 125 Burnwood's observations. Receptors 27a Vialls and 5 Vialls revealed a trend of increasing likelihood of detection from left to right along the horizontal axis. The odour threshold appeared to correspond to the range 1-10 COU for receptor 27a Vialls. The threshold corresponded to the range 0.1-1 COU at 5 Vialls. At 144 Wattle, the receptor situated furthest from the landfill, reported odour observations met the predefined criteria and the threshold appeared to coincide with the 0.1-1 COU bin. At 78 Wandsbeck a threshold in the range 0.1-1 COU was observed.

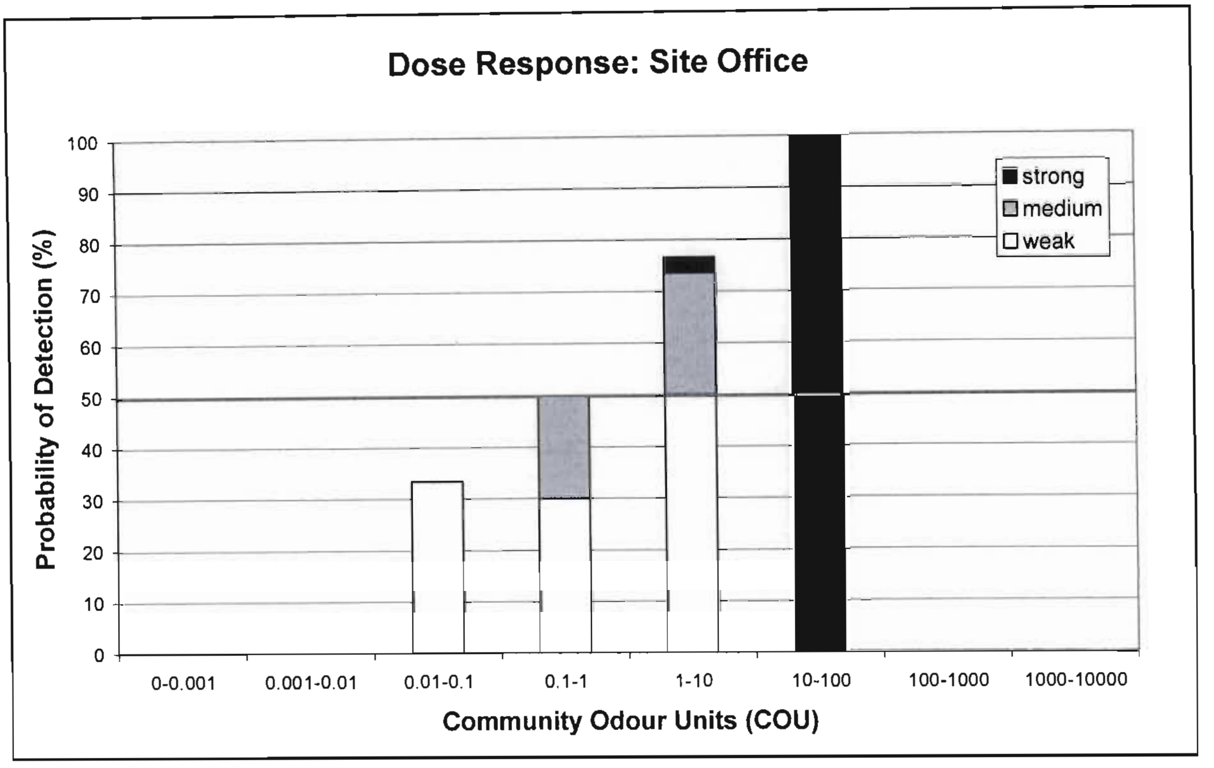


Figure 5-8: Histogram showing dose response for receptor at Bisasar site office.

The other receptors did not meet the criteria. This may be due to there being insufficient observations for a particular receptor to establish a complete picture of their dose response. For instance, it was difficult to get observations of odour at higher concentrations for some receptors due to their distance from the landfill or position outside of the effect of the dominant wind directions. This might explain why the threshold was never met or exceeded at some receptor locations. Another problem lies in the fact that receptors were generally only making direct observations over a maximum of 30 seconds, but the model was generating odour predictions based on a ten minute average. The receptor may have observed the odour when there was a fluctuation in the odour plume resulting in an observation that did not necessarily coincide with the odour prediction generated by the model. To smooth out the effect of plume fluctuations, the intention was to get as many observations as possible, but this was not always possible for the full range of odour concentrations for each receptor. Of course, some receptors may have a poor sense of smell or the location where they work or live might mean the odour from the landfill is masked by another odour source.

Table 5-3 shows a summary of the number of positive and negative observations used in the analysis of each receptor and where possible, the concentration range that coincided with 50th percentile threshold.

Table 5-3 : Summary of individual receptor responses used in analysis. Highlighted receptors are those that met the two criteria as defined previously.

Receptor	Ref. #	Total Observations Used	Positive Observations Used	Negative Observations Used	Odour Threshold range (COU)
Burnwood 60	*1*	30	7	23	
Burnwood 34	2	40	8	32	
Burnwood 125	*3*	51	18	33	0.1-1
Dodoma 11	*4*	35	7	28	
Foreman 192	*5*	27	1	26	
Kennedy 79	*6*	18	6	12	0.1-1
Kennedy 105	*7*	31	11	20	
Kennedy 131	*8*	35	19	16	
Kennedy 93	*9*	38	14	24	0.1-1
Kennedy 127	*10*	32	12	20	0.1-1
Kennedy 159	*11*	23	4	19	0.1-1
Rosemary 15	*12*	29	5	24	
Site Office	*13*	62	29	33	0.1-1
Vialls 5	*14*	29	9	20	0.1-1
Vialls 27	*15*	28	5	23	1-10
Vialls 33	*16*	35	8	27	
Vialls 7	*17*	29	2	27	
Wandsbeck 78	*18*	19	5	14	0.1-1
Wattle 144	*19*	36	6	30	0.1-1
Total		*627*	*176*	*451*	

5.4.3 Dose Response: Perceived Intensity

Dose responses in terms of perceived intensity were generated for some of the receptors and for the combined response of the receptor panel. During the survey, receptors reported on the intensity of the odour perceived by defining it on a scale of 1 to 3 where 1 was weak, 2 was medium and 3 was strong. These observations of odour intensity were correlated with odour predictions made by the ADMS model using an odour emission rate of 250 $COU/m^2/s$. Intensity-concentration plots were generated for each receptor. Mathematical psychological dose-response functions were fitted to the data to give an indication of the persistence of the landfill odour. McGinley (1998) suggests the rate of change in intensity verses odour concentration is an indication of the persistence of the odour.

Hobbs et al. (2002), used community modelling to investigate the relationship between odour concentration and perceived odour intensity in a community living around a landfill in the UK. They investigated four psychological models (dose-response functions) for the analysis of odour perception and concluded that the Weber-Fechner and Stephen's power law models fitted the data consistently. These two psychological laws are considered to have widespread acceptance for defining the relationship between odour intensity and concentration for a particular odourant as well as complex mixtures (e.g. DEP, 2002).

The Weber Fechner model has the form of:

$$I = k_1 \log C + k_2 \qquad (5\text{-}3)$$

Stephen's Power Law has the form of:

$$I = k_1 (C)^{k_2} \qquad (5\text{-}4)$$

where I stands for a perceived intensity and C stands for the corresponding odour concentration, and k_1 and k_2 are constants. The parameters for the Weber Fechner model and Stephen's Law (k_1 and k_2) were estimated for each receptor by fitting the models to the data. Receptors in the community survey conducted by Hobbs et al. (2003) reported odour intensities on a scale of 1 to 7. The intensity scaling of the Bisasar Road survey was adjusted to a 1 through 6 Intensity scale (comparable to the intensity scale in Table 2-2) to allow for better comparison with the Intensity Dose Response functions from Hobbs (2003). In instances at Bisasar where the receptor made many observations for a given intensity level, the corresponding odour predictions from the model were averaged for that intensity level. Hobbs et al. (2003) did not fit Stephen's law or the Weber Fechner law to their receptor observations and corresponding odour predictions. These models have been fitted to the data from the UK survey here and the model parameters are tabulated in Table 5-4.

The site office observations were used once again as a benchmark to assess the validity of the other receptor responses. Observations of intensity at the site office were logically consistent with regards to the intensity scaling. In other words, for an increasing concentration, there was an increase in the perceived odour intensity. Only those receptors that met this expectation had the psychological dose-response functions for perceived intensity fitted and are listed in Table 5-5. Only 9 out of the 19 receptors demonstrated an increasing trend in perceived odour intensity and odour concentration.

Table 5-4: Weber-Fechner and Stephen's Law model parameters calculated from the data reported in Hobbs et al. (2003).

Receptor	Intensity Scale	Dispersion Estimates OU/m^3	Weber-Fechner Model		Stephen's Power Law	
			k_1	k_2	k_1	k_2
1	2 3 4 5	1.12 1.72 2.05 2.75	7.84	1.46	1.76	0.46
2	3 4 5 6	1.14 2.39 4.04 4.85	4.46	2.60	2.76	0.46
3	2 3 5 6	1.35 1.41 2.87 3.65	8.23	1.32	1.80	0.95
4	3 4 5 6 7	2.17 2.21 2.61 3.61 5.12	9.48	0.51	1.94	0.83
5	2 3 4 5	1.80 1.99 2.21 3.61	8.63	0.27	1.30	1.11
Average			*7.72*	*1.23*	*1.91*	*0.76*
Standard deviation			*1.92*	*0.92*	*0.53*	*0.28*

Table 5-5: Dispersion estimates corresponding to intensity scales observed by some receptors around Bisasar. Model parameters estimated by fitting Weber-Fechner and Stephens Power Law models to the data.

Receptor	Intensity Scale (1-3) x 2	Dispersion estimates (COU)	Weber-Fechner Model		Stephen's Power Law	
			k_1	k_2	k_1	k_2
Burnwood 34	2 6	0.35 1.34	6.89	5.12	4.68	0.82
Burnwood 60	2 4 6	0.11 1.44 3.02	2.54	4.26	3.89	0.32
Dodoma 11	2 6	0.06 0.35	13.73	1.09	11.74	0.65
Kennedy 79	2 4 6	1.96 9.80 10.78	4.28	0.70	1.38	0.55
Kennedy 131	2 4 6	5.58 6.97 17.10	7.34	-2.91	0.60	0.82
Rosemary 15	2 4	0.03 1.19	1.32	3.90	3.89	0.20
Site Office	2 4 6	2.07 2.58 6.29	7.40	0.22	1.36	0.84
Vialls 27a	2 4 6	0.55 0.98 1.04	11.81	4.96	4.79	1.51
Wattle 144	2 4	0.03 0.13	3.49	7.00	11.22	0.52
Average			*6.53*	*2.70*	*4.83*	*0.69*
Standard deviation			*4.16*	*3.11*	*4.06*	*0.37*

Comparing the k_1 and k_2 parameters in Table 5-4 and Table 5-5 reveals that there is wider variability in the values for these parameters amongst the Bisasar receptors. This is apparent when comparing the averages and the standard deviations for these parameters in Table 5-4 and Table 5-5. This is an indication of the wider variability of odour perception amongst the Bisasar receptors. In the case of the survey conducted in the UK, there are no intensity observations made below 1 OU. However, In the case of Bisasar, a number of receptors assigned intensity ratings to average concentrations well below the odour threshold (1 COU). The capacity for some receptors at Bisasar to perceive odour well below 1 COU, as shown in Table 5-5, is also an indicator of the persistence of the odour being emitted from the open waste piles. In other words, some members of the community will still detect the odour below its threshold. The average k_1 parameter in the case of the

Weber Fechner model for Bisasar and the UK are similar, but the average k_2 parameters for this model differ somewhat. Hence, the rate of change in intensity with odour concentration is similar at Bisasar and the UK, according to Weber Fechner. This suggests the odours being analysed in each case have a similar persistence. The average values for k_2 in Stephen's law are similar for Bisasar and the UK suggesting a similar rate of change in intensity with odour concentration.

The intensity observations for the receptors listed in Table 5-5 were used to fit a combined Intensity-concentration plot. In this instance, the average of the model parameters in Table 5-5 was not used, but rather the odour concentration predictions corresponding to each intensity rating for all receptors were averaged and then plotted with the intensity ratings. Two intensity-concentration plots were fitted, one was based on a weighted concentration average for each intensity rating and the other was based on an unweighted concentration average for each intensity rating. The reason for plotting a weighted average plot was that some receptors had many concentration predictions associated with a particular odour intensity level and hence a smaller degree of error. The least squares estimate of the model parameters for both the Weber Fechner and the Steven's Power law model were solved for and are reported in Table 5-6. The difference in the parameters is not significant and the Weber-Fechner and Steven's Law models are plotted for the weighted intensity-concentration data in Figure 5-9.

Table 5-6: Model parameters for combined perceived intensity dose response.

	Intensity Scale (1-3) x 2	Dispersion estimates (COU)	Weber-Fechner Model		Stephen's Power Law	
			k_1	k_2	k_1	k_2
Weighted Average	2 4 6	1.80 3.10 10.3	5.08	1.01	1.62	0.58
Unweighted Average	2 4 6	1.20 3.30 5.70	5.73	1.41	1.75	0.70

The curves in Figure 5-9 intercept the vertical axis between I = 1 and I =2 which corresponds to 1 COU – k_2 for Weber Fechner and k_1 for Stephen are the vertical axis intercepts when C = 1 COU. We expect the intensity to be in this "very weak" to "weak" range as 1 COU corresponds to the concentration at which the fresh waste odour becomes just detectable to the receptor group. Stephen's law curve intercepts the horizontals axis at 0 COU and the Weber Fechner law intercepts the horizontal axis at around 0.6 COU.

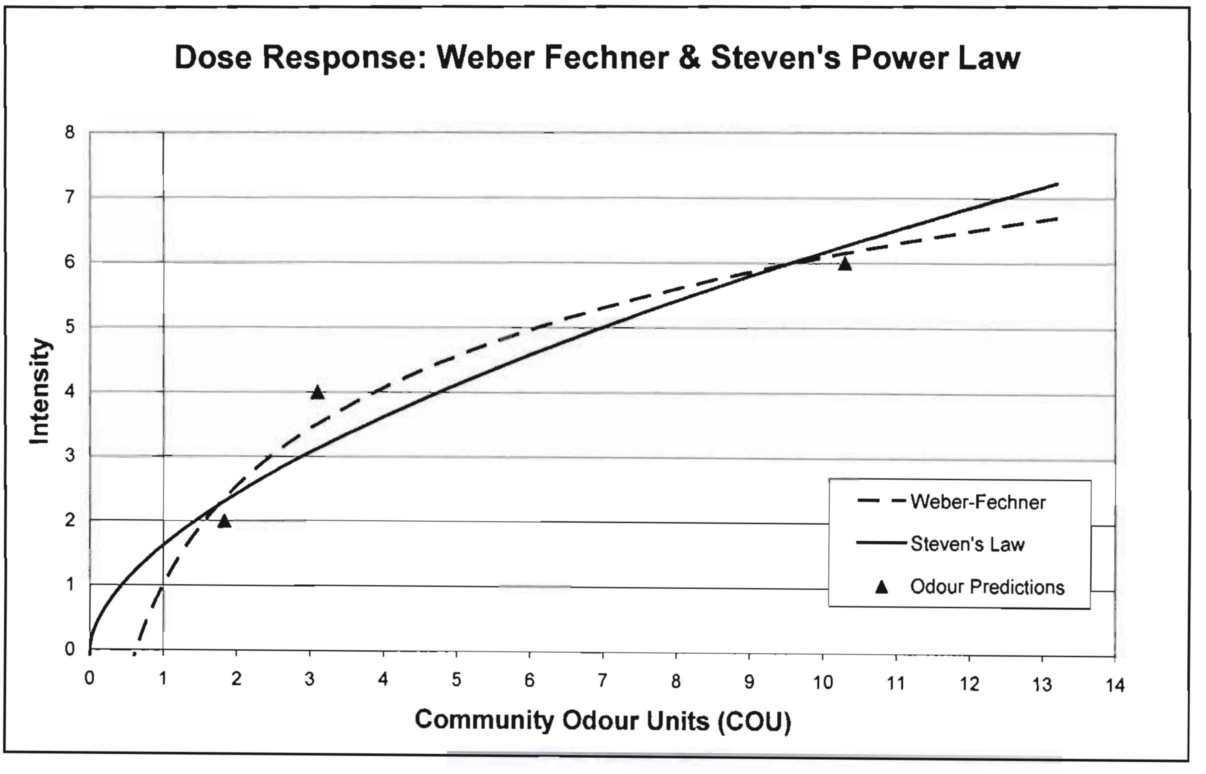


Figure 5-9: Dose response functions for perceived intensity for combined community observations.

5.5 Discussion

5.5.1 Practical Application of dose response functions

The dose response functions, which are mathematical expressions relating the probability of detection and perceived intensity to odour concentration, can be used practically out in the field for assessing the impact of the odour plume on the community. This is based on the assumption that the functions are derived from a representative sample of the population living around the landfill.

An individual, who is calibrated against the community odour panel, could go out into the field and make an observation of the odour anywhere in the surrounding community. By rating the intensity of the odour on a scale of 1 through 6, the individual could establish the corresponding odour concentration by reading it off the horizontal axis of the dose response function derived from their perception of odour intensity. Using this concentration in conjunction with the combined dose response function for probability of detection, as shown in Figure 5-7, it would be possible to establish the impact of the odour on the community in the immediate vicinity. In other words, one could estimate the percentage of people, in the vicinity of the observation, that would likely detect the odour at that moment in time. In a similar sense, the curve for perceived intensity, as shown in Figure 5-9, could be used to estimate the odour impact in terms of the perceived intensity. An individual who is calibrated against the receptor group could also go to each receptor location and make an observation of the odour and have a sense of how each receptor might perceive the odour.

5.5.2 Comparison of community modelling techniques

One of the aims of this research was to establish the most effective means for capturing data from the community for the purposes of establishing the odour impact and characterizing landfill odour sources. The direct method of phoning receptors and establishing the instantaneous odour impact proved to be the better of the two techniques as was demonstrated by comparing the dose response histograms generated from the data from the 2002 and 2004 community surveys. "Noise" in the 2002 survey data contributed to the high number of positive observations in the lower concentration ranges. This was likely due to positive observations for odour being made for sources other than the open waste piles. The 2002 survey was not designed to separate the contribution from the various landfill sources and did not require the receptors to discriminate the odours they perceived. A better correlation between odour observation and odour prediction was achieved with the 2004 survey data which allowed for a more precise estimate of the odour emission rate.

5.5.3 Odour mitigation

Direct telephonic surveys in conjunction with dispersion modelling can be used to help design mitigation strategies and test their effectiveness. For an example, one could test the effectiveness of an odour mitigation chemical which is applied directly to the open waste pile at the working face. Firstly, one would seek to establish the response of the community to a range of odour concentrations before any chemical treatment is applied to the open waste pile. Secondly, one would perform a similar survey of the population responses when the odour abatement chemical is applied to the open waste pile over an extended period. Dose response curves –in terms of perceived intensity and probability of detection – would then be plotted for both sets of responses. If there is a distinct difference in the plots, then this would suggest that the chemical treatment is effective in reducing the odour emission rate from the source. If the odour mitigation treatment is effective, this will be reflected in a higher population odour threshold and a lower inferred emission rate for times when the chemical was applied.

5.6 Summary

A telephonic survey was carried out in 2004 to collect direct odour observations from residents living around the Bisasar Road landfill site. From an analysis of the dose-response histogram for the combined observations of all the survey participants, the emission rate from an open waste pile was estimated as being 250 $COU/m^2/s$. Mathematical dose response functions were fitted to the observations and odour predictions to relate probability of detection and perceived intensity to odour concentration. The fresh waste odour emitted from open waste piles has a high persistence, as a result, some members of the community will be affected by it for subthreshold concentrations. Dose response functions have a practical application, as they allow a calibrated individual to venture into a community and assess the likely population response to an odour. Community feedback and dispersion modelling can also be used to establish the effectiveness of various odour mitigation strategies.

CHAPTER 6

6. BUFFER ZONE METHODOLOGY

6.1 Introduction

Ideally, a landfill should be located where there is no or very little human activity. However, in reality this would mean moving land filling sites to the outskirts of cities which becomes impractical due to transport costs. Consequently, landfills are often situated near people and the need therefore arises to specify buffer zones around disposal sites as part of an odour abatement strategy.

Currently, in South Africa, there is no methodology for the specification of a buffer zone around a landfill. The Minimum Requirements for Waste Disposal by Landfill (DWAF, 1998) simply recommends a buffer zone of between 500 m and 1000 m be defined around a landfill site to protect its neighbours from landfill activities. A more scientific approach to specifying a buffer zone could reveal that a buffer zone of a fixed distance from the landfill boundary of 1000 m is not necessary in order to prevent a serious odour nuisance in the surrounding population. A scientific approach for defining a buffer zone around a landfill would consider the following factors: the type of disposal facility; the type of development in close proximity to the site; the predominant weather patterns; the effect of complex terrain; the OER from the site; and the dose response of the community in terms of probability of detection and perceived intensity. The Bisasar landfill was used as a case study to demonstrate the implementation of a scientific methodology for the specification of a buffer zone based on odour being the major source of nuisance from the site. The emission rate of 250 $COU/m^2/s$ established previously was used to generate proposed buffer distances for the case study.

6.2 Buffer zone modelling

A scientific methodology for specifying a buffer zone would take advantage of a numerical dispersion model such as ADMS. The model would be used to plot contours of odour impact in the surrounding community using one or more year's historical weather data. Based on what is established as an acceptable level of human exposure to odour, one of these contours could be chosen to represent a suitable buffer distance.

Typically odour regulations are defined in terms of the percentage of time in a year (percentile criterion) that a certain number of odour units (threshold criterion) may be exceeded. Often regulations will state the averaging time over which the mean concentration should be calculated. By changing the threshold criterion the percentile criterion, and the averaging time, great variations in the contours of impact are observed. Consequently, it is extremely difficult to specify a buffer zone boundary unless these parameters are chosen carefully and appropriately.

6.2.1 Varying averaging time

The importance of taking short-term fluctuations into account when modelling odour has been discussed previously. The fluctuations module in ADMS allows the effect of fluctuations over short time scales to be included in long term average calculations. If an odour criterion states that the 3 minute average concentration shall not exceed 10 OU for more than 175 hours in a year, then this can be modelled by setting the fluctuations module averaging time (T_f) equal to 180 seconds (3 minutes).

Specifying different averaging times (T_f) in the fluctuations module of ADMS has a large impact on the prediction of the number of exceedances as shown in Figure 6-1. The grey, inner contour represents 175 one hour periods in the year that 10 COU is exceeded by the mean concentration (T_f = 1 hour). The black, outer contour represents 1500 three minute periods in the year (175 hours) that 10 COU is exceeded by the mean concentration (T_f = 3 minutes).

It is more likely that 10 COU mean will be exceeded over a 3 minute average concentration than over a 1 hour average concentration. In other words, peak concentrations are more evident over short time scales (3 minutes) than over long time scales (1 hour).

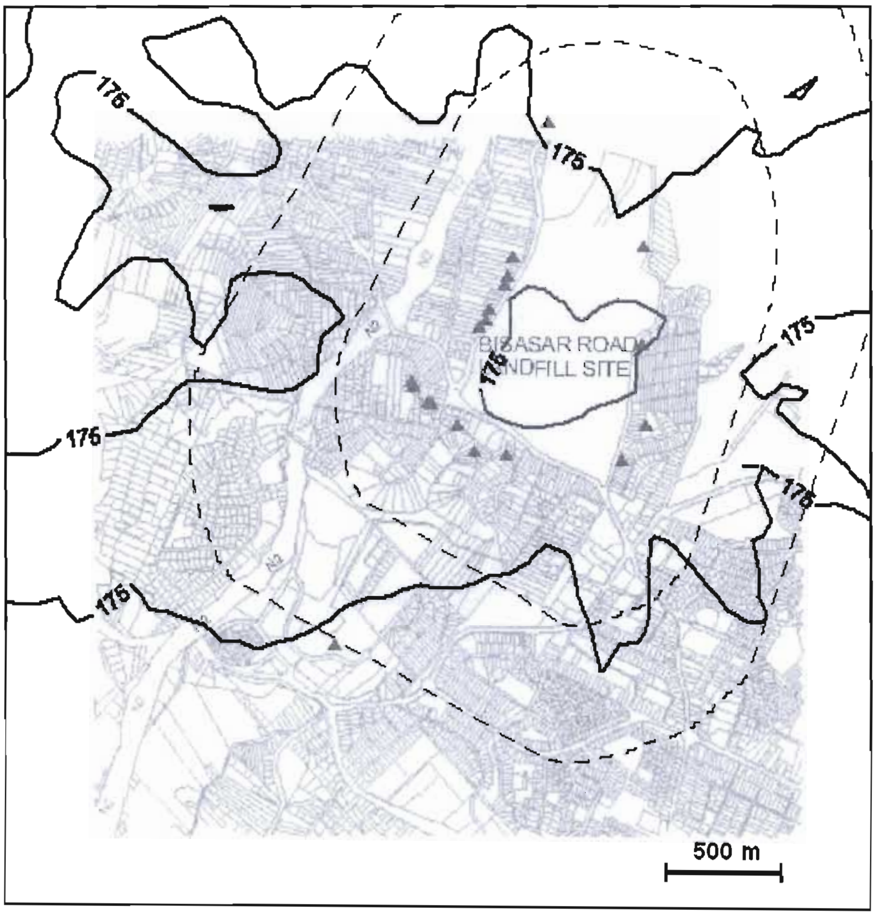


Figure 6-1: Contours of exceedance of 10 COU, averaged over 1 hour (grey inner contour) and averaged over 3 minutes (black outer contour) at the 98% percentile. Dotted lines are DWAF proposed buffer zones at 500m and 1000m. Emission rate: 250 COU/m²/s.

6.2.2 Varying the percentile criterion

Figure 6-2 shows the number of hours that the 5 COU threshold is exceeded by the hourly mean concentration (*Tf* = 1 hour) for a range of percentile criteria. The hours in a year shown on the figure correspond to the percentiles shown in Table 6-1.

Table 6-1: Percentiles and corresponding hours.

Percentile	Hours
99.9%	9
99.5%	44
99%	88
98%	175
97%	263
96%	350
95%	438

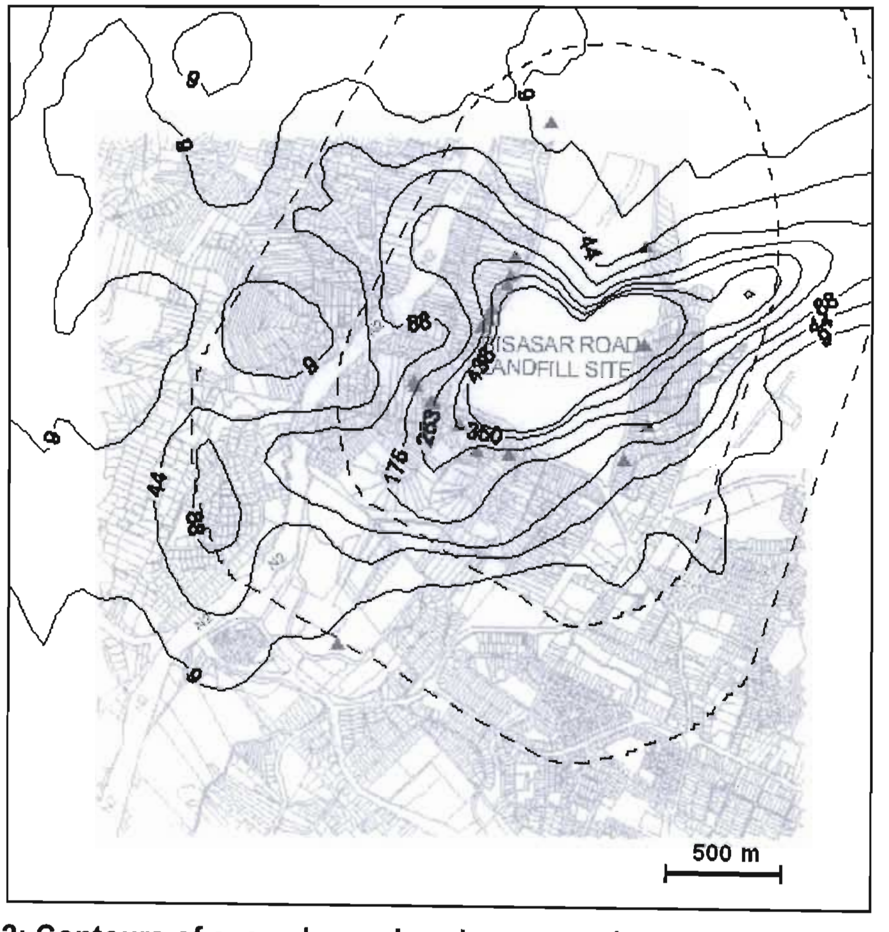


Figure 6-2: Contours of exceedance, hourly averaged mean concentration, of 5 COU at the 99.9%, 99.5%, 99%, 98%, 97%, 96%, 95% Percentiles. Dotted lines are DWAF proposed buffer zones at 500m and 1000m. Emission rate: 250 COU/m²/s.

6.2.3 Varying the threshold criterion

Figure 6-3 shows contours of the 99.5% percentile (a total of 44 one hour exceedances a year) for thresholds 2 COU, 5 COU and 10 COU. One hour average concentrations were used by setting $Tf = 1$ hour.

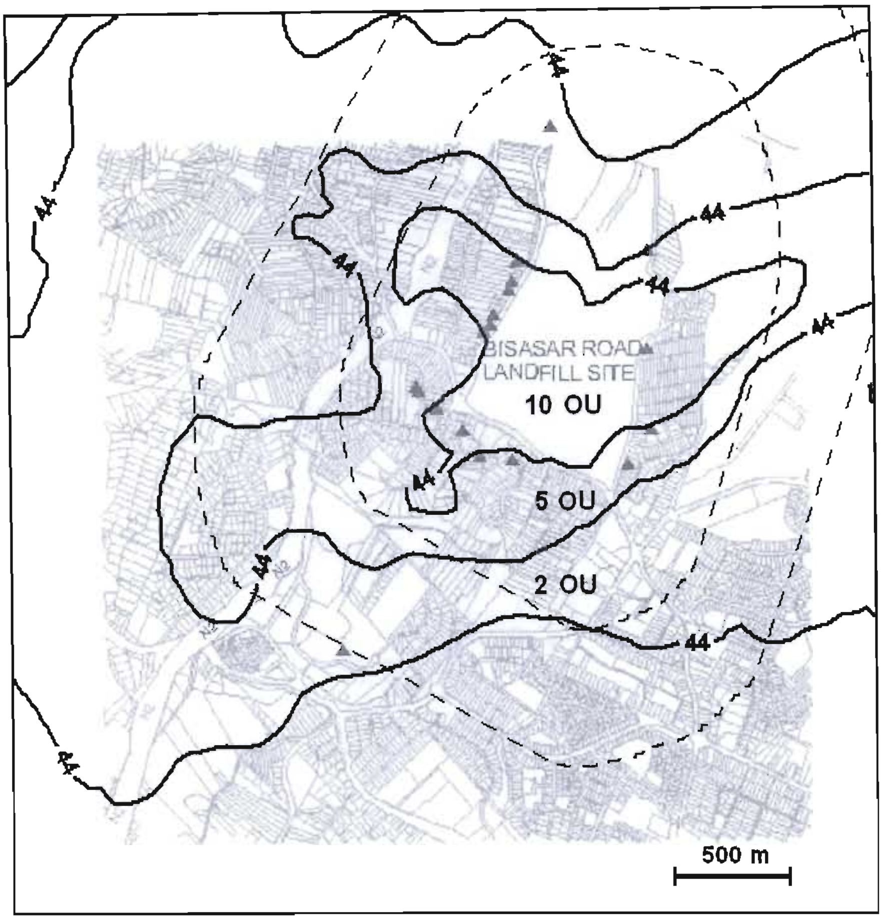


Figure 6-3: Contours of exceedance, hourly averaged mean concentration, of 2 COU, 5 COU and 10 COU at the 99.5 percentile . Dotted lines are DWAF proposed buffer zones at 500m and 1000m. Emission rate: 250 COU/m²/s.

6.3 Buffer zones based on local and international regulations

From the South African perspective, no laws exist defining minimum buffer zone distances for landfills and there is certainly no suggested scientific methodology for specifying a buffer zone around a landfill site. The only legal documentation, which discusses buffer zones for landfills, is the DWAF's Minimum Requirements for Waste Disposal by Landfill

(DWAF, 1998). Buffer zone distances are set to 200m for communal landfills and 400m for small landfills (DWAF, 1998). For medium and large landfills, buffer zones are considered a "flagged" option and the distance is decided by the DWAF on a case-by-case basis (DWAF, 1998), and can range from 500m to 1000m. Approximate buffer zone boundaries of 500m and 1000m are shown by concentric dashed lines around the Bisasar landfill footprint in Figure 6-4.

International odour regulations take the form of the percentage of time (percentile) that a certain number of odour units may be exceeded (Laister, 2003b). The number of odour units selected for the threshold criterion as well as the percentile criterion tends to vary. In Queensland, Australia the criterion suggested are 2 OU, hourly averaged, at the 99.5th percentile for ground-level sources (EPA, 2004). In other words, in a year, there should be no more than 44 one hour periods where the mean concentration exceeds 2 OU. Yang and Hobson (1999) state that odour as low as 5 OU may lead to a nuisance if they result from an unpleasant odour and in the case of a landfill, the hedonic tone is especially unpleasant. The Air Quality Technical Report prepared by the Environmental Ministry in New Zealand (Freeman, 2002) suggests that the threshold criterion be set to 5 OU when the sensitivity of the receiving environment is high, which in the case of Bisasar, it is.

Using ADMS, the above guidelines were used to plot odour impact contours for Bisasar using the Randles cell as the odour source, emitting at 250 COU/m^2/s. Long term calculations were carried out for a year's met data with the ADMS Fluctuations model averaging time set equal to one hour (T_f = 1 hour). Figure 6-4 shows two contours: the outermost representing the 2 COU threshold at the 99.5th percentile and the innermost representing the 5 COU at the 99.5th percentile. Both contours include the effects of fluctuations. The 99.5th percentile equates to 44 hours in a year. The DWAF buffer zones of 500m and 1000m are shown here for comparison.

The Randles cell is situated at the South Eastern corner of the landfill and according to the contour for the 5 COU threshold in Figure 6-4, this threshold is not exceeded for more than 44 hours of the year over most of the area South West of the landfill. This shows that a general buffer of 500m to 1000m all around the footprint of a landfill site is unnecessary to avoid an odour nuisance in the sensitive areas to the South East of the site. According to the odour impact contour, the regions most affected by the odour are to the North East, North West and South West of the landfill.

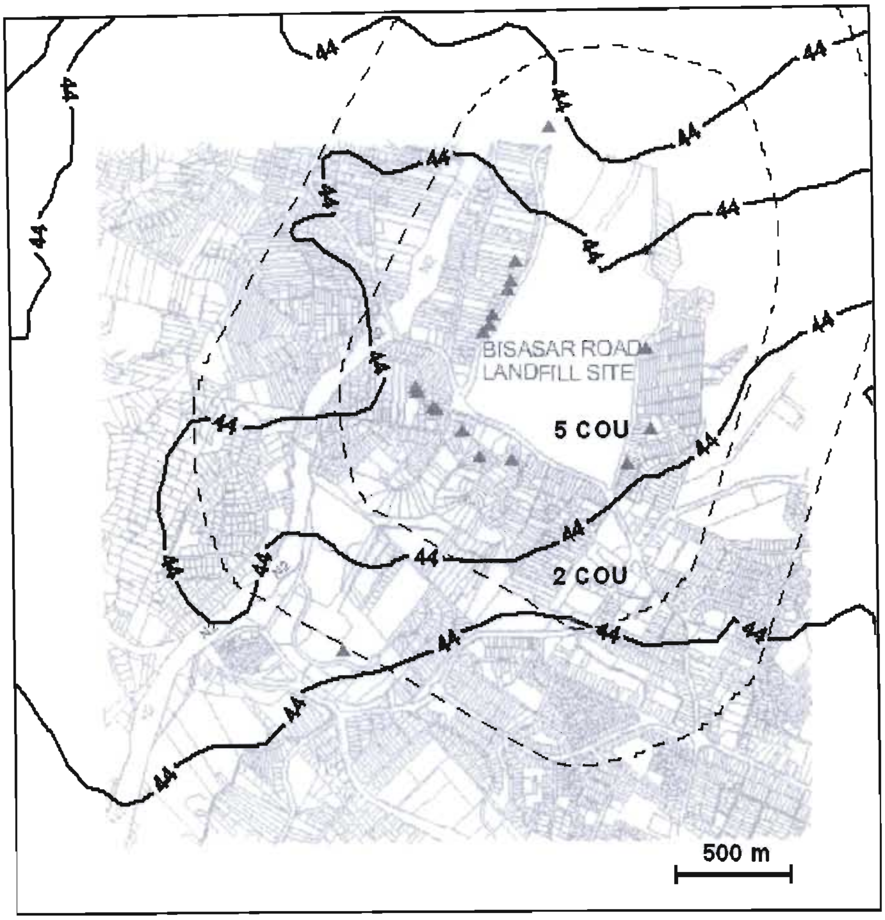


Figure 6-4: Contours for exceedance of 2 COU and 5 COU at the 99.5 percentile. Dotted lines are DWAF proposed buffer zones at 500m and 1000m. Emission rate: 250 COU/m²/s. T_f = 1 hour

6.4 Buffer zones based on community dose response

The international guidelines discussed previously are largely based on laboratory findings and tend to be applied generally to varying cases of potential odour nuisance. The 2004 community survey provided information about the combined dose-response as well as the individual dose-responses for each receptor which aided in establishing odour impact criterion that were more relevant to the circumstances at Bisasar.

The combined dose-response function for intensity using the Weber Fechner Model produced the following expression to relate perceived intensity to odour (see section 5.4.3):

$$I = 5\log C + 1 \qquad (6\text{-}1)$$

This function was derived for an intensity scale of 1 though 6 and the intensity gradings can be described as shown in Table 6-2.

Table 6-2: Intensity Scale.

Scale (*I*)	Intensity Description
0	Not detectable
1	Very weak
2	Weak
3	Distinct
4	Strong
5	Very strong
6	Extremely strong

The Odour Methodology Guideline for Western Australia (DEP, 2002) suggests choosing an intensity level as a criterion and then using an intensity-concentration plot to back-calculate the corresponding odour concentration. On the intensity scale in Table 6-2, a perceived intensity of 3 corresponds to a distinct odour. The concentration corresponding to 'distinct' is 2.5 COU using equation 6-1. Consequently, a threshold criterion of 2.5 COU was chosen.

The following dose-response function to relate probability of detection to concentration was established previously:

$$P = \frac{100}{1 + \left(\frac{1}{C}\right)^{(1-0.7)/0.7}} \qquad (6\text{-}2)$$

The probability of detection in the community at a concentration of 2.5 COU is established by substituting into equation 6-2 and solving for P. Sixty percent of the members in the community are likely to detect the odour when it equals the chosen exceedance criterion of 2.5 COU.

An odour concentration of 5 COU was used as the threshold criterion to generate an odour impact contour in Figure 6-4. This odour concentration corresponds to a perceived intensity rating of I = 4.5 when substituted into equation 6-1. This defines a strong to very strong odour, according to the intensity scaling in Table 6-1. Consequently, using 5 COU for the threshold criterion could produce an underestimate of the impact of the odour in the community as any odour with a concentration greater than or equal to 2.5 COU (distinct) is likely to cause serious annoyance.

Figure 6-5 shows the contours of exceedance of the 2.5 COU thresholds at the 99.5% and the 99% percentiles using averaging times (T_f) of 1 hour and 3 minutes. Using an averaging time of 3 minutes is perhaps too stringent a criterion as demonstrated by the wide contours for the 3 minute averaged concentrations in Figure 6-5. Simms et al. (2000) suggest that odour does not become a concern until it is detectable for significant periods of time, well in excess of three minutes.

The odour impact contours plotted in this case study have only been generated for one odour source. However; to establish a buffer zone around a large site like Bisasar, the contours of impact for a number of source positions around the perimeter of the landfill need to be generated and then overlaid to obtain an accurate buffer zone specification.

The distance that defines a buffer zone will also vary according to the roughness of the terrain. The terrain around the landfill is suburban (roughness = 0.5m). However; if the land around the landfill site was flat and grassy, then there would be less mechanical turbulence generated in the atmosphere and the odour would be dispersed less rapidly. A larger buffer zone would be necessary in this instance to ensure that the odour was sufficiently dispersed before it reached any receptors.

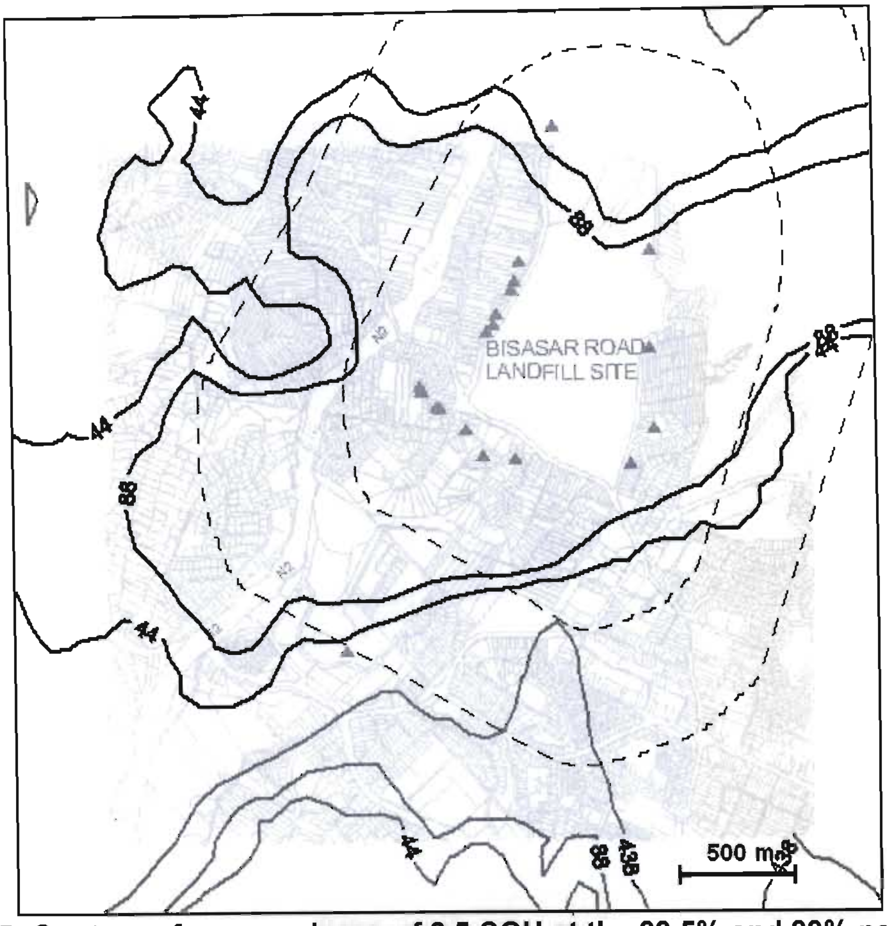


Figure 6-5: Contours for exceedance of 2.5 COU at the 99.5% and 99% percentiles for 1 hour (black inner contours) and 3minute (grey outer contours) averaging times. Dotted lines are DWAF proposed buffer zones at 500m and 1000m. Emission rate: 250 COU/m^2/s.

6.4 Summary

The dispersion model ADMS 3.1 was used to generate contours of odour impact around the Bisasar landfill site to help demonstrate a scientific methodology for the specification of protection distances around nuisance odour sources. The importance of selecting the appropriate threshold criterion, percentile criterion and averaging time was demonstrated by the sensitivity of the of odour impact contours to these three parameters. Proposed buffer contours were generated by using both national and international regulations as a guide. The dose response relationships established from the 2004 community survey provided a case specific threshold criterion to plot contours of odour impact at Bisasar.

CHAPTER 7

7. SUMMARY AND CONCLUSIONS

7.1 Summary of investigation

A review of the literature and case studies revealed the various techniques for OER measurement that have been developed and used globally. To complete the characterization of an odour, its perceived intensity, potential annoyance and impact in terms of probability of response need to be investigated. There is an international trend towards using community feedback to investigate odour and its impact. A review of the literature explored buffer zone regulations and attempts at applying more scientific methodologies to the specification of protection distances. An OMS was developed for Bisasar and an attempt at calibrating it using community feedback and dispersion modelling was carried out previously.

Odour dispersion modelling differs from conventional dispersion modelling. To accurately model the dispersion of odour requires careful consideration to be given to the transport of the plume from the source to the receptor and the response time of the receptor. The steady-state numerical dispersion model ADMS 3.1 was chosen to meet the objectives of this research as it has been tested internationally for landfill odour modelling.

A reanalysis of the data captured from the 2002 community survey was performed in order to investigate the odour emission rate from the open waste piles – transfer station and working face - at the Bisasar road Landfill. The methodology for inferring emission rates was developed by testing various analysis techniques. The reanalysis also provided an idea as to the relative contributions of the working face and the transfer station to the offsite odour impact.

A telephonic survey was carried out during 2004 to collect direct odour observations from residents living around the Bisasar Road landfill site. From an analysis of the dose-response histogram for the combined observations of all the survey participants, the emission rate from an open waste pile was estimated. Mathematical dose response functions were fitted to the observations and odour predictions to relate probability of detection and perceived intensity to odour concentration. The combined response of the population as well as the individual receptor responses were analysed and discussed.

Contours of odour impact around the Bisasar landfill site were plotted to demonstrate a scientific methodology for the specification of protection distances around nuisance odour sources. The dose response relationships established from the 2004 telephonic community survey provided the threshold criterion which was used to plot buffer zones.

7.2 Main Conclusions

Below is a summary of the main findings of this study:

Analysis of the results of the telephonic community survey suggested that open waste piles emit odour at a rate of 250 $COU/m^2/s$, which lies in the range established from the reanalysis of the 2002 survey data. To differentiate the odour threshold established from data gathered in the field from a possible threshold established in a laboratory, the Bisasar threshold was identified as being measured in 'community odour units' (COU) instead of conventional odour units (OU)

The 2002 survey provided an indication as to the relative contributions of the working face and the transfer station to the offsite perception of odour. For the duration of the 2002 community survey, the working face contributed 82% to the odour perceived at the receptors and the Transfer Station contributed 18% during operating hours when the working face was uncovered.

Characterizing the odour in terms of perceived intensity and probability of detection provided an insight into the persistence of the odour from the open waste piles once it entered the community. The odour can be said to have a high persistency and will be detected by receptors at concentrations well below the odour threshold. Mathematical dose response functions fitted to population odour responses can serve as important tools for field assessment of the odour impact in the community.

The telephonic survey proved to be a more effective means of capturing data from the community. The reanalysis of the 2002 survey proved difficult and the correlation between receptor response and odour prediction was not as strong when compared with the analysis of the telephonic survey data.

Dose response relationships and emission rates established from community surveys coupled with dispersion modelling can be used as the basis for a scientific methodology for the specification of buffer zones around nuisance odour sources.

7.3 Suggestions for further research

- The 'indirect' observations gathered from the 2004 telephonic survey were not analyzed. Analysis of these observations could reveal the impact of the biogas sources versus the impact from the open waste piles in terms of perceived odour in the community.

- The telephonic survey could be extended to try and achieve a similar number of observations from each receptor for each major concentration range for use in the analysis.

- Whilst the 2004 telephonic community survey served as a starting point to help characterize the odour being emitted from the open waste piles, it is suggested that a similar survey be conducted in the future to meet various new objectives:

    - A new survey could aim to establish the emission rates from the biogas sources at the landfill. This would require the accurate identification of the main sources of biogas at the site. This might be difficult as biogas is typically released as fugitive emissions. Receptors would likely be contacted at night when the biogas odour is dominant.
    - A choice of modelling averaging time is important as it can be used to represent the exposure period to odour that will likely result in an annoyance event amongst the population. It is not clear what period of exposure will result in an annoyance event or a complaint, but it is likely that

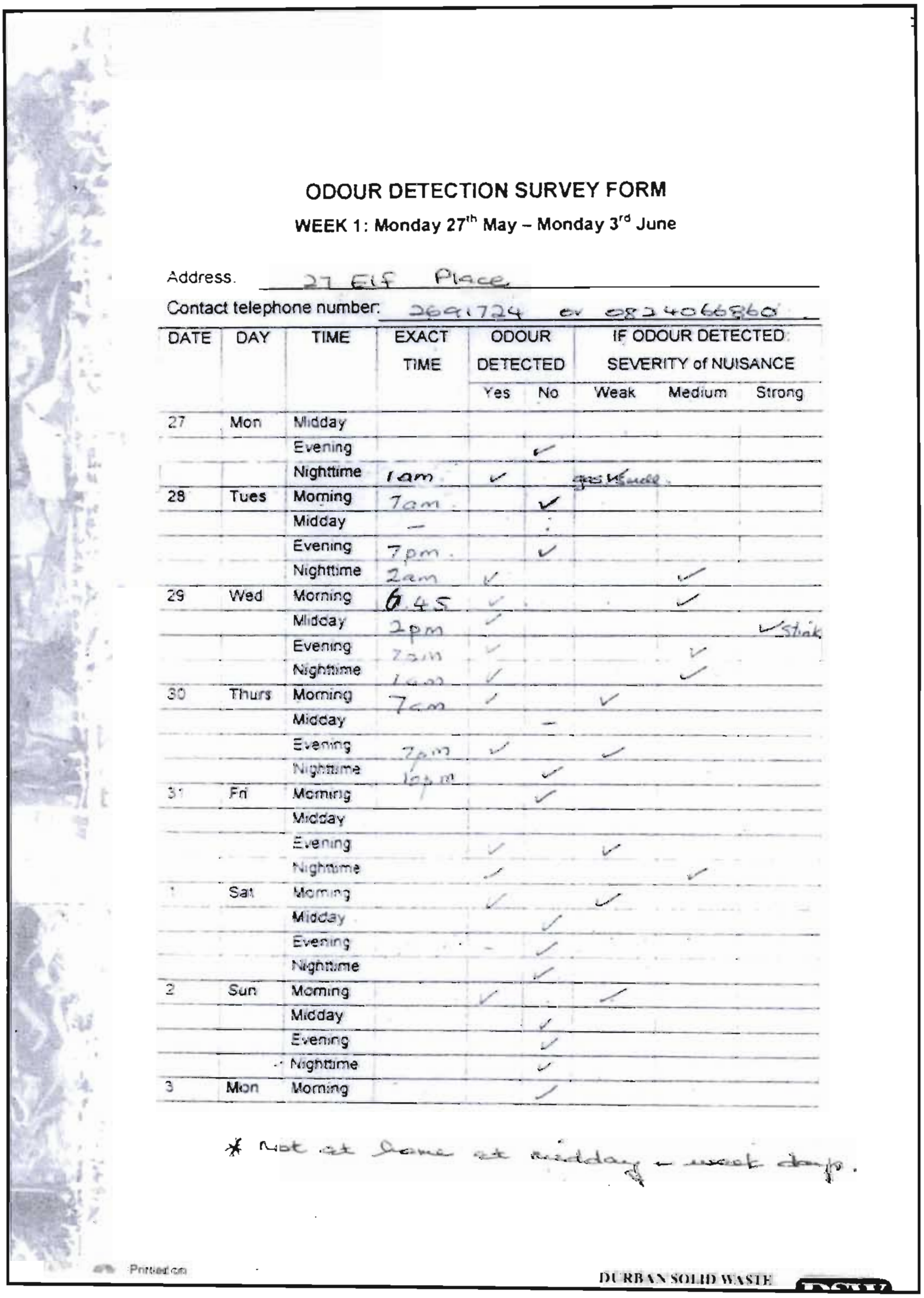
it lies between 3 minutes and 1 hour. A new survey could establish from the population what period of exposure they are willing to tolerate and at what intensity.

- A new survey could establish the dose response of the population with respect to annoyance. Using the annoyance scales that have been discussed previously, the annoyance level of individual receptors and the combined annoyance response of the population to a range of odour concentrations could be established.

– Below are some suggestions for improving the survey technique:

- A new survey would ideally involve the cooperation of a smaller controlled receptor group which has been carefully selected and trained to identify various odours. The sensitivity of each receptor to various odours should be established under controlled laboratory conditions before the survey commences.
- Receptors should use a more comprehensive odour intensity scale with six intensity gradings instead of the three intensity gradings as was used during the 2004 survey. An intensity scale with six gradings is what is typically used internationally for odour analysis.
- Receptors should step outside and make odour observations at the same location on their properties each time they are contacted by the researcher. During the 2004 survey, receptors weren't asked to make their observations from the same location and they weren't always asked to step outside.
- During the 2004 survey, sometimes a member of a household other than the regular survey participant would make an odour observation and this was included in the analysis. Only observations from the trained survey participant should be used.
- Because of the difficulty of getting positive odour observations for certain receptors, observations that weren't necessarily made at the time of the call were used in the analysis. Ideally, to exercise greater control over the collection of data, only observations made at the time of call should be used.

APPENDIX A: IMAGES



ODOUR DETECTION SURVEY FORM

WEEK 1: Monday 27th May – Monday 3rd June

Address. 27 Elf Place

Contact telephone number: 2691724 or 0824066860

DATE	DAY	TIME	EXACT TIME	ODOUR DETECTED Yes	No	IF ODOUR DETECTED: SEVERITY of NUISANCE Weak	Medium	Strong
27	Mon	Midday						
		Evening			✓			
		Nighttime	1am	✓		gas smell		
28	Tues	Morning	7am		✓			
		Midday	–					
		Evening	7pm		✓			
		Nighttime	2am	✓			✓	
29	Wed	Morning	6.45	✓			✓	
		Midday	2pm	✓				✓ stink
		Evening	7pm	✓			✓	
		Nighttime	1am	✓			✓	
30	Thurs	Morning	7am	✓		✓		
		Midday			–			
		Evening	7pm	✓		✓		
		Nighttime	10pm		✓			
31	Fri	Morning			✓			
		Midday						
		Evening		✓		✓		
		Nighttime		✓			✓	
1	Sat	Morning		✓		✓		
		Midday			✓			
		Evening			✓			
		Nighttime			✓			
2	Sun	Morning		✓		✓		
		Midday			✓			
		Evening			✓			
		Nighttime			✓			
3	Mon	Morning			✓			

* Not at home at midday – week days.

Printed on

DURBAN SOLID WASTE

Plate A-1: Scan of a 2002 survey sheet (Laister, 2003a)

Plate A-2: Screen shot of a page from the database used to directly record telephonic survey data

Date: 17-Sep **FRIDAY**

Odour type : 0 = Landfill gas; 1 = fresh waste; 2 = combination of the above

Odour: 0 = no odour; 1 = weak odour; 2 = medium odour; 3 = strong odour

Highlighted data means observation made at time prior to call, I.e. receptor is asked to recall the time the odour was detected.

street name	number	receptor name	contact number	*Time*	*Odour Type*	*Odour (0-3)*	*Time*	*Odour Type*	*Odour (0-3)*
Bisasar Rd		Landfill site office	#	*13:54*	-	*0*			
Burnwood	34	Business. Mrs Malthe	#	*13:56*	-	*0*			
Burnwood	125	Renusha Bahal	#	*16:30*	-	*0*			
Burnwood	60	Burnwood Secondary / Mrs Pillay	#	*13:58*	-	*0*			
Clare Rd	178	Place of Safety	#	*13:58*	*0*	*1*			
Constantine Rd	31	Mr Ishmail	#						
Dodoma	3	Mrs Ramkoosun	#						
Dodoma	11	Mr Glen Harrinsunker	#	*13:59*	-	*0*			
Elf	27	Jugmhum, Premmie	#						
Foreman Rd	192	(Sashni) Kennedy Mutton Market	#	*14:00*	-	*0*	*08:00*	*1*	*1*
Kennedy	79	Misthry Residence	#						
Kennedy	93	Misthry meat/ Kennedy Super market	#	*14:04*	*1*	*2*			
Kennedy	105	Mr and Mrs Seedat	#	*14:47*	*1*	*1*			
Kennedy	127	Mr Jonothan Naicker	#	*14:05*	*1*	*3*			
Kennedy	131	Ryan and Rosie Gunga	#	*14:15*	*1*	*3*			
Kennedy	159	Mrs Jithoo	#	*14:21*					
Mayflower Rd	29	Marion/Mr Smith	#						
Revenge Rd	3	Mr + Mrs Seedat	#						
Rosemary	15	Mr KR C229Matal	#	*14:40*	-	*0*			
Vialls Place	5	Mr and Mrs ismail	#	*14:41*	*1*	*1*			
Vialls Place	33	Mrs Ramdas	#	*14:43*	-	*0*			
Vialls Place	27a	Mr and Mrs Arthar	#						
Vialls Place	27b	Anusha (property owned by Mr Arthar)	#						
Vialls Place	7	Mr Pillay.	#	*14:45*	-	*0*	*6:15*	*0*	*1*
Wandsbeck	78	Mr Trevor Noel / Mr Noel's father	#						
Wattle Rd	144	Adele Nelson	#	*14:39*	-	*0*			

Comments: *NE blowing. dust is bad at misthry meat market*

APPENDIX B: 2002 SURVEY

B-1: Analysis Approach

Run 1

The first simulation run and subsequent analysis helped establish the best approach to processing the ADMS outputs and the corresponding community observations. It also helped establish how best to interpret the odour observations recorded on the weekly survey sheets. The met data for the 10 month period over which the survey was conducted were used to generate odour predictions every ten minutes. Various techniques for analyzing the vast ADMS output in conjunction with the receptor observations were tested and provided an insight into how best to manage and interpret the data. Approximately 45 000 lines of met data were processed by the dispersion model and the output generated consisting of 45 000 odour predictions for each receptor. Predicted odour concentrations were averaged over the morning (7:00-10:00), midday (11:00-14:00), evening (17:00-20:00) and night time (20:10-23:00) periods and correlated with the odour observations made by the receptors. The data generated by the first run of the model was analyzed in three ways: analysis 1, analysis 2 and analysis 3.

<u>Run 1, Analysis 1</u>

Often survey participants would leave fields unfilled for certain times of the day, and it was unclear whether these should be interpreted as negative observations, or not. In other words, it was initially assumed that where no observation was recorded, that the receptor did not perceive an odour at that time. This assumption was tested by first performing an analysis where the blank observations were included as negative observations in the analysis.

<u>Run1, Analysis 2</u>

An analysis was also conducted where the blank observations were excluded from the generation of a combined dose response histogram.

Run 1, Analysis 3

As mentioned previously, we are interested in establishing the odour threshold for an open waste pile and so are only interested in observations of odour where either the working face or the transfer station is the dominant source. Analysis 1 and Analysis 2 used observations for morning, midday, evening and night time and the average of the 10 minute ADMS outputs over these periods. Analysis 3 excluded observations and ADMS outputs for evening and night time on the assumption that the dominant odour during the day is from open waste piles and that positive odour observations made at night are generally of LFG since at night time when the waste surface is covered.

Run 2

The aim of the second run was to investigate the benefits, if any, in processing hourly averaged met data. As discussed earlier, the advantages to averaging the met data hourly lay in the reduced processing time and the better estimate of boundary layer height. The second run of the model generated odour predictions for each receptor for a total of 7000 lines of hourly averaged met data.

The community survey divided each day into four observation times. i.e. morning, midday, evening and night time. On the survey form, the receptor was given the option to specify the exact time when the odour observation was made. If the receptor did not record an observation time (which was often the case), either an average of the ADMS outputs over the time period (morning or midday), or the peak odour concentration over the time period, was used. The average over the observation period was used to test the assumption that receptors recorded their general impressions of the odour for the given time period. The peak concentration over the observation period was used to test the assumption that receptors reacted to peak concentrations over the time periods and made diary recordings accordingly. It was assumed that the four time periods in a day were represented by the following ranges: morning 7:00 – 10:00; midday 11:00 – 14:00; evening 17:00 – 20:00 and night time 20:00 -23:00. Only observations made during the morning and midday periods or observations made between 7:00 AM and 4:00 PM were used and correlated with ADMS outputs.

Run 2, Analysis 1

If a receptor did not specify an exact time but acknowledged that they had either made a positive or negative observation for odour in the morning or midday time period, then the average ADMS odour prediction over that period was used. In the case where the receptor recorded the exact time of observation, the model prediction for that hour was used

Run 2, Analysis 2

Here, instead of using the average concentration over either the morning or midday period when an exact time was not specified, the maximum concentration over the period was used instead. Once again, if the receptor did record a specific time when the observation was made, then the model prediction for that hour was used.

Run 3

The third run of the model used the same met data as was used in the first run and generated odour predictions every 10 minutes for the duration of the survey for each receptor. In the analysis of run 1, averages of odour concentration over the morning, midday, evening and night time periods were used regardless of whether a receptor specified an exact observation time or not. In the analysis of the results of run 3, however; if a receptor did specify an exact odour observation time, then the corresponding concentrations for that time were used. In the case where a receptor didn't specify an exact observation time but indicated that an observation –negative or positive – was made during the morning or midday, then the average or maximum over that time period was used. The output from the third run of the model and the community observations were analyzed using two approaches.

Run 3, Analysis 1

The first approach used the average of the ADMS outputs over the observation time. In the instances where a receptor did not record a specific observation time, the average of the ADMS outputs for the observation period was used, i.e. morning: 7:00-10:00; midday 11:00-14:00. If the receptor did record an exact observation time, then the average of the ADMS predictions made in the previous hour were used. For instance, if a receptor made an observation at 8:30, then the average of the ADMS predictions generated at 8:30, 8:20, 8:10, 8:00, 7:50 and 7:40 was used.

Run 3, Analysis 2

In this case, instead of using the average of the 10 minute ADMS outputs over a time period, the maximum ADMS output for that time period was used. When an observation time was recorded by the receptor, the maximum ADMS odour prediction from the previous hour was used.

B-2: Analysis Results

Error bars were generated for each bin and posted on the combined dose response histograms to indicate the margin of error for each concentration range. Error bars on the Dose Response plots indicate the 95% confidence interval of the probability of detection for a particular odour concentration bin. In other words, 1.96 standard deviations were taken on either side of the mean. This assumes guassian sampling errors. The 95% confidence interval for proportion is calculated as follows:

$$95\%\ \text{confidence interval} = P \pm 1.96s \qquad (B\text{-}1)$$

Where P is the proportion of positive observations in a bin and s is the standard error. The standard error for proportion is calculated as follows (Cheremisinoff, 1987):

$$s = \sqrt{\frac{p(1-p)}{n}} \qquad (B\text{-}2)$$

where n is the total number of observations, negative and positive, in the bin.

Run 1

The difference between including and not including the blank fields on the receptor weekly response forms in the analysis 1 and 2 is demonstrated in Figure B-1 and Figure B-2 respectively. The combined dose response histogram in Figure B-2 demonstrates a strong trend of probability of detection increasing from left to right along the horizontal axis, suggesting it is correct to exclude blank fields from the analysis and not to view them as negative observations. The combined dose response histogram in Figure B-3 (analysis 3, where nights are excluded) demonstrates a strong trend with more positive observations appearing in the upper concentration ranges. This supports the theory that the daytime observations (morning and midday) correspond to odours originating from open waste piles, which are active, uncovered and dominant during the day.

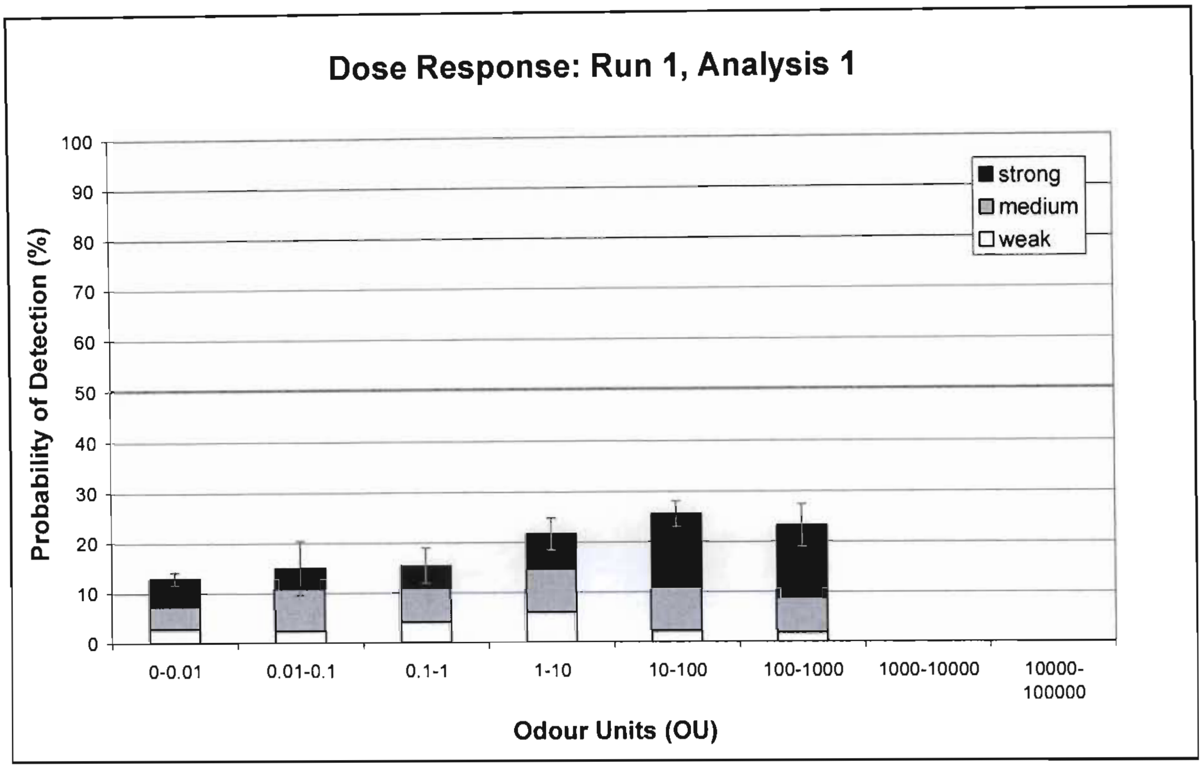


Figure B-1: Histogram showing combined dose response: Run 1, Analysis 1

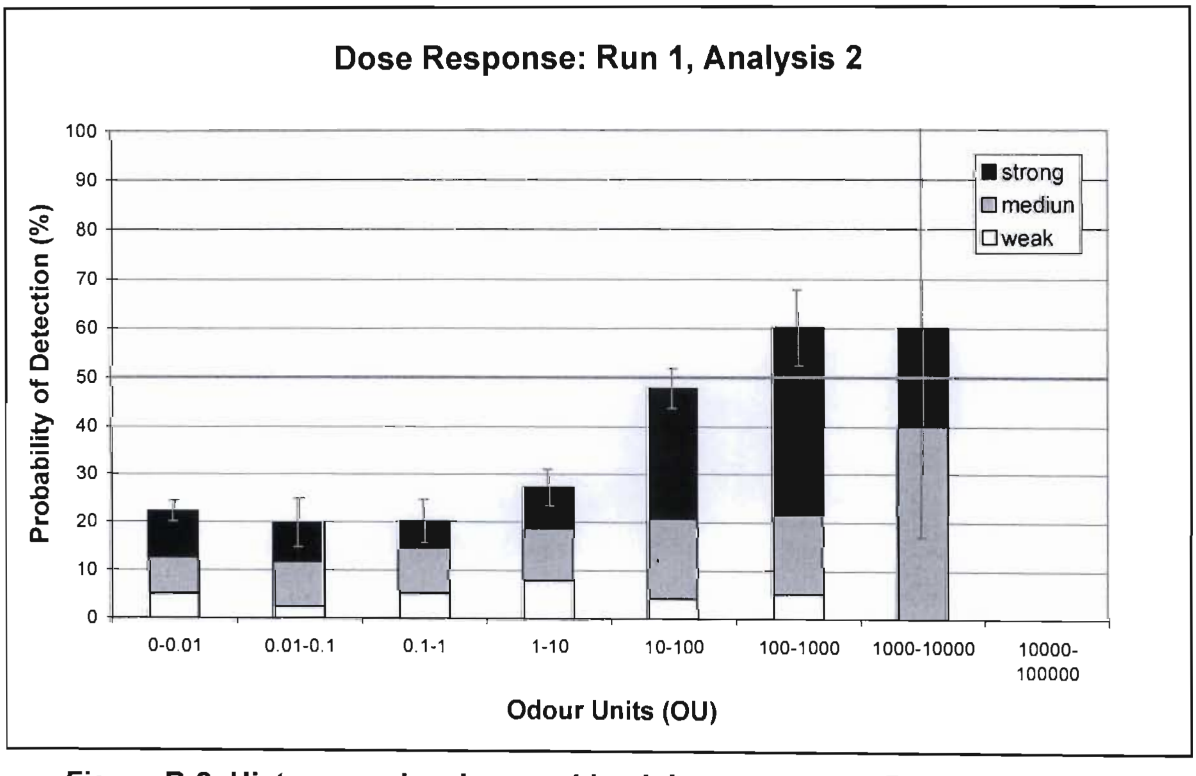


Figure B-2: Histogram showing combined dose response: Run 1, Analysis 2

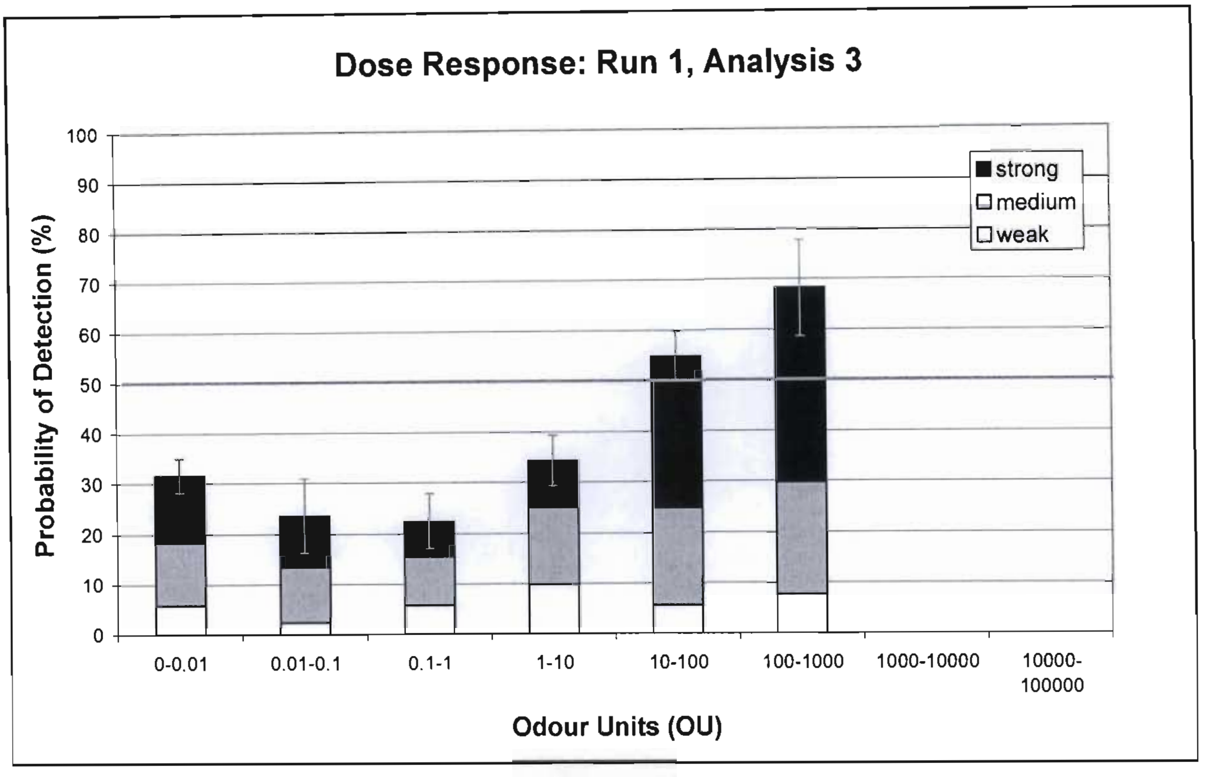


Figure B-3: Histogram showing combined dose response: Run 1, Analysis 3

Run 2

Figure B-4 and Figure B-5 show combined dose response histograms where the odour predictions have been generated by the model using hourly averaged met data. Averaging the met data hourly appears to have reduced the number of positive observations in the higher concentration ranges and at the same time, increased the number of positive observations in the lower concentrations rages. It appears that this approach has a tendency to underestimate the odour concentration at receptor when a positive observation has been made. It is likely that averaging the met data over the hour smoothes out to too great a degree the fluctuations in wind speed and wind direction experienced during the hour. Allowing the ADMS to process the data hourly sequentially may provide better estimates of the boundary layer, but the benefits of this are lost due to the exclusion of fluctuations in concentration during that hour.

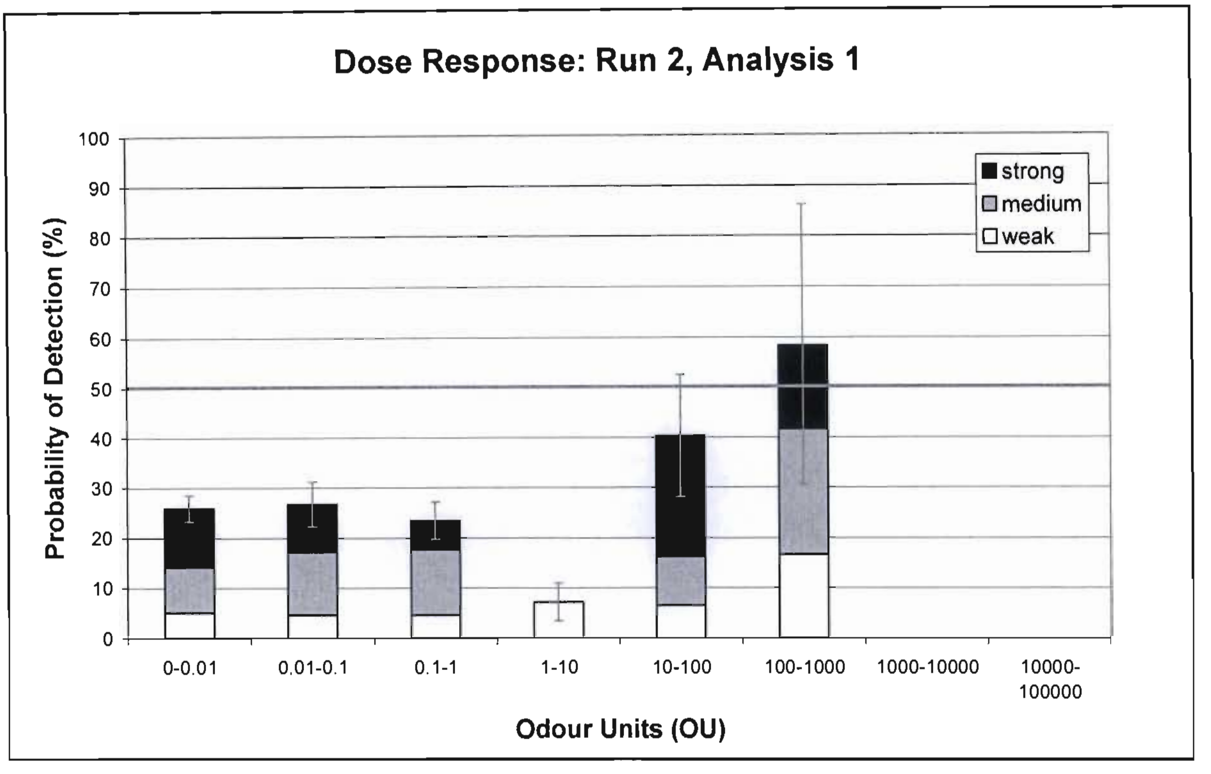


Figure B-4: Histogram showing combined dose response: Run 2, Analysis 1

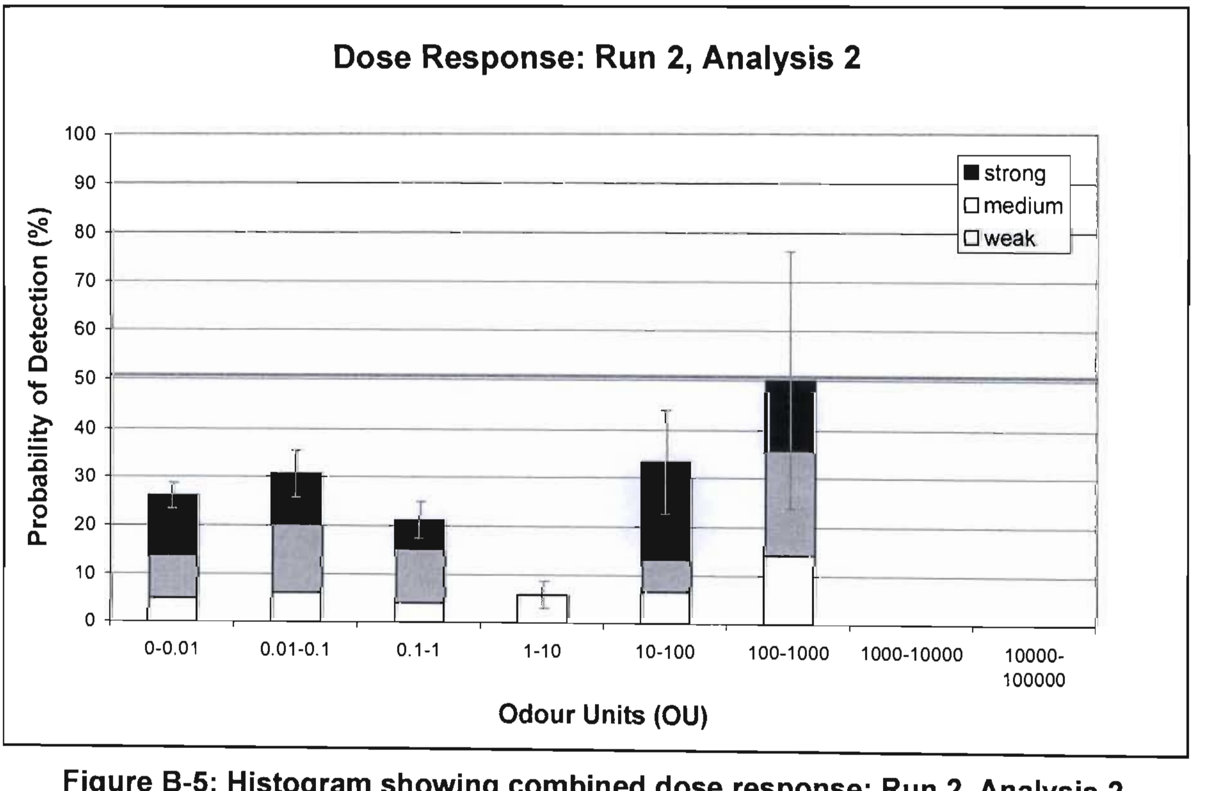


Figure B-5: Histogram showing combined dose response: Run 2, Analysis 2

Run 3

See section 4.4.3 for the analysis results for Run 3, analysis 1.

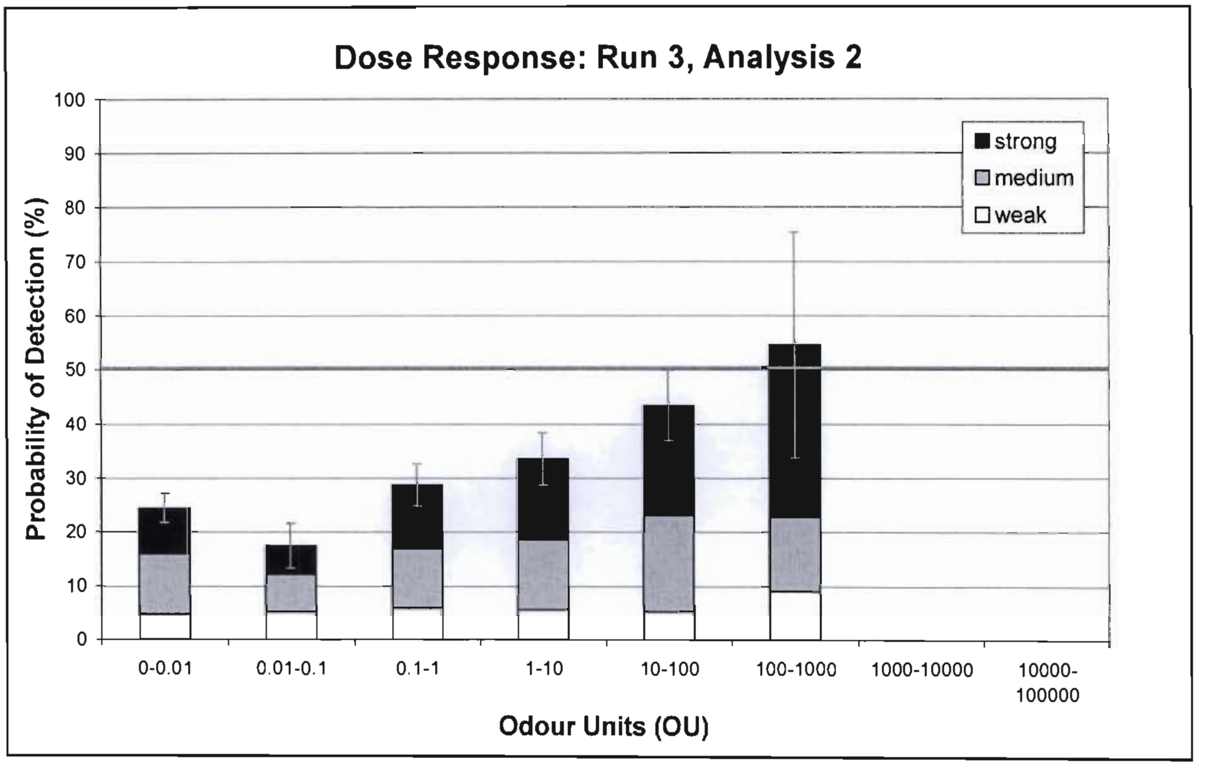


Figure B-6: Histogram showing combined dose response: Run 3, Analysis 2

B-3: Individual receptor responses

A dose response histogram was plotted for each receptor demonstrating the relationship between the probability of detection and the concentration of the odour. The histograms were plotted using the raw data in Table B-1. An emission rate of 1000 $OU/m^2/s$ was specified in the dispersion model for the generation of odour predictions to correlate with the receptor observations. These histograms were based on the 1st analysis approach used on the data from run 3 of the model.

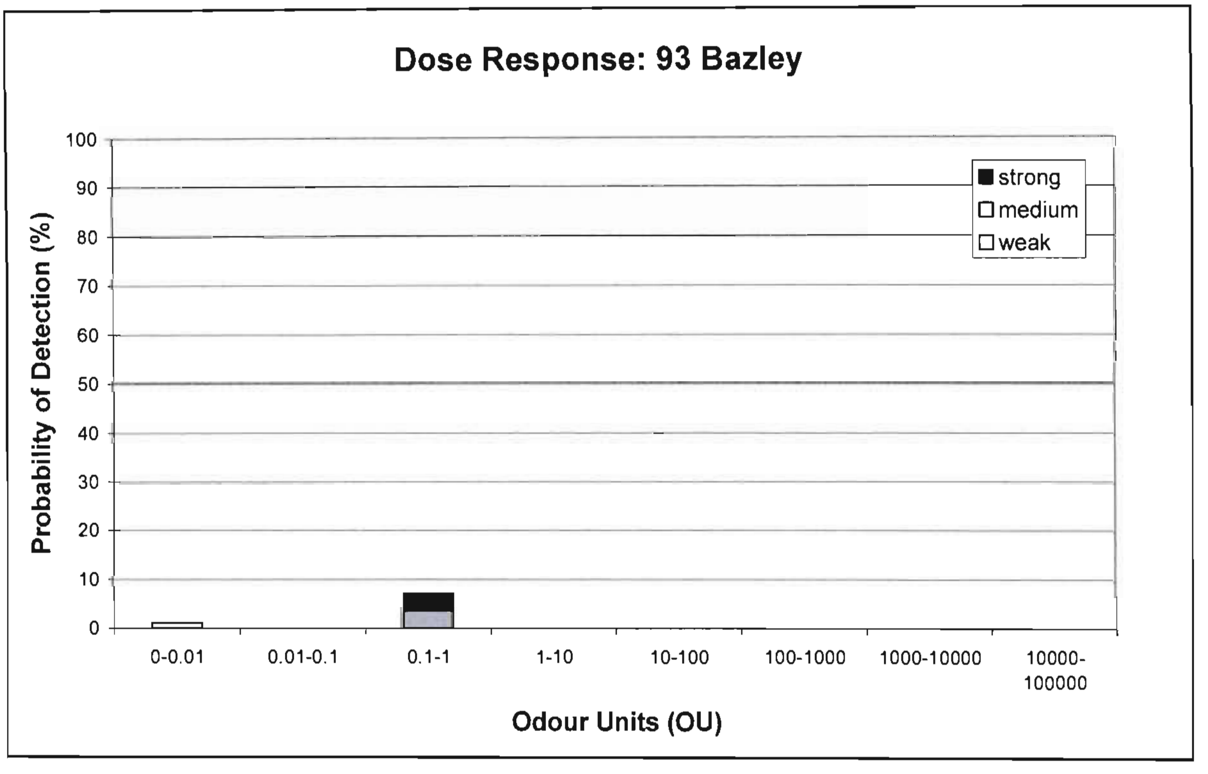


Figure B-7: Histogram showing dose response for receptor at 93 Bazley

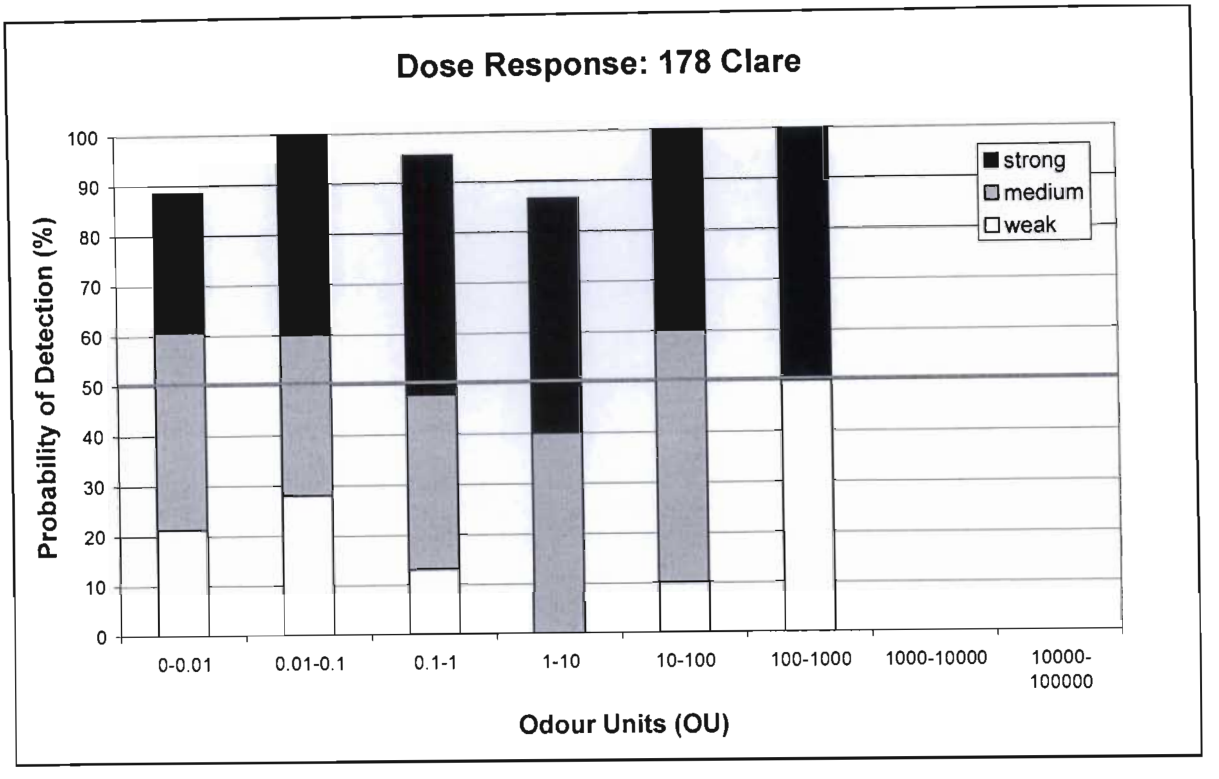


Figure B-8: Histogram showing dose response for receptor at 178 Clare

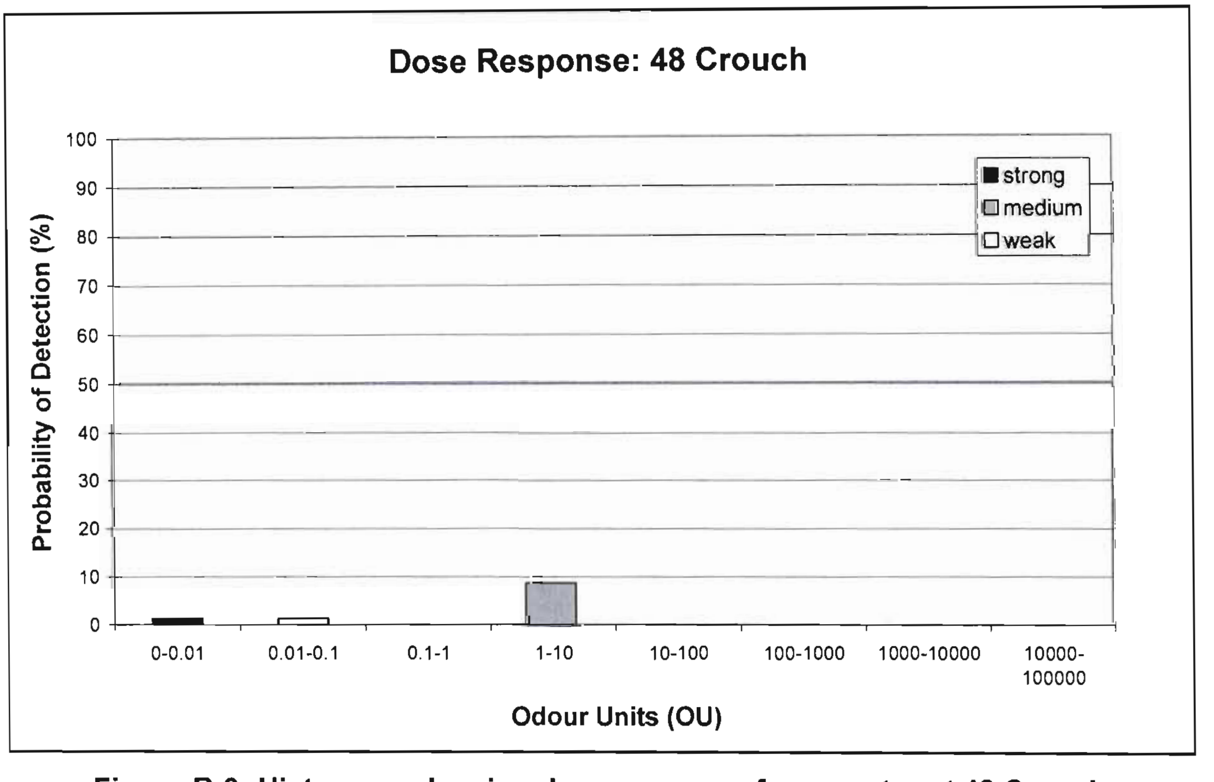


Figure B-9: Histogram showing dose response for receptor at 48 Crouch

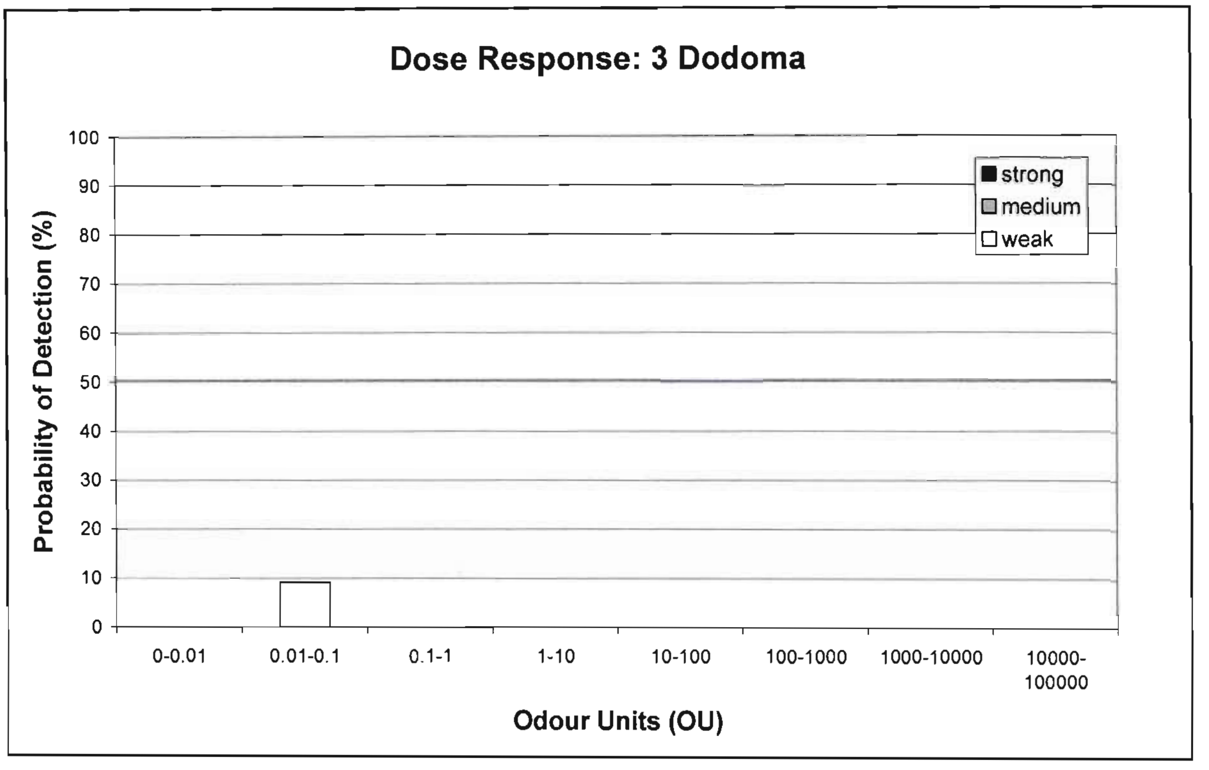


Figure B-10: Histogram showing dose response for receptor at 3 Dodoma

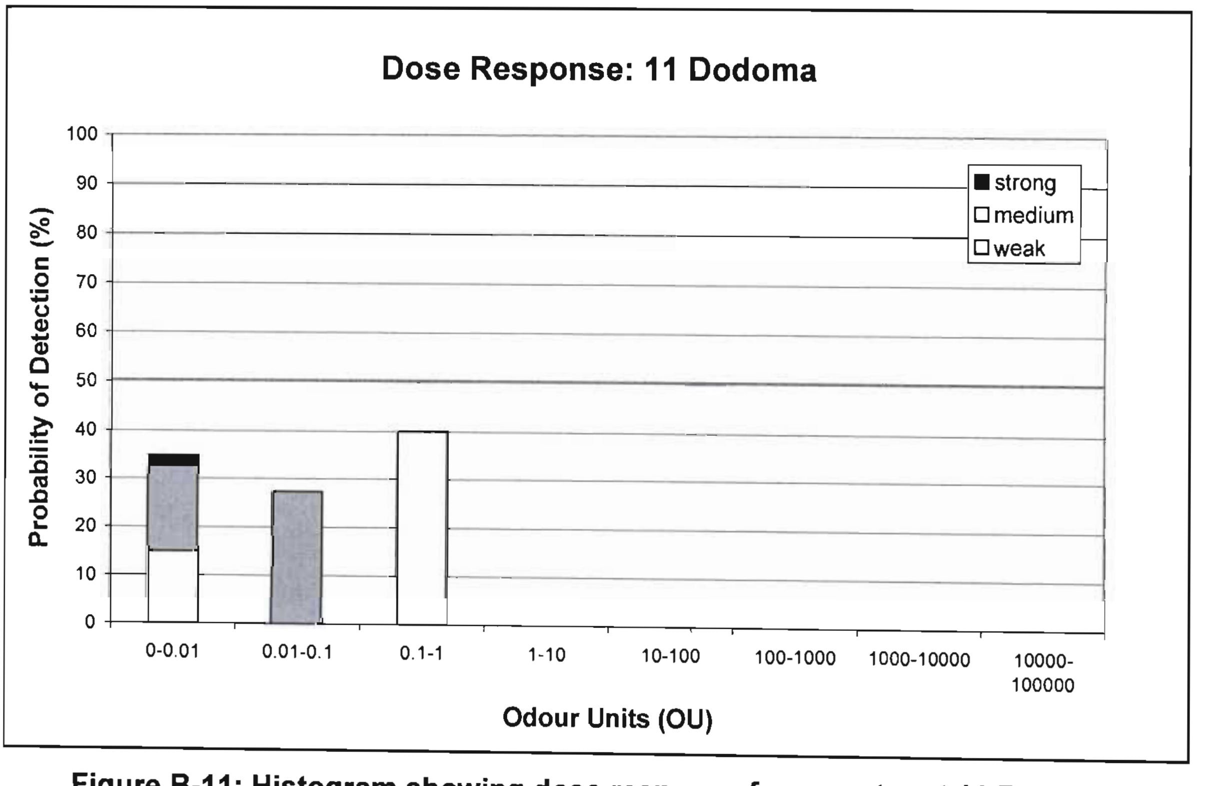


Figure B-11: Histogram showing dose response for receptor at 11 Dodoma

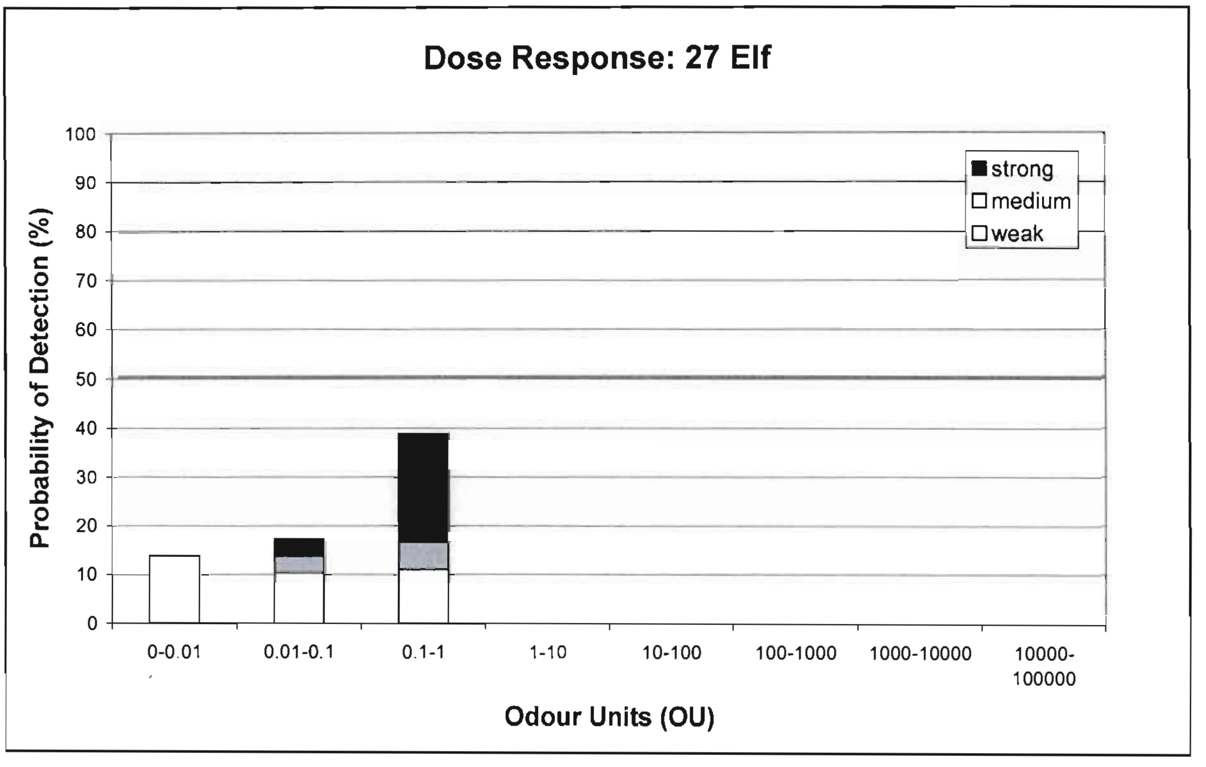


Figure B-12: Histogram showing dose response for receptor at 27 Elf

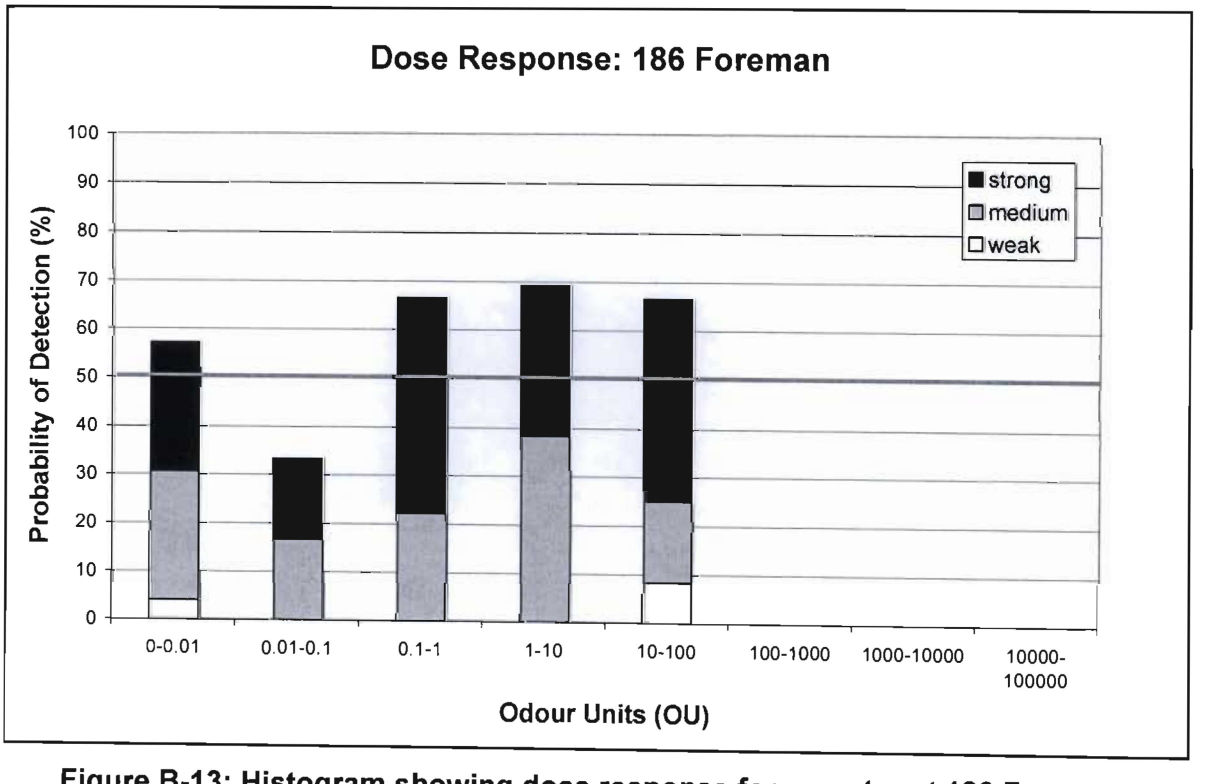


Figure B-13: Histogram showing dose response for receptor at 186 Foreman

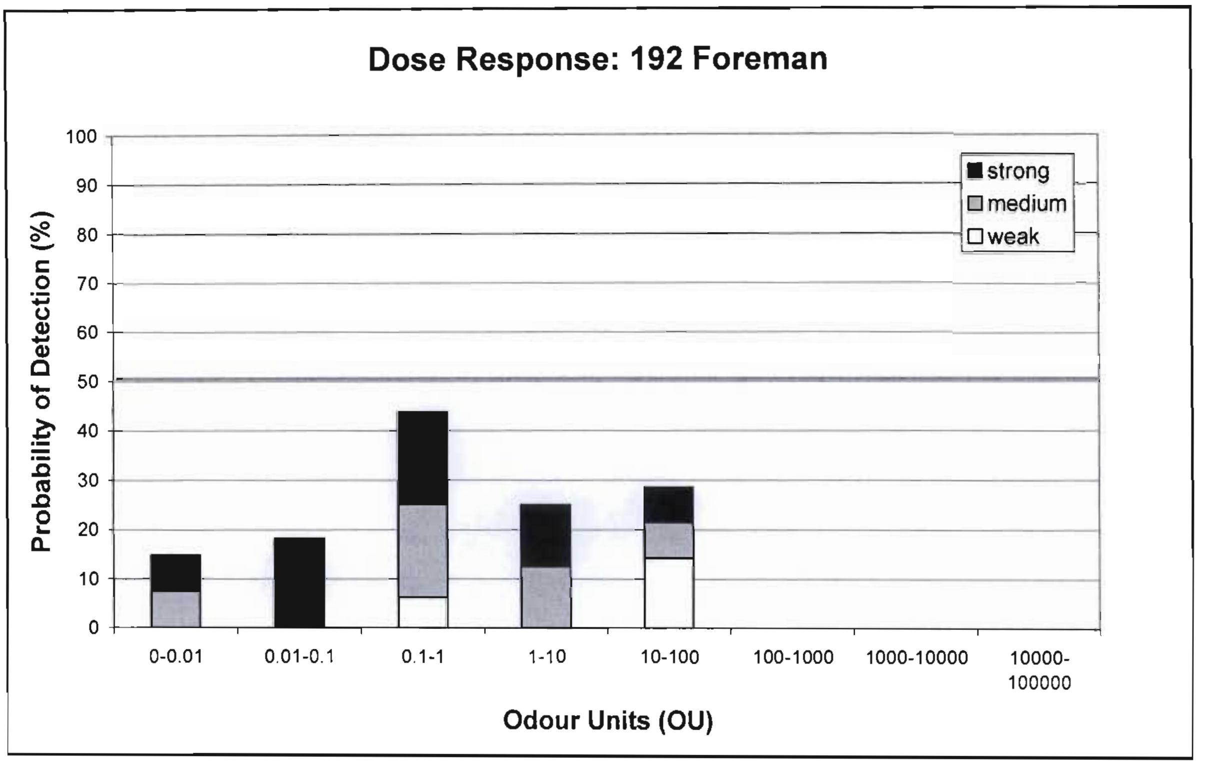


Figure B-14: Histogram showing dose response for receptor at 192 Foreman

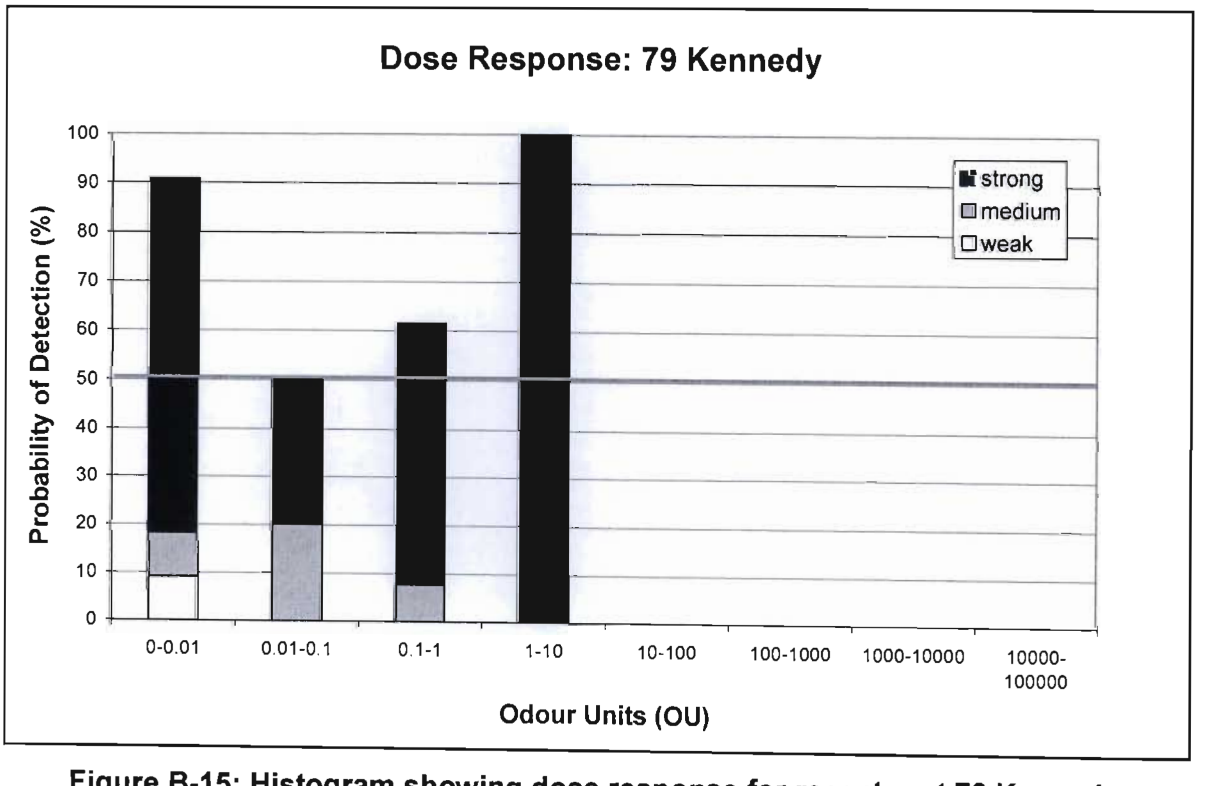


Figure B-15: Histogram showing dose response for receptor at 79 Kennedy

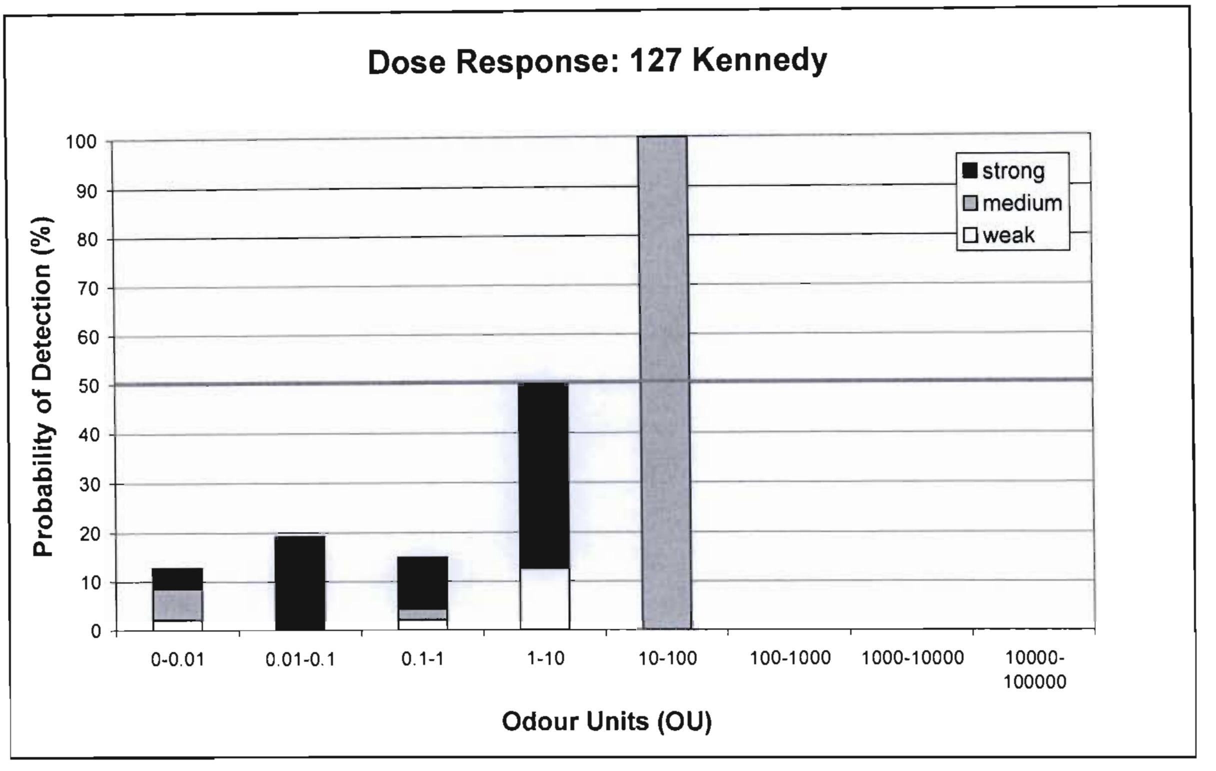


Figure B-16: Histogram showing dose response for receptor at 127 Kennedy

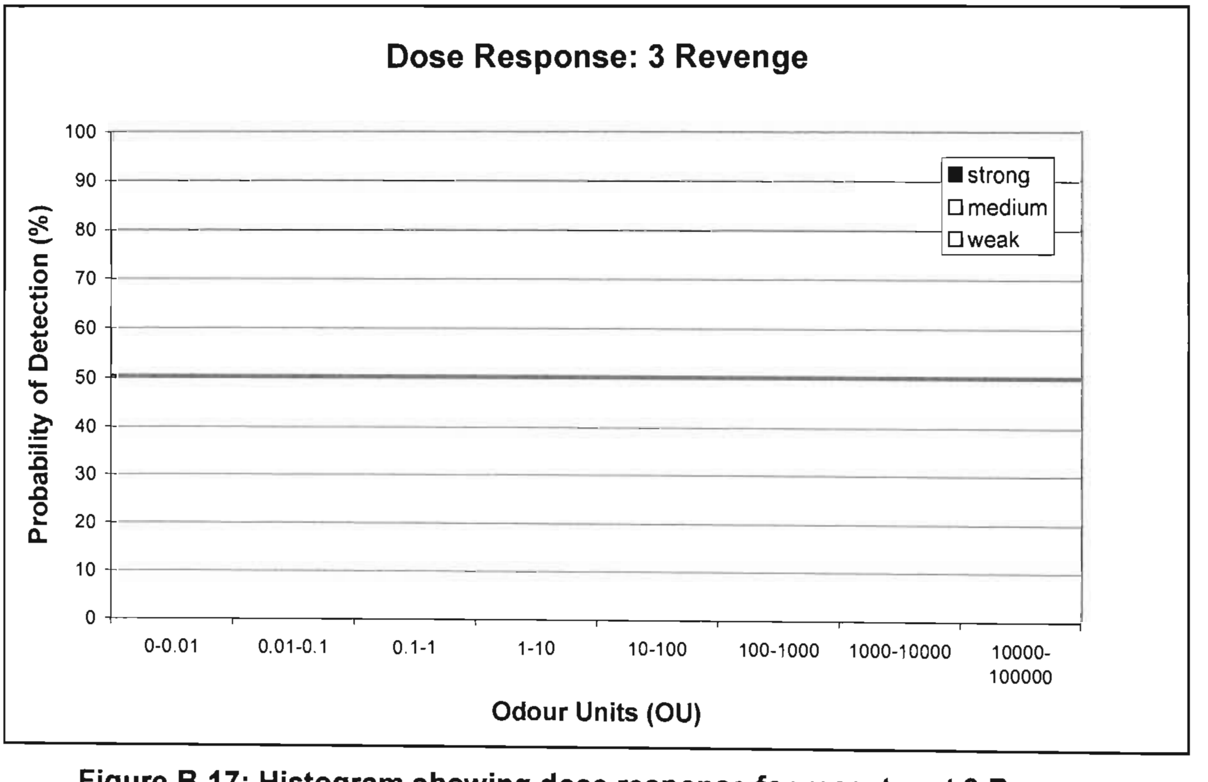


Figure B-17: Histogram showing dose response for receptor at 3 Revenge

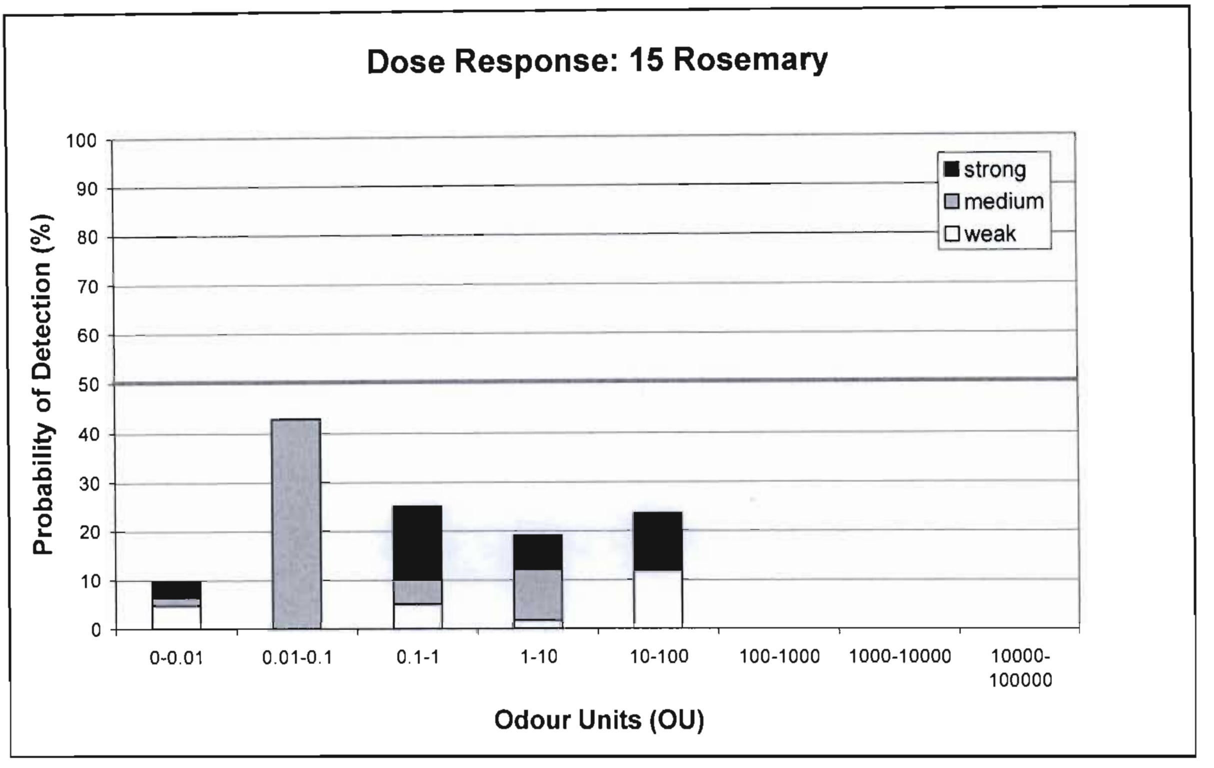


Figure B-18: Histogram showing dose response for receptor at 15 Rosemary

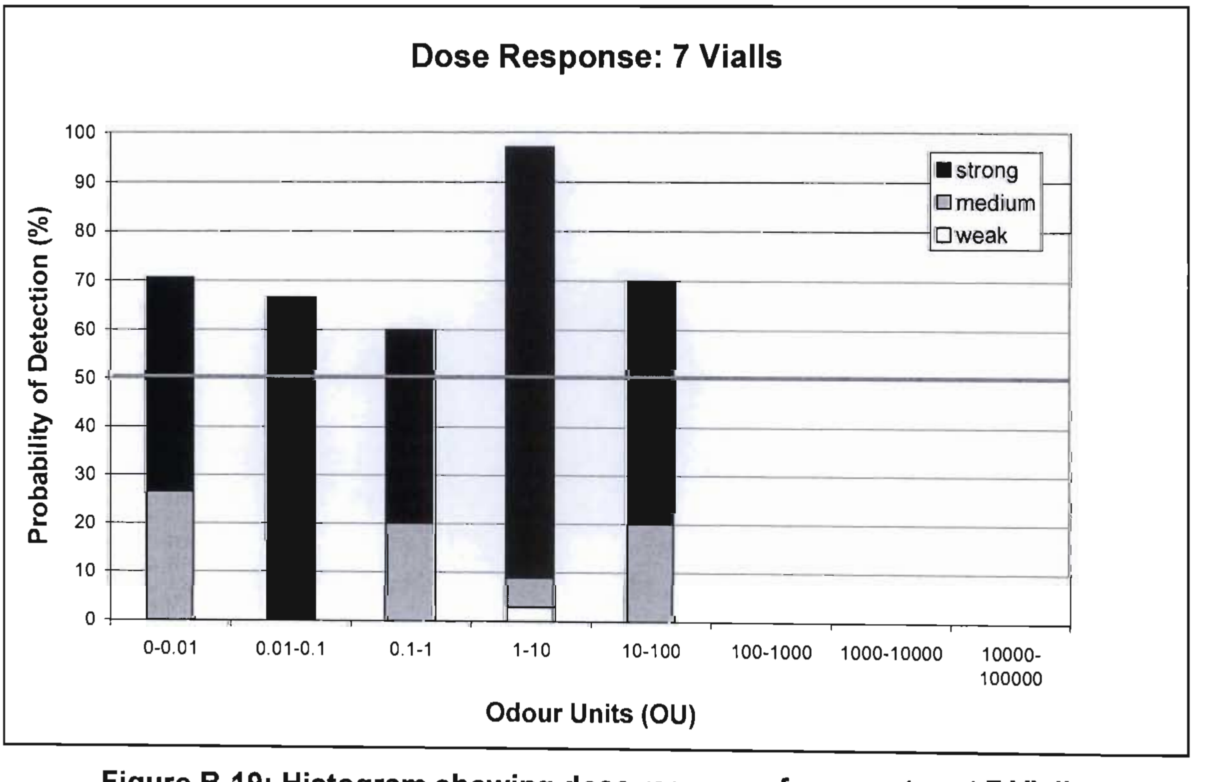


Figure B-19: Histogram showing dose response for receptor at 7 Vialls

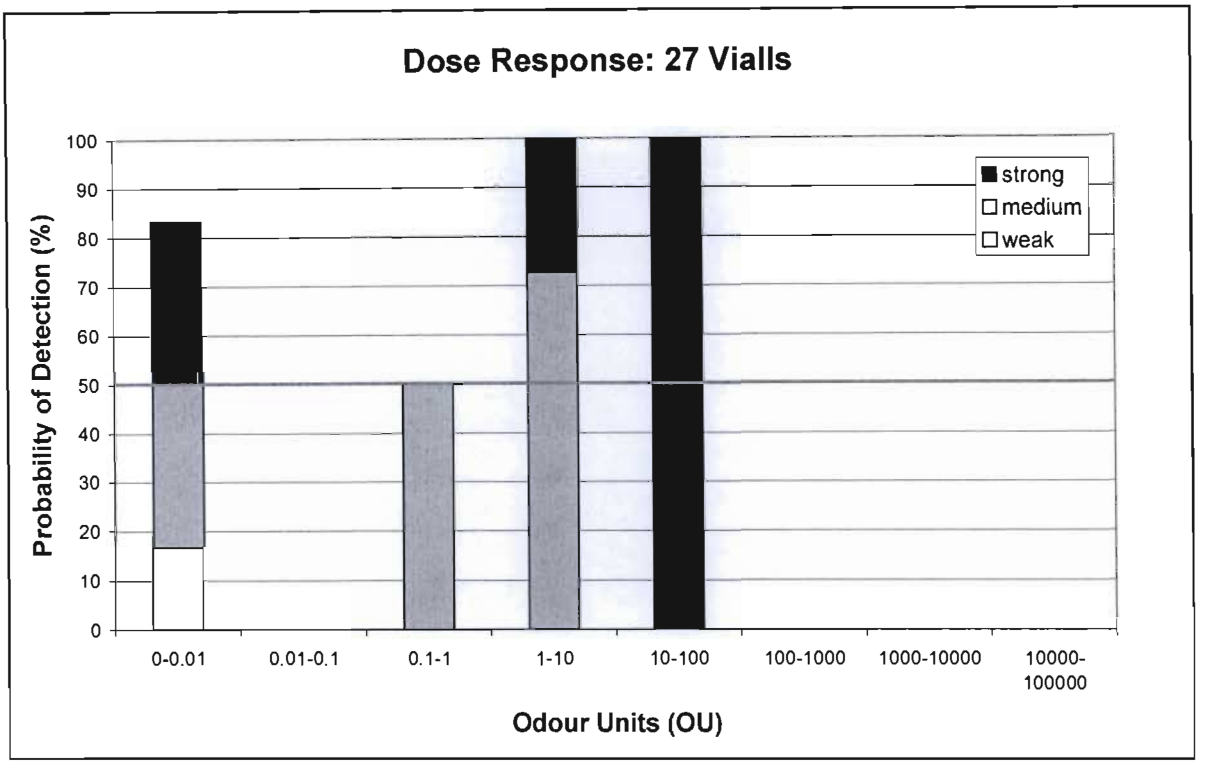


Figure B-20: Histogram showing dose response for receptor at 27 Vialls

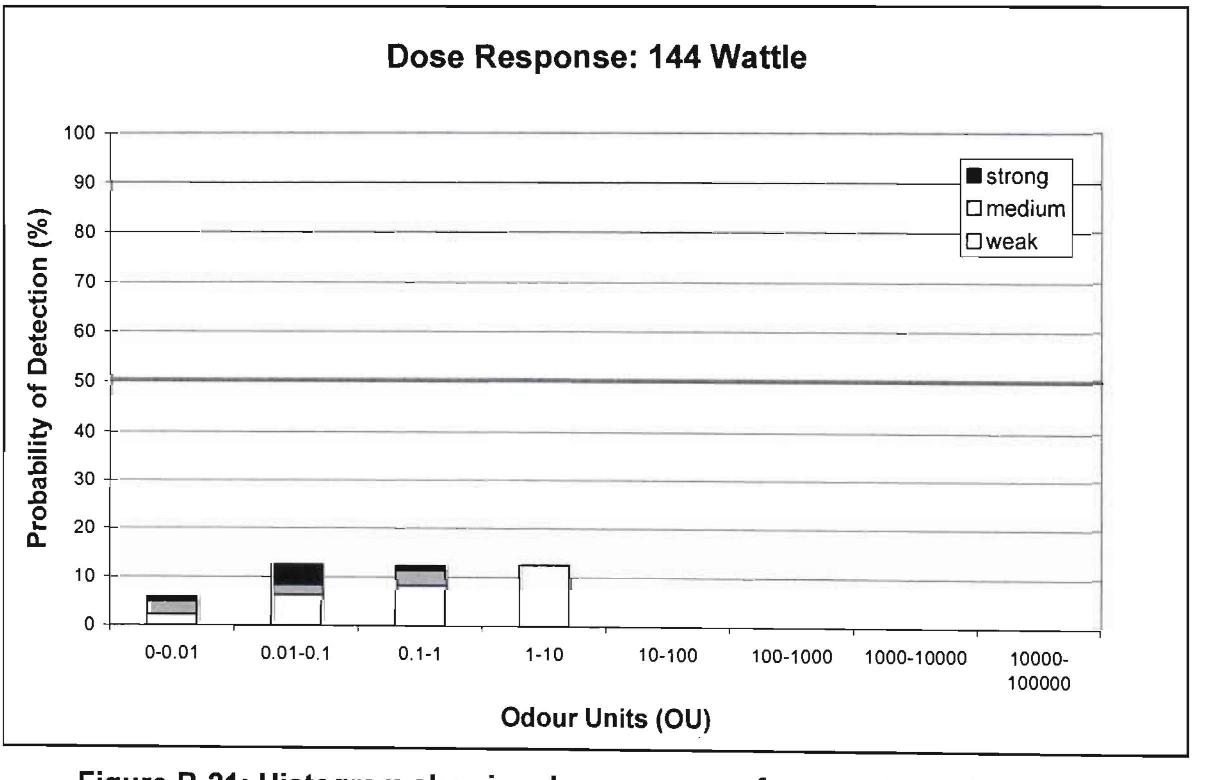


Figure B-21: Histogram showing dose response for receptor at 144 Wattle

Table B-1: Summary of raw data used to generate histograms for each receptor. 2002 survey using technique: Run 3, analysis 1.

	Number of Odour Observations per Concentration Range							
	0-0.01	0.01-0.1	0.1-1	1-10	10-100	100-1000	1000-10000	10000-100000
93 Bazley	92	15	26	22	1			
0	1							
1			1					
2			1					
3								
34 Burnwood								
0	11	14	12	12	2			
1	19	4	12	8				
2	55	23	22	9	2			
3	16	10	9	4	1			
178 Clare								
0	7		1	2				
1	13	7	3		1	1		
2	24	8	8	6	5			
3	17	10	11	7	4	1		
48 Crouch								
0	73	73	11	21	2			
1								
2		1		2				
3	1							
3 Dodoma								
0	48	10	11					
1		1						
2								
3								
11 Dodoma								
0	26	8	3					
1	6		2					
2	7	3						
3	1							
27 Elf								
0	37	24	11	1				
1	6	3	2					
2		1	1					
3		1	4					
186 Foreman								
0	21	4	3	4	4	1		
1	2				1			
2	13	1	2	5	2			
3	13	1	4	4	5			
192 Foreman								
0	23	9	9	6	10			
1			1		2			
2	2		3	1	1			
3	2	2	3	1	1			
79 Kennedy								
0	2	5	5					
1	2							
2	2	2	1					
3	16	3	7	10				

Table continued on next page..................

	0-0.01	0.01-0.1	0.1-1	1-10	10-100	100-1000	1000-10000	10000-100000
127 Kennedy								
0	41	21	40	4				
1	1		1	1				
2	3		1		1			
3	2	5	5	3				
3 Revenge								
0	242	91	84	15				
1								
2								
3								
15 Rosemary								
0	56	4	15	47	13			
1	3		1	1	2			
2	1	3	1	6				
3	2		3	4	2			
7 Vialls								
0	10	1	2	1	3			
1				1				
2	9		1	2	2			
3	15	2	2	30	5			
27 Vialls								
0	1		1					
1	1							
2	2		1	16				
3	2			6	1			
144 Wattle								
0	209	42	85	7				
1	5	3	8	1				
2	6	1	3					
3	2	2	1					

APPENDIX C: 2004 SURVEY

C-1: Individual receptor responses

A dose response histogram was plotted for each receptor demonstrating the relationship between the probability of detection and the concentration of the odour. The histograms were plotted using the raw data in Table C-1. An emission rate of 250 $COU/m^2/s$ was specified in the dispersion model for the generation of odour predictions to correlate with the receptor observations.

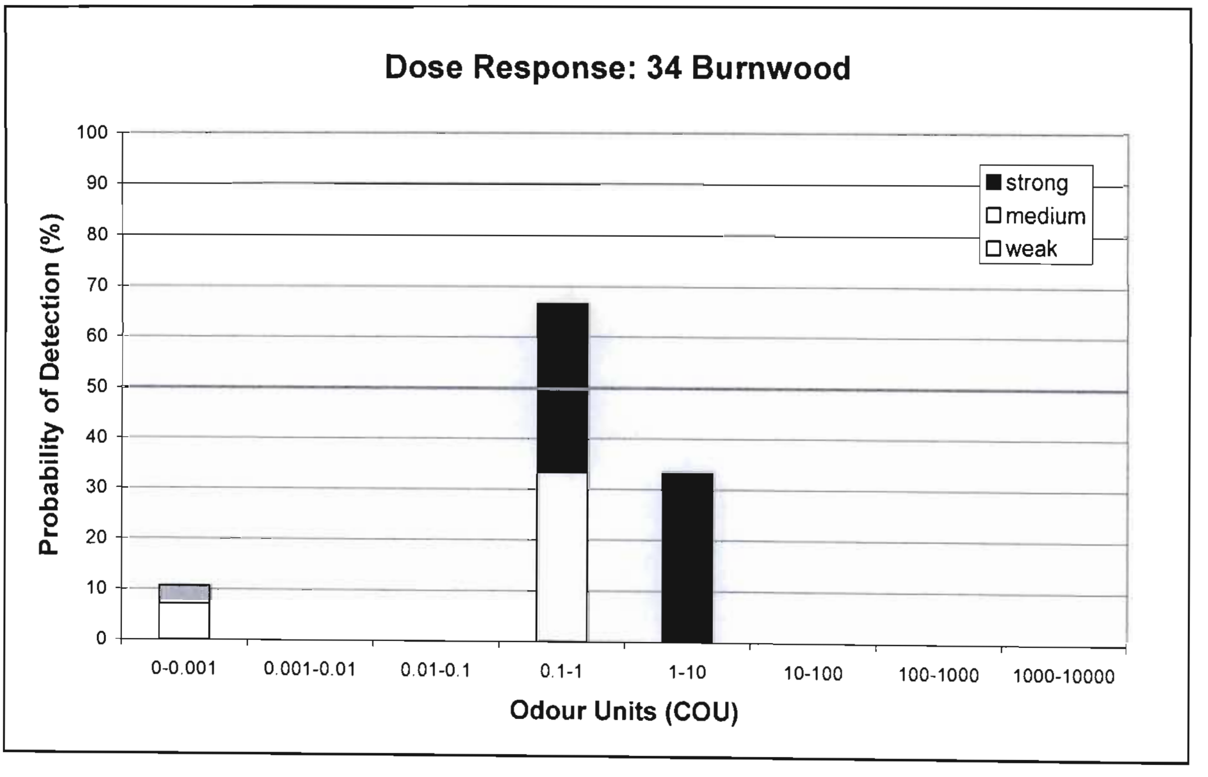


Figure C-1: Histogram showing dose response for receptor at 34 Burnwood

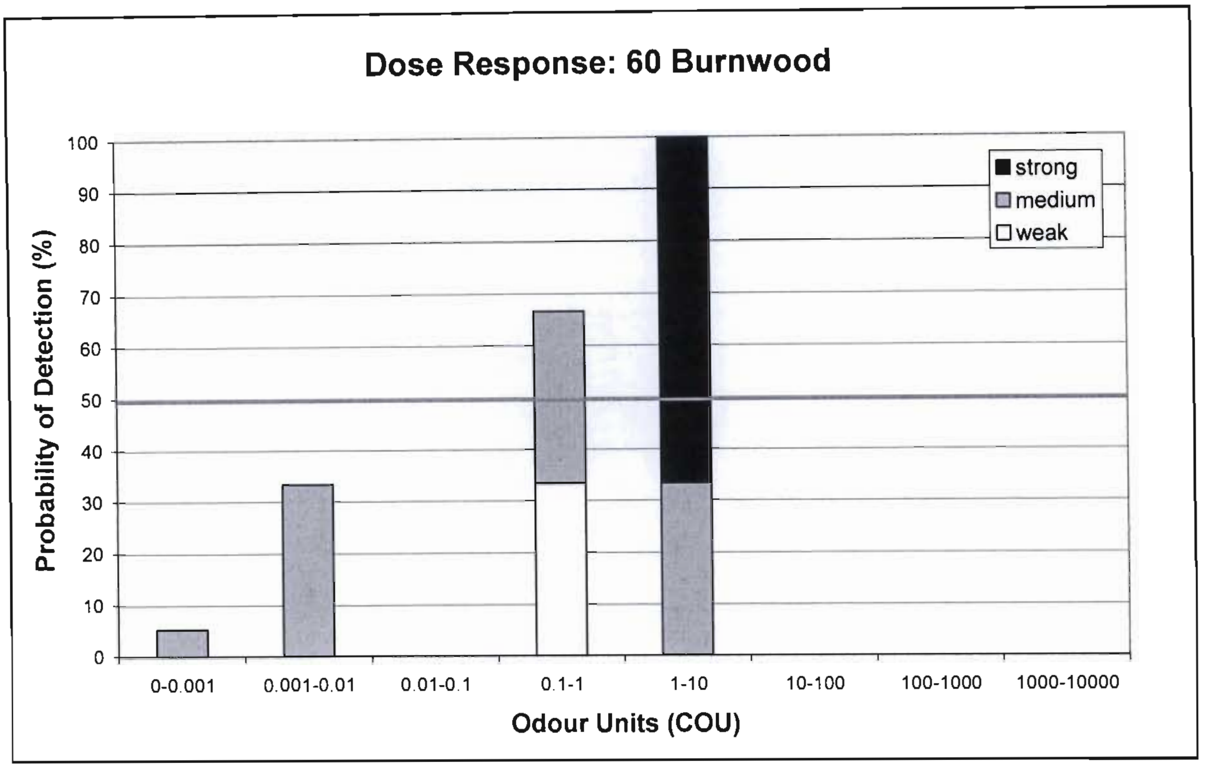


Figure C-2: Histogram showing dose response for receptor at 60 Burnwood

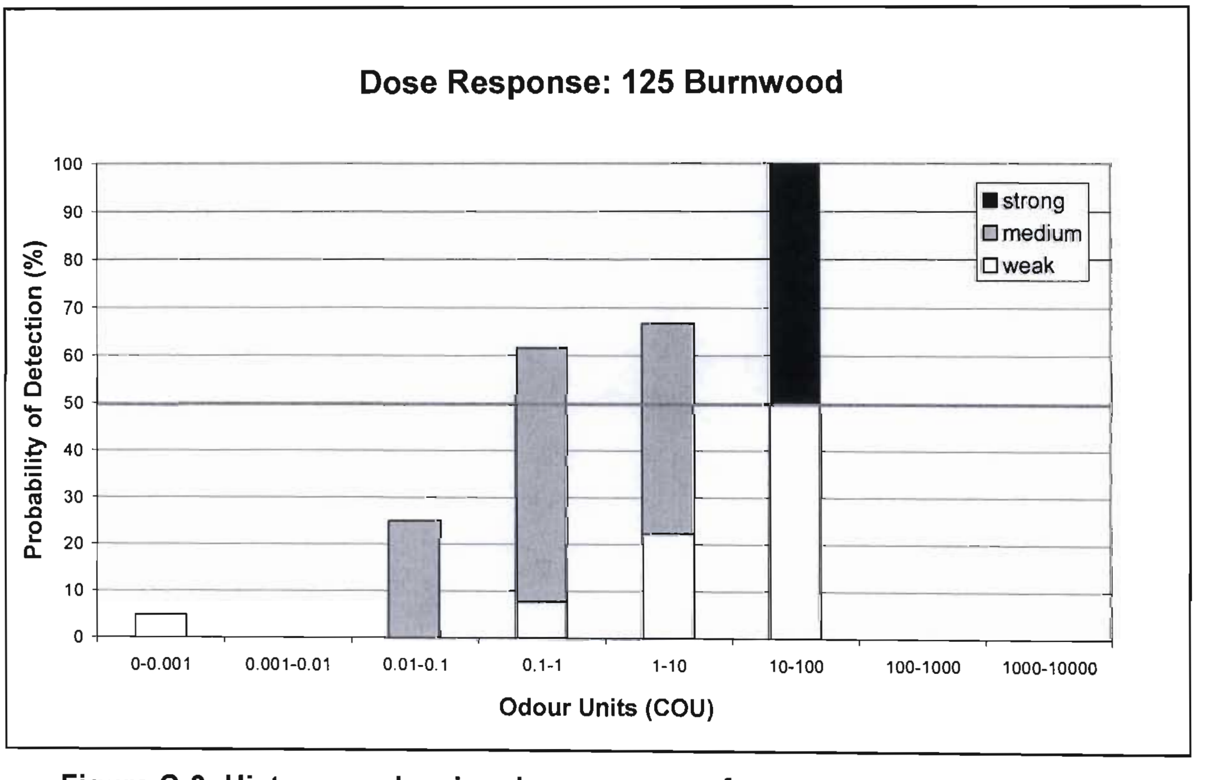


Figure C-3: Histogram showing dose response for receptor at 125 Burnwood

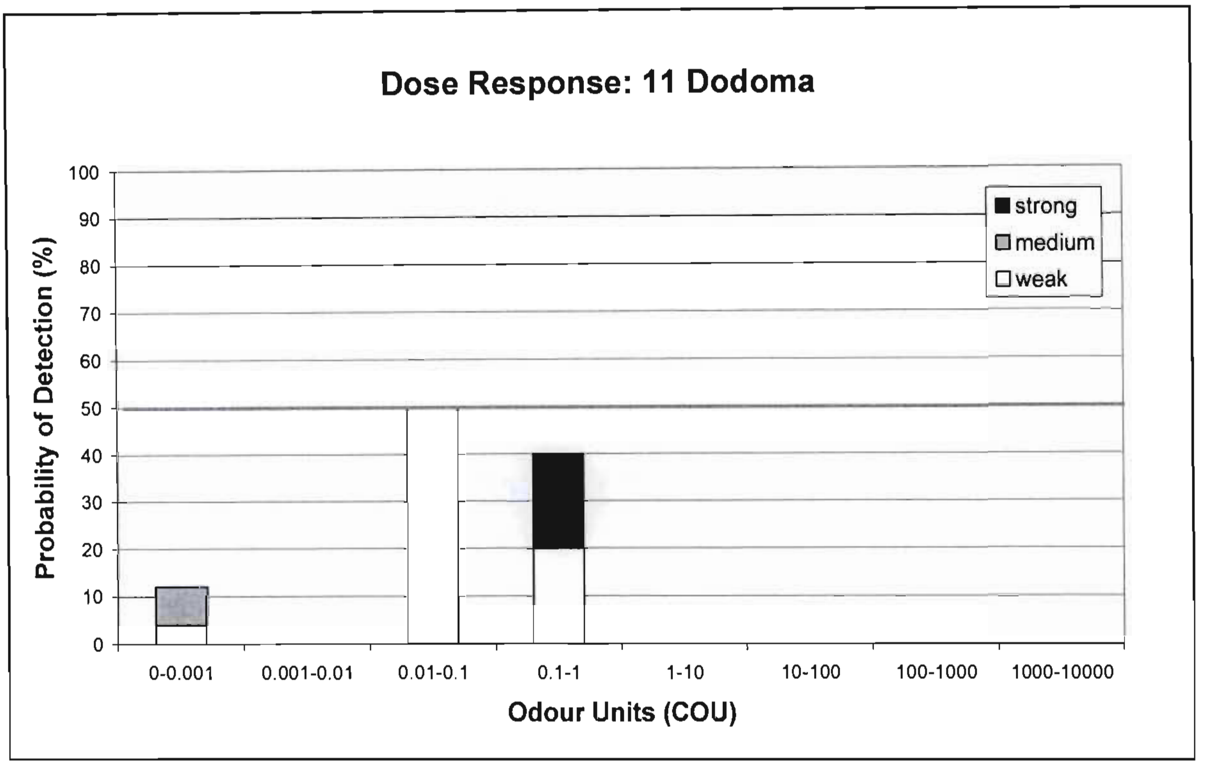


Figure C-4: Histogram showing dose response for receptor at 11 Dodoma

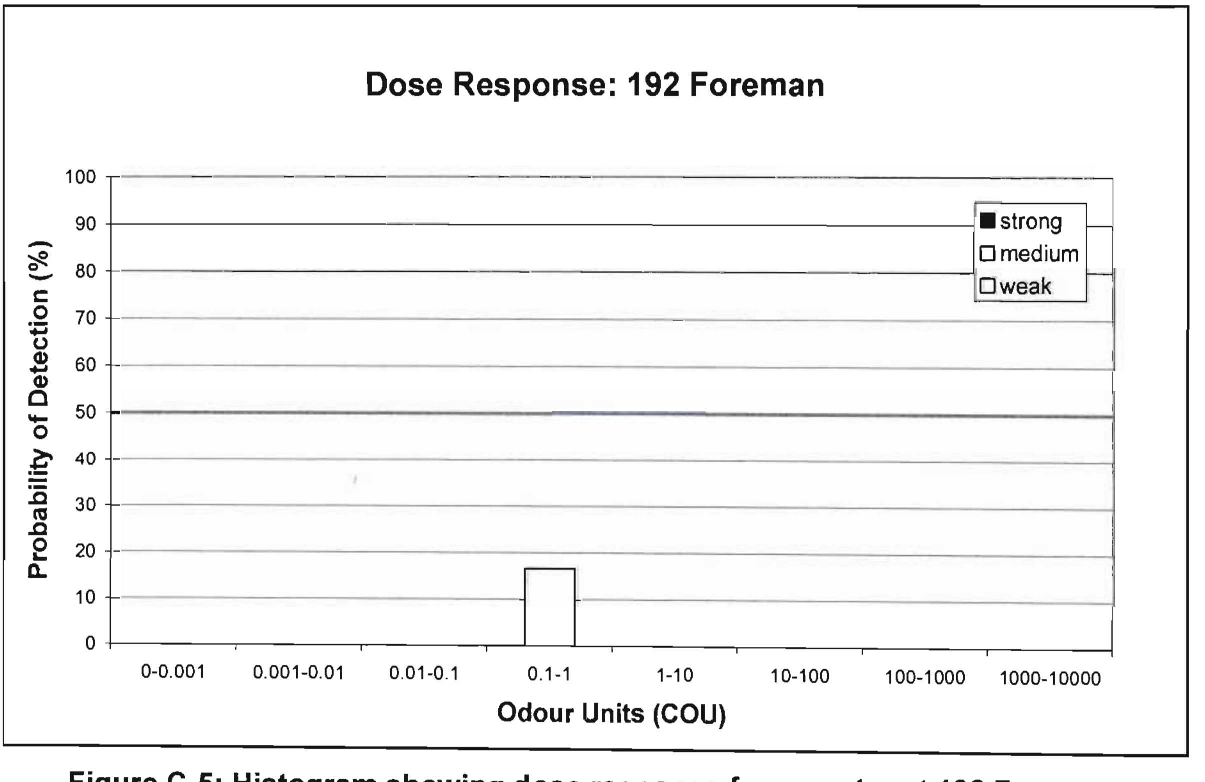


Figure C-5: Histogram showing dose response for receptor at 192 Foreman

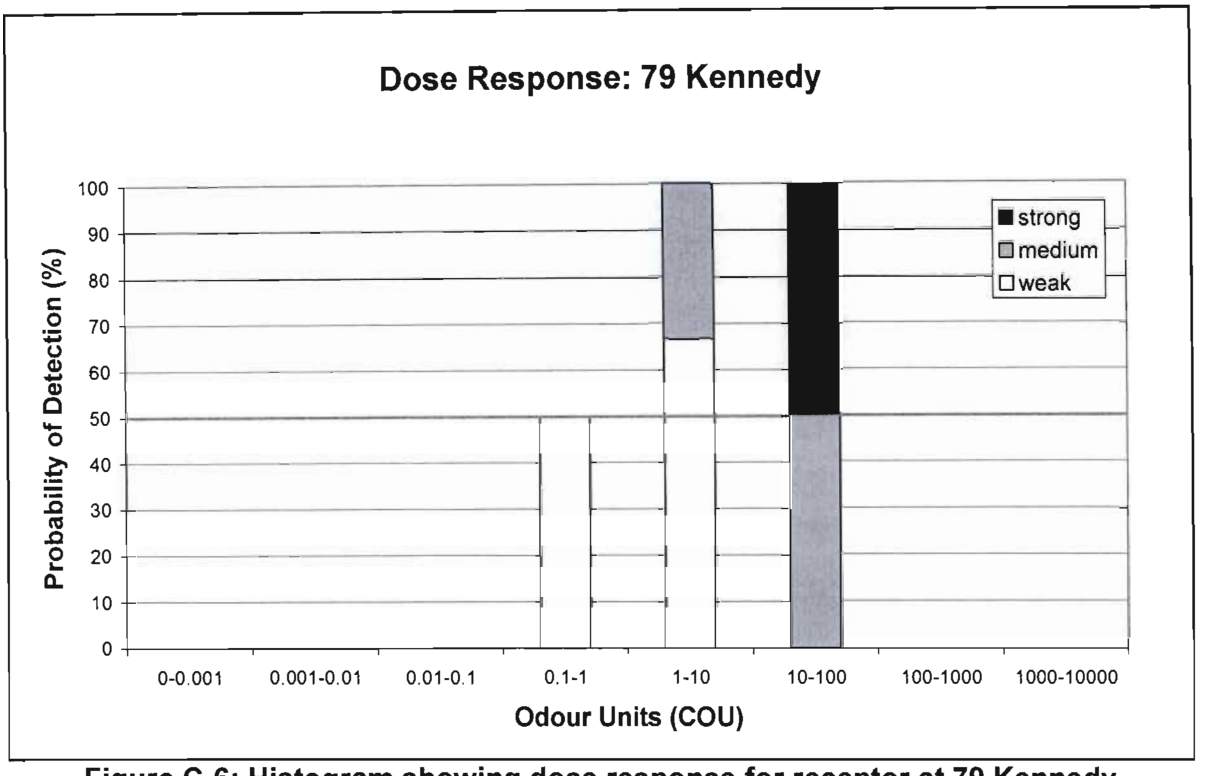


Figure C-6: Histogram showing dose response for receptor at 79 Kennedy

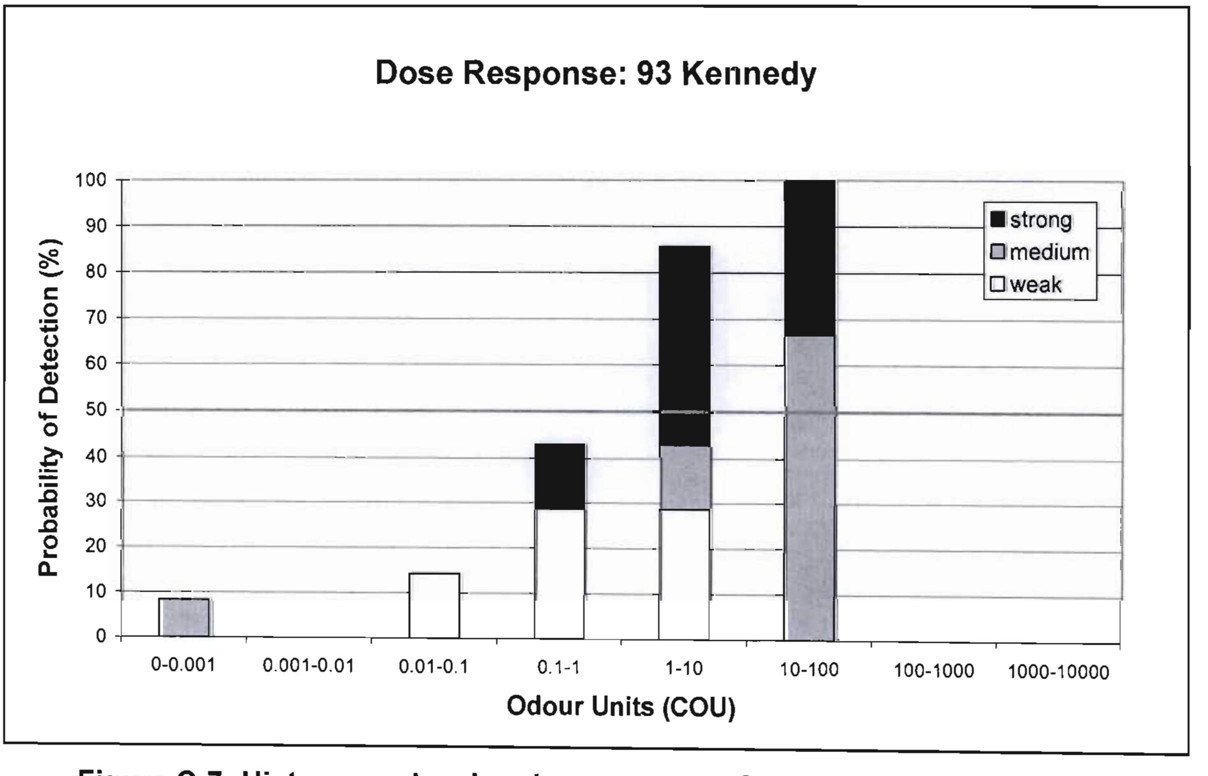


Figure C-7: Histogram showing dose response for receptor at 93 Kennedy

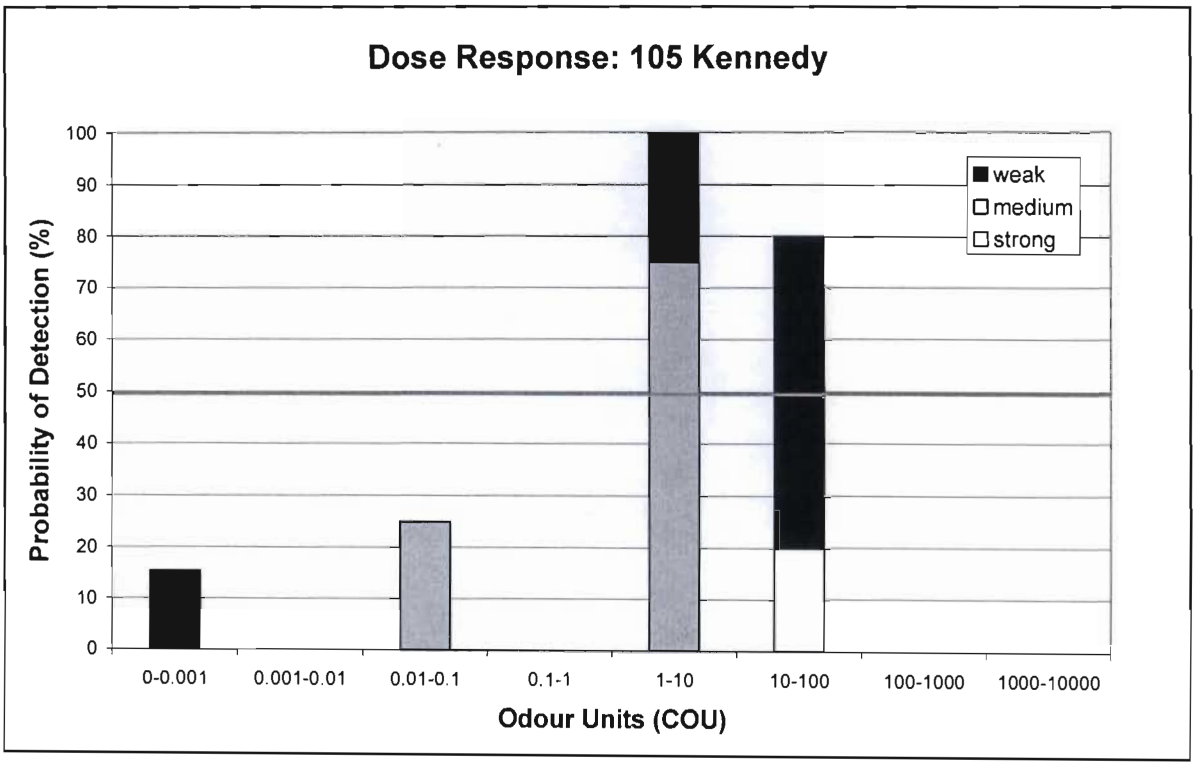


Figure C-8: Histogram showing dose response for receptor at 105 Kennedy

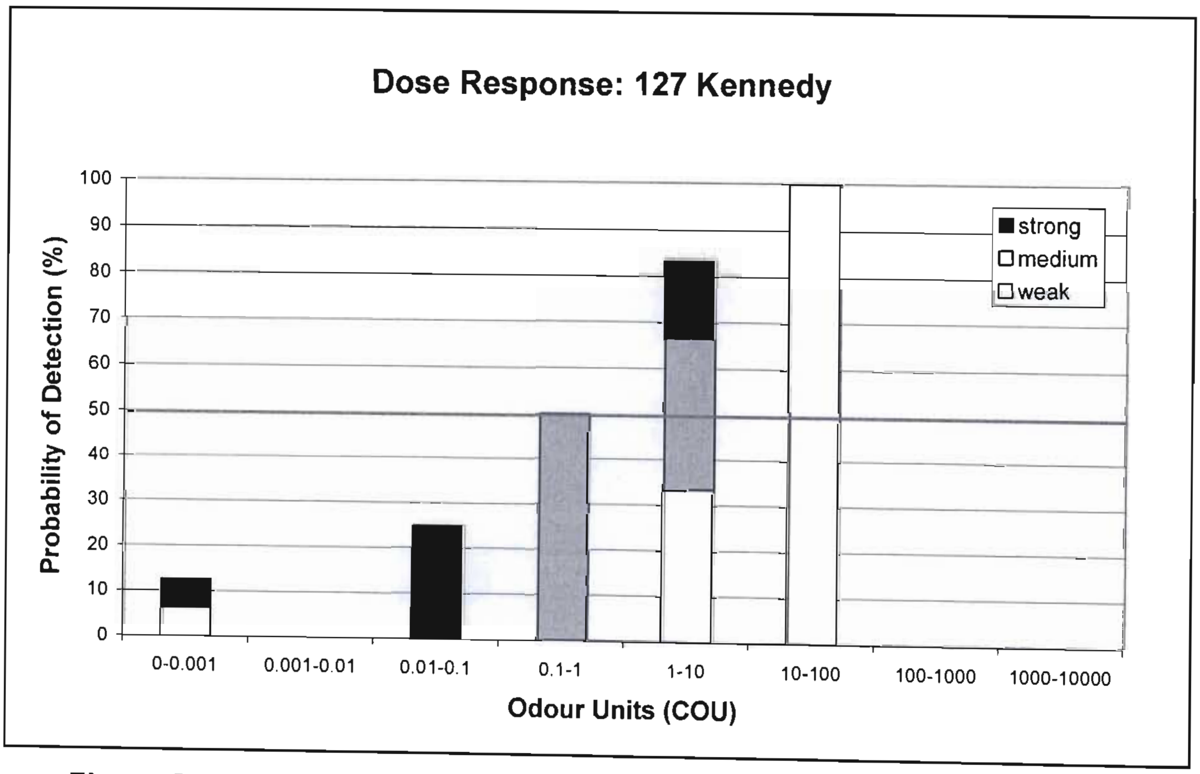


Figure C-9: Histogram showing dose response for receptor at 127 Kennedy

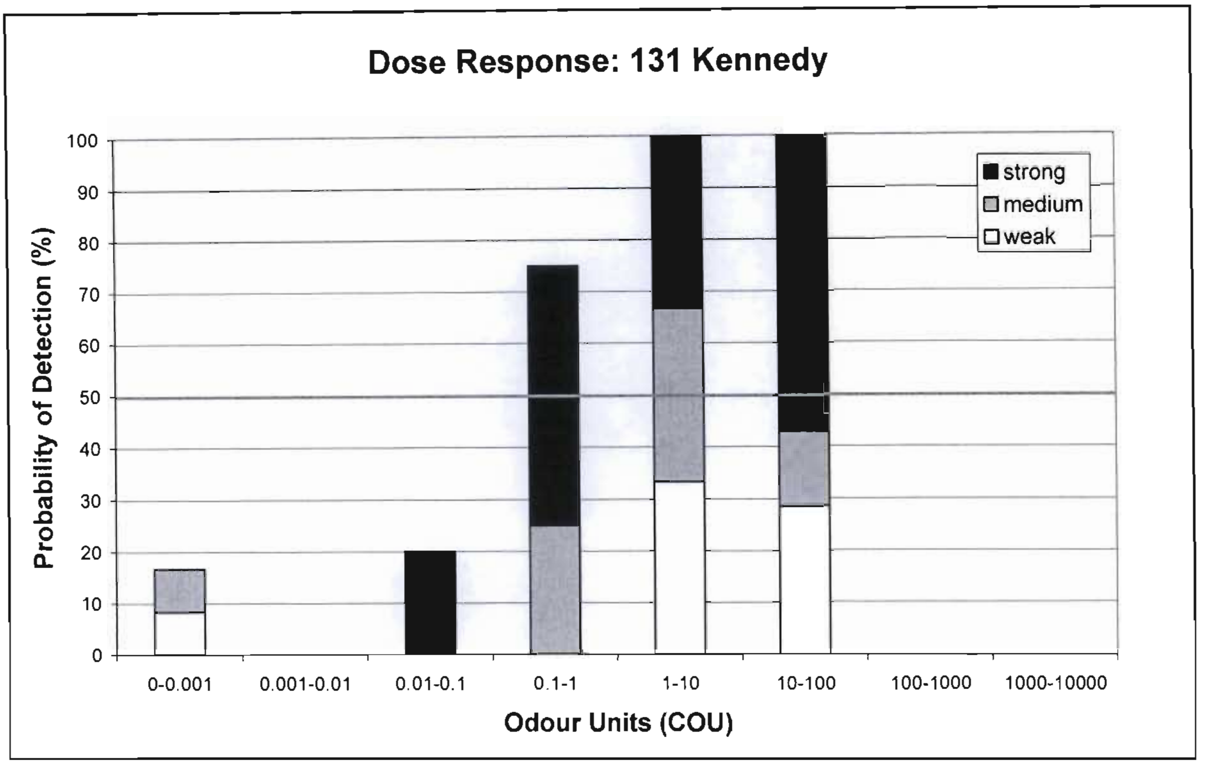


Figure C-10: Histogram showing dose response for receptor at 131 Kennedy

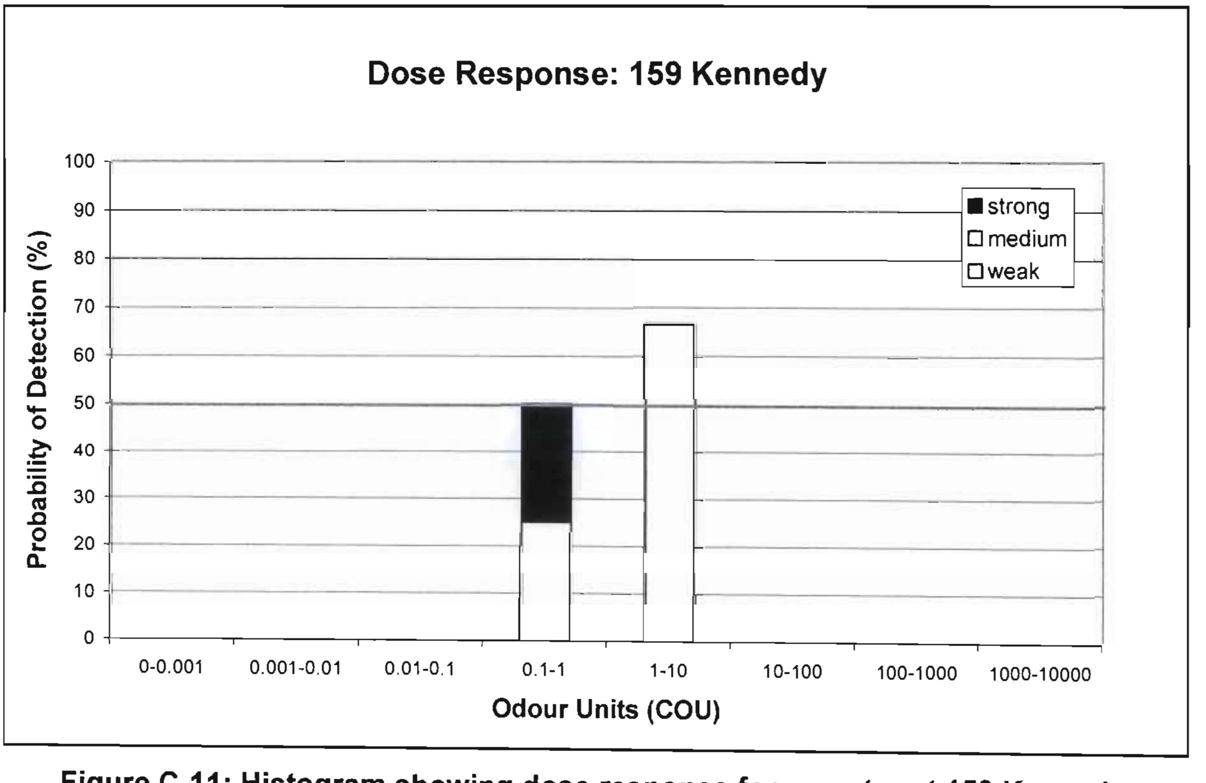


Figure C-11: Histogram showing dose response for receptor at 159 Kennedy

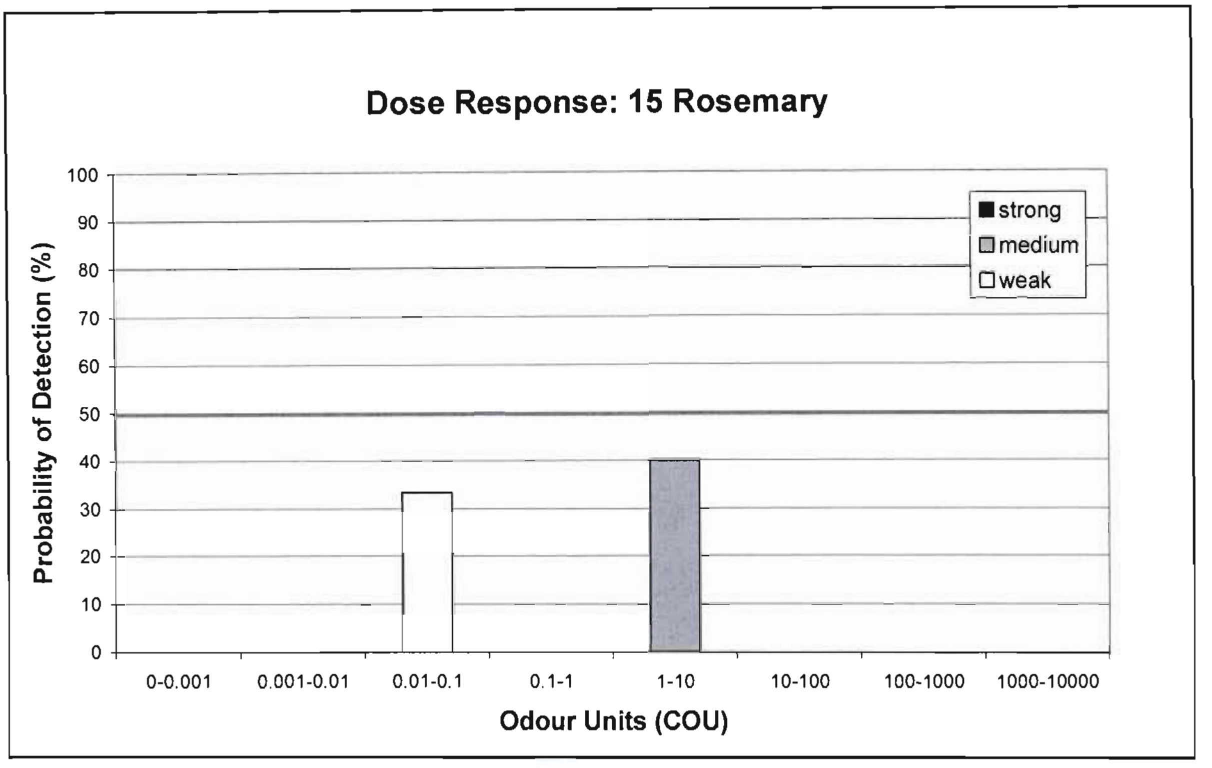


Figure C-12: Histogram showing dose response for receptor at 15 Rosemary

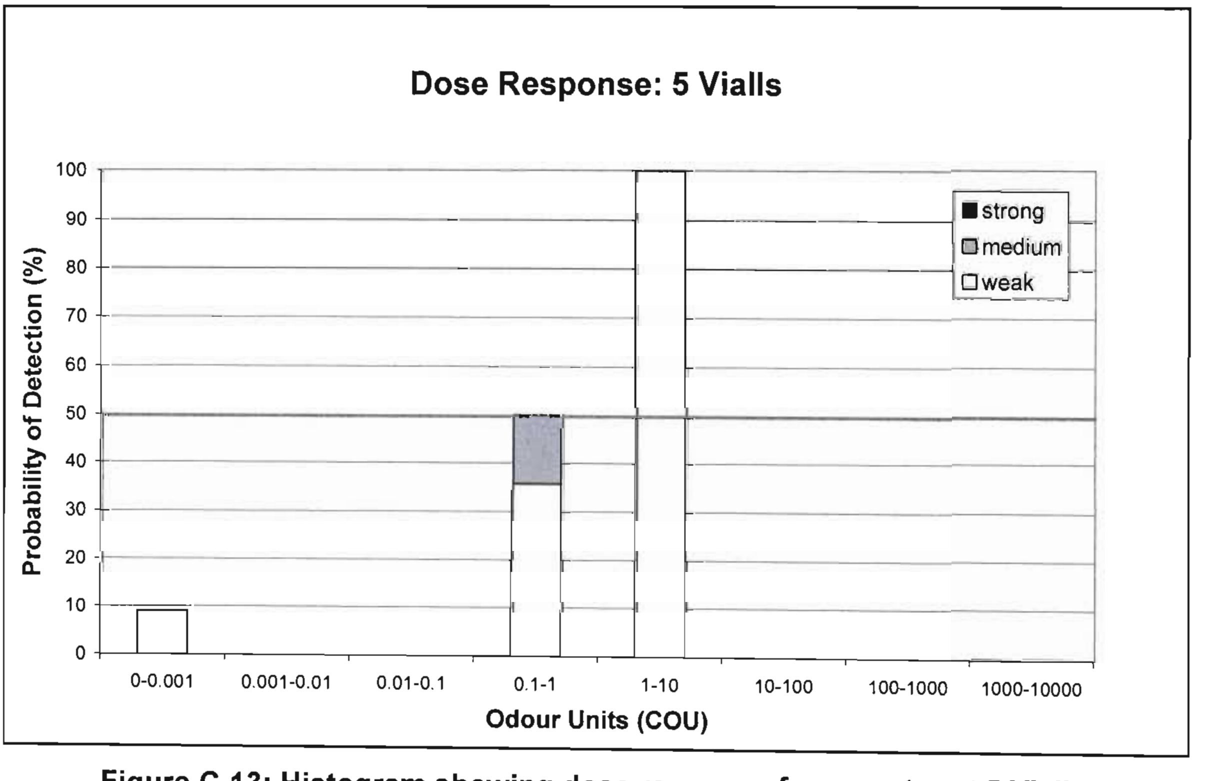


Figure C-13: Histogram showing dose response for receptor at 5 Vialls

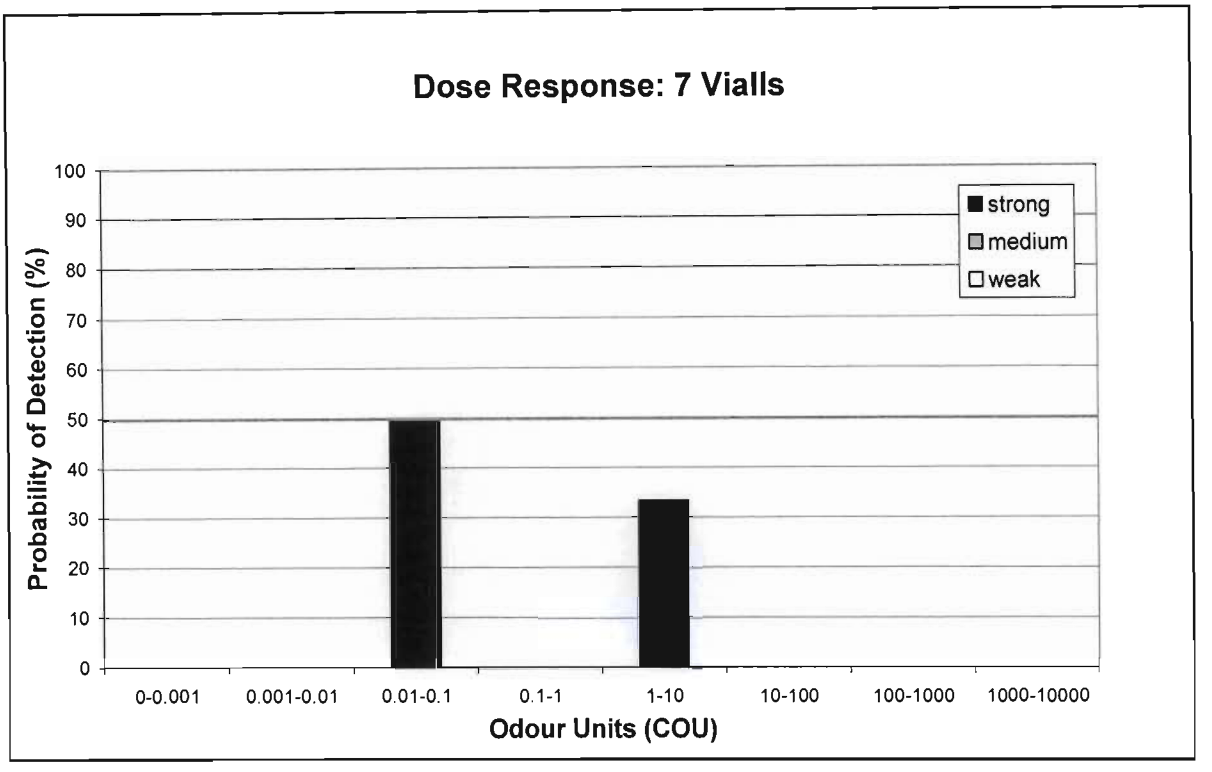


Figure C-14: Histogram showing dose response for receptor at 7 Vialls

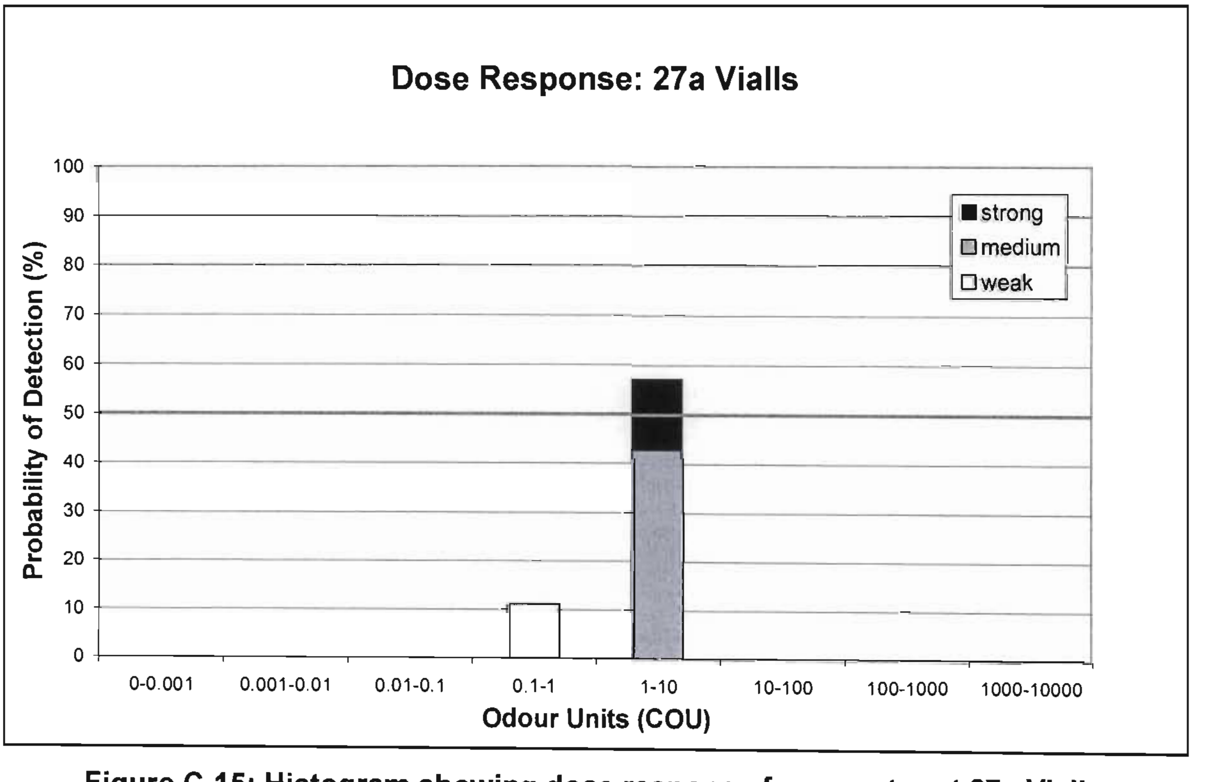


Figure C-15: Histogram showing dose response for receptor at 27a Vialls

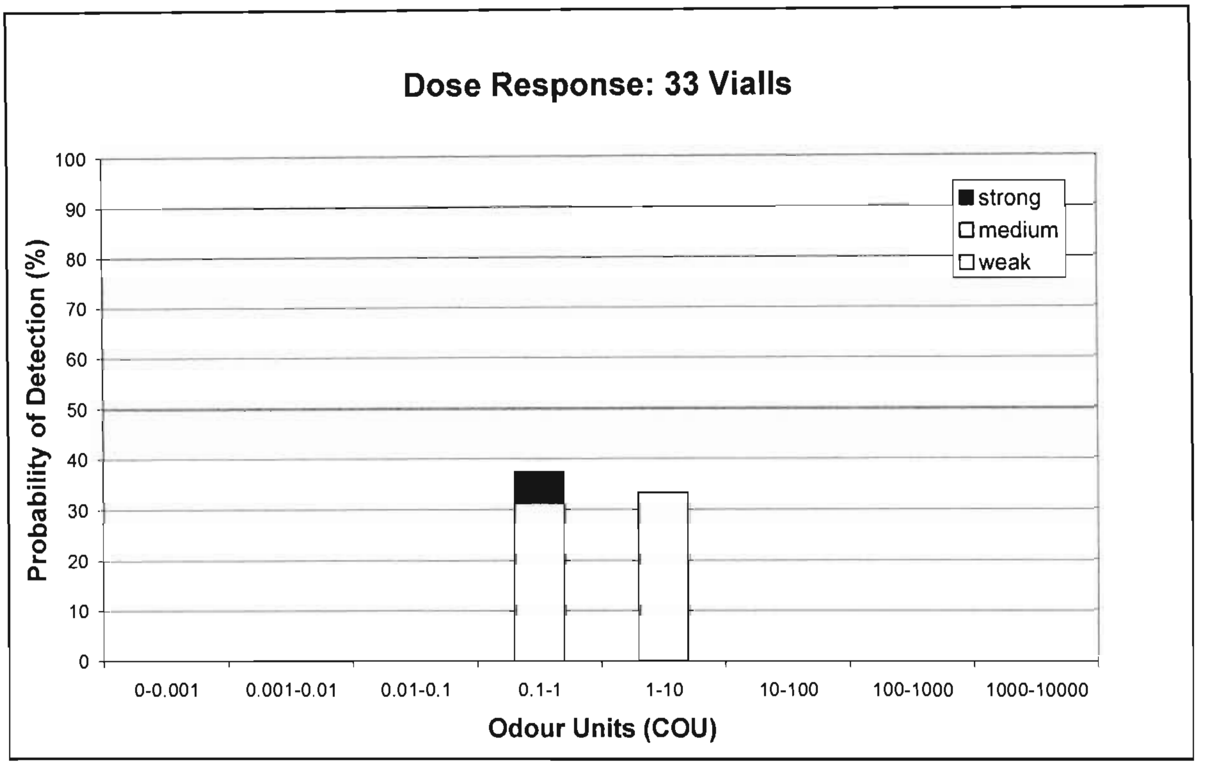


Figure C-16: Histogram showing dose response for receptor at 33 Vialls

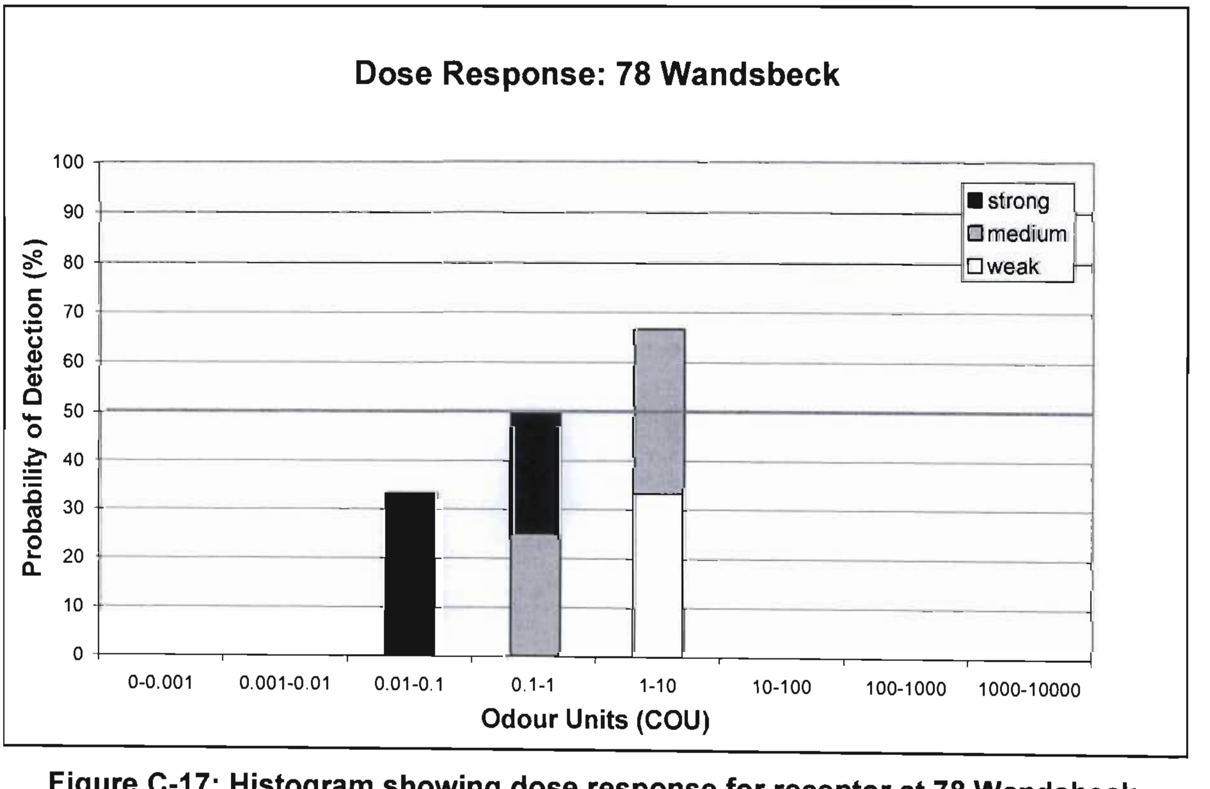


Figure C-17: Histogram showing dose response for receptor at 78 Wandsbeck

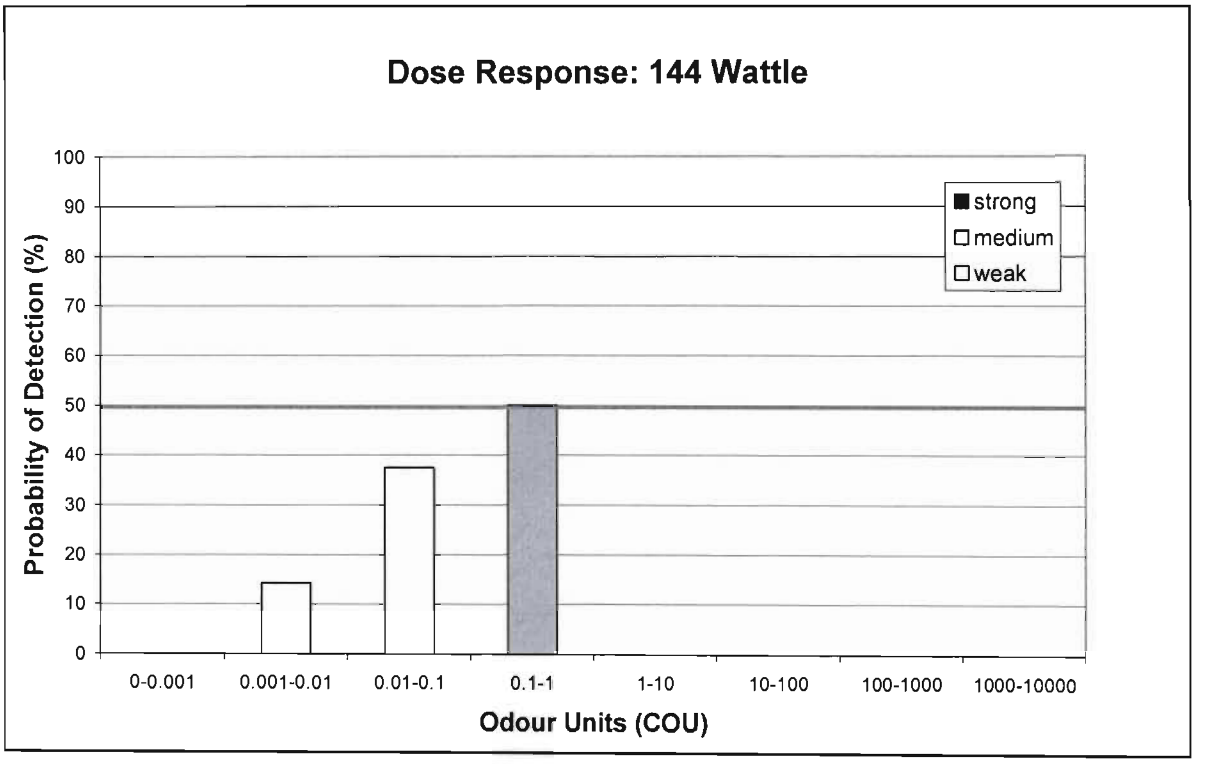


Figure C-18: Histogram showing dose response for receptor at 144 Wattle

Table C-1: Summary of raw data used to generate histograms for each receptor. 2004 survey.

	Number of Odour Observations per Concentration Range							
	0-0.001	0.001-0.01	0.01-0.1	0.1-1	1-10	10-100	100-1000	1000-10000
34 Burnwood								
0	25	3		2	2			
1	2			2				
2	1							
3				2	1			
60 Burnwood								
0	18	2	2	1				
1				1				
2	1	1		1	1			
3					2			
125 Burnwood								
0	20		3	5	3			
1	1			1	2	1		
2			1	7	4			
3						1		
11 Dodoma								
0	22	1	2	3				
1	1		2	1				
2								
3				1				
192 Foreman								
0	11		6	5	3	1		
1				1				
2								
3								
79 Kennedy								
0	7	1	2	1				
1				1	2			
2					1	1		
3						1		
93 Kennedy								
0	11	2	6	4	1			
1			1	2	2			
2	1				1	2		
3				1	3	1		
105 Kennedy								
0	11	4	3	1		1		
1	2				1	3		
2			1		3			
3						1		
127 Kennedy								
0	14	1	3	1	1			
1	1				2	3		
2				1	2			
3	1		1		1			
131 Kennedy								
0	10	1	4	1				
1	1				1	2		
2	1			1	2	1		
3			1	2	2	4		

Table is continued on next page......

	0-0.001	0.001-0.01	0.01-0.1	0.1-1	1-10	10-100	100-1000	1000-10000
159 Kennedy								
0	9	3	4	2	1			
1				1	2			
2								
3				1				
15 Rosemary								
0	13	1	2	2	6			
1			1					
2					4			
3								
Site Office								
0	21		2	5	7			
1			1	3	15			
2				2	7			
3					1	1		
5 Vialls								
0	10	1	1	7				
1	1			5	1			
2				2				
3								
7 Vialls								
0	9	2	1	13	2			
1								
2								
3			1		1			
27a Vialls								
0	10	1	1	8	3			
1				1				
2					3			
3					1			
33 Vialls								
0	11		2	10	4			
1				5	2			
2								
3				1				
78 Wandsbeck								
0	9		2	2	1			
1					1			
2				1	1			
3			1	1				
144 Wattle								
0	17	6	5	2				
1		1	3					
2				2				
3								

APPENDIX D: RECORD OF RECEPTOR OBSERVATIONS AND ODOUR PREDICTIONS

34 Burnwood Road
Co-ordinates:

x	*y*
-1730	-3300214

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
26/01/04	13:28	-	0	1a	0	0
04/02/2004	13:30	1	1	1a	0	0
06/02/2004	12:40	-	0	1a	8.81025	0.041866875
06/02/2004	13:30	1	3	1a	0.60530875	0.096142375
09/02/2004	11:22	-	0	1a	0	0
16/2/04	14:30	-	0	1a	0	0
01/03/2004	12:48	-	0	1a	0	0.000139126
17/03/04	13:50	-	0	1a	0	0
19/03/04	10:51	-	0	1a	0	0.000199279
23/03/04	14:56	-	0	1a	0	0
29/03/04	14:21	-	0	1a	0	0
02/04/04	10:24	-	0	1a	0	0.000618829
06/04/04	10:11	-	0	1a	0	0
20/04/04	10:39	-	0	1a	0.04629068	0.074765875
29/04/04	12:21	-	0	1a	0	0.002113719
04/05/04	15:32	-	0	1a	0	5.6529E-12
14/05/2004	12:52	-	0	1a	0	0
21/05/2004	10:14	-	0	1a	0	0
28/05/2004	9:00	1	2	1a	0	0
28/05/2004	11:00	-	0	1a	0.24466375	0.000897548
08/06/2004	13:17	-	0	1a	4.2429	1.51641E-05
11/06/2004	12:08	-	0	1a	0	0.002029869
11/06/2004	13:35	-	0	1a	0	0.001832453
14/06/2004	10:30	1	3	1a	0.08723275	0.16567075
15/06/2004	09:36	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:37	1	1	1a	4.62518E-05	0.11267616
23/06/2004	10:15	1	1	1a	0.514859213	0.078020386
19/07/2004	09:00	1	3	1a	3.071675	6.4388E-09
19/07/2004	10:28	1	1	1a	0	9.95485E-15
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/2004	11:20	-	0	2a	0	0
04/08/2004	12:19	-	0	2b	0	0
06/08/2004	10:45	-	0	2b	0	0
10/08/2004	12:25	-	0	2b	0	0
11/08/2004	11:12	-	0	2c	0	0
20/08/2004	13:12	-	0	2c	0	0
27/08/2004	12:15	-	0	2d	0	0
09/09/2004	10:37	-	0	2a	0	0
13/09/2004	10:35	-	0	2b	0	0
17/09/2004	13:56	-	0	2a	0	0
21/09/2004	11:15	-	0	2b	0	0
30/09/2004	10:05	-	0	2d	#VALUE!	#VALUE!
29/10/2004	9:15	-	0	2d	0	0
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
22/12/2004	10:55	-	0	3		
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

60 Burnwood Road
Co-ordinates:

x	*y*
-1628	-3300064

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	**Filling Location Reference #**	**ADMS Output** **Working Face (ou)**	**Transfer Station (ou)**
WORKING FACE AT RANDLES CELL 1a						
9/2/04	*07:45*	*1*	*3*	1a	1.97794	0.011797463
16/2/04	*14:50*	*-*	*0*	1a	0	4.23626E-17
01/03/04	*09:00*	*1*	*2*	1a	7.4318E-08	0
08/03/04	*07:54*	*1*	*2*	1a	0	0.00638974
19/03/04	*10:55*	*-*	*0*	1a	0	9.57103E-07
23/03/04	*15:05*	*-*	*0*	1a	0	0
29/03/04	*16:05*	*-*	*0*	1a	0	0
16/04/2004	*9:00*	*1*	*3*	1a	4.04121257	0.018241871
20/04/2004	*07:00*	*0*	*3*	1a	4.0923E-16	0
20/04/2004	*08:00*	*0*	*1*	1a	0	0
29/04/2004	*13:00*	*-*	*0*	1a	0	0.002113719
21/05/2004	*10:17*	*-*	*0*	1a	0	0
25/05/2004	*07:30*	*1*	*3*	1a	#VALUE!	#VALUE!
28/05/2004	*11:12*	*-*	*0*	1a	0.04387615	0.583058375
08/06/2004	*13:25*	*-*	*0*	1a	0	0
10/06/2004	*10:00*	*1*	*2*	1a	3.6739761	0.001013929
11/06/2004	*12:15*	*-*	*0*	1a	0	0.002623708
15/06/2004	*10:22*	*-*	*0*	1a	#VALUE!	#VALUE!
18/06/2004	*10:37*	*1*	*1*	1a	4.6252E-05	0.11267616
23/06/2004	*10:10*	*1*	*2*	1a	0.51485921	0.1320075
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/2004	*11:34*	*-*	*0*	2a	0	0
04/08/2004	*12:05*	*-*	*0*	2b	0	0
06/08/2004	*10:50*	*-*	*0*	2b	0	0
10/08/2004	*12:15*	*-*	*0*	2b	0	0
11/08/2004	*11:20*	*-*	*0*	2c	0	0
20/08/2004	*12:23*	*-*	*0*	2c	0	0
27/08/2004	*13:30*	*-*	*0*	2d	0	1.07691E-17
09/09/2004	*10:35*	*-*	*0*	2a	0	0
13/09/2004	*10:47*	*-*	*0*	2b	0	0.024371945
17/09/2004	*13:58*	*-*	*0*	2a	0	0
21/09/2004	*15:45*	*-*	*0*	2b	0	0.0372005
30/09/2004	*10:07*	*-*	*0*	2d	#VALUE!	#VALUE!
29/10/2004	*10:00*	*-*	*0*	2d	0	2.776E-15
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
WORKING FACE MOVED TO RANDLES CELL 1b 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

125 Burnwood Road
Co-ordinates:

x	*y*
-1641	-3299728

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
26/01/04	13:20	-	0	1a	0.219463375	0
29/01/04	13:30	-	0	1a	0.070734	0
30/01/04	08:30	1	2	1a	0.50647625	0
4/02/04	13:30	-	0	1a	0.185084375	0
5/02/04	09:05	1	2	1a	1.733641125	0
5/02/04	14:15	-	0	1a	1.44883625	0
06/02/2004	09:00	1	1	1a	0.250025	0
06/02/2004	12:30	-	0	1a	1.69123E-19	0.44988875
12/02/2004	09:50	1	2	1a	0.274508	0
18/02/04	14:30	1	2	1a	0.601625	0
01/03/2004	11:31	-	0	1a	0	0.058768125
08/03/2004	09:00	1	1	1a	0	0.000510754
08/03/2004	17:43	-	0	1a	0	3.27461E-07
19/03/04	10:52	-	0	1a	0	4.59667E-12
22/03/04	06:40	1	3	1a	#VALUE!	#VALUE!
24/03/04	08:30	1	1	1a	16.55875	0
24/03/04	09:30	-	0	1a	3.870975	0
31/03/04	08:00	1	2	1a	3.215275	0
31/03/2004	11:00	1	1	1a	1.79499	0
02/04/2004	11:40	-	0	1a	0	1.21846E-09
03/04/2004	23:00	1	2	1a	#VALUE!	#VALUE!
06/04/2004	09:00	1	2	1a	7.5651625	0
06/04/2004	10:23	-	0	1a	1.3404825	0
13/04/2004	09:30	0	2	1a	#VALUE!	#VALUE!
13/04/2004	15:19	-	0	1a	0	0
20/04/2004	09:00	1	2	1a	0.203857875	0.000110216
20/04/2004	11:06	-	0	1a	0	0.03883516
20/04/2004	13:54	-	0	1a	0	0.001777608
26/04/2004	09:45	1	2	1a	0.08276825	0
26/04/2004	10:21	1	1	1a	2.4436	0
29/04/2004	12:36	-	0	1a	0	0
04/05/2004	15:37	-	0	1a	0	0
14/05/2004	10:00	1	2	1a	1.166195188	2.31448E-11
14/05/2004	12:56	-	0	1a	0.228900453	0
18/05/2004	08:30	1	3	1a	10.28575	0
18/05/2004	09:00	1	3	1a	#VALUE!	#VALUE!
19/05/2004	13:00	1	2	1a	0.118000638	0
19/05/2004	17:43	-	0	1a	0.000173065	0
21/05/2004	13:10	-	0	1a	0.233384875	0
25/05/2004	07:00	1	3	1a	#VALUE!	#VALUE!
28/05/2004	12:30	-	0	1a	0	2.35133E-09
08/06/2004	11:40	1	2	1a	0.10825	0
11/06/2004	12:14	-	0	1a	0	0

11/06/2004	13:35	-	0	1a	0	0
15/06/2004	09:31	1	1	1a	#VALUE!	#VALUE!
18/06/2004	10:36	-	0	1a	0	0.002762233
23/06/2004	10:18	1	2	1a	0	0.243330913
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/2004	11:15	-	0	2a	0.000029751	0
04/08/2004	12:00	-	0	2b	1.93481E-14	0
06/08/2004	10:47	-	0	2b	5.74408E-05	0
10/08/2004	12:27	-	0	2b	1.62989E-07	0
11/08/2004	11:15	-	0	2c	1.55258E-05	0
20/08/2004	15:51	-	0	2c	0	4.22543E-21
27/08/2004	14:53	-	0	2d	0	0
09/09/2004	10:30	-	0	2a	3.81326E-05	0
13/09/2004	11:10	-	0	2b	0	5.46095E-17
17/09/2004	16:30	-	0	2a	0.003202675	0
21/09/2004	15:58	-	0	2b	0	5.19875E-05
30/09/2004	10:10	-	0	2d	#VALUE!	#VALUE!
29/10/2004	9:20	-	0	2d	0	0
25/11/2004	11:13	-	0	2d	3.66719E-25	0
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
22/12/2004	11:00	-	0	3	#VALUE!	#VALUE!
WORKING FACE MOVED TO RANDLES CELL 1b 11/01/05						
12/01/2005	10:20	-	0	1b	#VALUE!	#VALUE!
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 1b 08/03/05						

11 Dodoma
Co-ordinates:

x	*y*
-2048	-3298796

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
26/01/04	12:00	1	1	1a	0.13466325	0.008199438
26/01/2004	14:30	-	0	1a	0.000168885	7.94656E-23
09/02/2004	11:31	-	0	1a	0	8.40827E-11
16/02/2004	14:14	-	0	1a	0.036726538	0.025417613
23/02/2004	08:00	1	2	1a	1.94562E-05	0
01/03/2004	14:05	-	0	1a	0	3.70688E-20
17/03/2004	14:20	-	0	1a	0	1.22192E-11
19/03/2004	14:48	-	0	1a	0	0
23/03/2004	15:19	-	0	1a	0	0
29/03/2004	11:00	1	1	1a	6.08785E-07	1.38327E-23
29/03/2004	14:25	-	0	1a	1.35419E-06	6.49706E-21
06/04/2004	10:31	-	0	1a	0.000944495	1.34769E-10
13/04/2004	15:00	-	0	1a	0	0
29/04/2004	12:41	-	0	1a	0	2.14514E-27
04/05/2004	15:39	-	0	1a	0	8.72719E-14
14/05/2004	13:11	-	0	1a	0.05566425	0.000642887
19/05/2004	17:55	-	0	1a	3.15661E-28	0
21/05/2004	11:00	-	0	1a	0.000322356	9.74529E-12
28/05/2004	11:08	-	0	1a	0	5.24074E-28
08/06/2004	14:01	-	0	1a	0.001134138	4.10924E-12
11/06/2004	10:00	1	2	1a	0	0
11/06/2004	12:25	-	0	1a	0	2.35359E-26
15/06/2004	09:45	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:56	-	0	1a	0	0
23/06/2004	11:20	-	0	1a	0	0
19/07/2004	10:00	1	1	1a	#VALUE!	#VALUE!
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/2004	14:30	1	1	2a	0.015163375	4.94248E-22
04/08/2004	12:45	-	0	2b	0.3347975	0.028964263
11/08/2004	12:00	-	0	2c	0.3535925	7.0257E-05
27/08/2004	13:33	-	0	2d	0	1.14738E-10
09/09/2004	10:34	1	1	2a	0.040709938	3.31223E-17
13/09/2004	12:30	-	0	2b	0	5.25333E-22
17/09/2004	13:59	-	0	2a	0.164844955	0.026465725
21/09/2004	16:05	-	0	2b	0	0
30/09/2004	9:40	-	0	2d	#VALUE!	#VALUE!
29/10/2004	10:02	-	0	2d	0	7.09084E-14
15/11/2004	11:26	-	0	2b	0	1.18798E-08
19/11/2004	10:57	-	0	2c	0	0
25/11/2004	11:14	1	3	2d	0.353732875	0.003945875
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

192 Foreman
Co-ordinates:

x	*y*
-2225	-3300188

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Locatio Reference #	ADMS Output Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
04/02/04	12:42	-	0	1a	0.011287734	0.000137046
09/02/04	11:32	-	0	1a	0.054307625	0.0127415
16/02/04	14:42	-	0	1a	0.058609019	0.009042738
17/03/04	14:27	-	0	1a	0.67405875	0.010479975
19/03/04	14:15	-	0	1a	0.820536	0.041836
29/03/04	14:40	-	0	1a	0	0
02/04/04	10:44	-	0	1a	0.901287	0.115245
13/04/04	15:23	-	0	1a	5.19164	0.115181
29/04/04	12:42	-	0	1a	0.4626525	0.034790625
14/05/04	14:35	-	0	1a	0	0
21/05/04	13:00	-	0	1a	0	0
28/05/04	11:02	-	0	1a	0.30045475	0.002218611
08/06/04	14:24	-	0	1a	0	0
15/06/04	10:03	-	0	1a	#VALUE!	#VALUE!
18/06/04	10:45	-	0	1a	10.0835625	0.12936725
23/06/04	12:00	-	0	1a	2.36855375	0.028309288
19/07/04	09:50	-	0	1a	0.743695	0.0112901
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/04	11:40	-	0	2a	0	0
06/08/04	11:30	-	0	2b	0	0
10/08/04	12:00	-	0	2b	0	0
11/08/04	12:10	-	0	2c	0	0
27/08/04	13:52	-	0	2d	0	0
09/09/04	10:42	-	0	2a	9.45745E-13	0.045969875
13/09/04	12:00	-	0	2b	0	0
17/09/04	14:00	-	0	2a	3.45631E-13	0.037096375
30/09/2004	9:45	-	0	2d	0	0
29/10/2004	10:32	-	0	2d	#VALUE!	#VALUE!
15/11/2004	11:39	-	0	2b	0	2.70944E-05
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:21	1	1	1b	0	0.018499902
18/01/2005	14:30	1	3	1b	0.13831575	0
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

79 Kennedy
Co-ordinates:

x	*y*
-2347	-3299657

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

					ADMS Output	
Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
8/03/04	17:23	-	0	1a	1.2189E-13	0.007319175
19/03/04	10:00	-	0	1a	0.001363	0.037364875
29/03/04	14:45	-	0	1a	0	0
15/06/04	10:35	-	0	1a	#VALUE!	#VALUE!
18/06/04	11:00	0	1	1a	0	0.01188704
23/06/04	10:35	-	0	1a	0	1.89408E-10
19/07/04	09:30	-	0	1a	0	0
WORKING FACE MOVED TO BENONI CELL 20/07/04						
04/08/04	12:30	-	0	2b	0	0
06/08/04	10:35	-	0	2b	0	0
10/08/04	12:50	-	0	2b	0	0
11/08/04	11:30	-	0	2c	0	0
27/08/04	12:50	1	1	2d	0.334434	0.067231875
27/08/04	14:38	-	0	2d	0.09989963	0.046249
13/09/04	10:40	1	2	2b	14.6665625	1.25723E-05
21/09/04	10:55	1	3	2b	10.78315	0.000347894
30/09/04	10:35	1	3	2d	#VALUE!	#VALUE!
19/11/04	10:49	1	1	2c	3.9785875	0.019683388
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/04	12:27	1	1	3	3.26035	0.034678075
05/1/05	10:25	1	2	3	4.879675	0.065921625
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:25	-	0	1b	0.00082533	0.006186575
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

93 Kennedy Rd
Co-ordinates:

x	*y*
-2314	-3299624

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Locatio Reference #	ADMS Output Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
26/01/04	13:41	-	0	1a	0	0
04/02/04	12:42	1	3	1a	0.82439	0.060359
09/02/04	11:40	1	1	1a	0.147613375	0.036554625
17/03/04	14:28	-	0	1a	0.60570375	0.052536375
19/03/04	14:13	-	0	1a	4.31042E-07	0.035746625
23/03/04	15:20	-	0	1a	0	0
29/03/04	14:47	-	0	1a	0	0
02/04/04	10:50	-	0	1a	8.27233E-09	0.021391963
06/04/04	10:20	-	0	1a	0	0
13/04/04	15:25	-	0	1a	0.000683269	0.07631725
16/04/04	15:41	-	0	1a	0.863609875	0.0564365
26/04/04	16:05	old waste	2	1a	0	0
29/04/04	12:46	-	0	1a	0.010380263	0.014429013
04/05/04	16:01	-	0	1a	0.004122648	0.022869538
14/05/04	14:33	-	0	1a	0.3323295	0
21/05/04	11:01	-	0	1a	0	0
28/05/04	11:00	-	0	1a	1.91493E-08	0.10246
15/06/04	10:07	-	0	1a	#VALUE!	#VALUE!
18/06/04	11:00	0	1	1a	0	0.011607471
23/06/04	10:30	-	0	1a	0	0
19/07/04	10:41	-	0	1a	0	0.004879556
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/04	11:42	-	0	2a	0	0
04/08/04	12:31	-	0	2b	0	0
06/08/04	11:40	-	0	2b	0	0
10/08/04	12:40	-	0	2b	0	0
11/08/04	11:35	-	0	2c	0	0
20/08/04	12:25	1	1	2c	0.208127875	0.05031625
27/08/04	12:30	1	2	2d	1.128043925	0.029843825
27/08/04	14:37	1	1	2d	0.035913388	0.04648825
13/09/04	10:43	1	3	2b	31.3425	7.05173E-05
17/09/04	14:04	1	2	2a	35.801125	0.000593304
21/09/2004	10:45	1	3	2b	8.643775	0.001743047
21/09/2004	11:30	1	3	2b	3.949575	0.01225105
21/09/2004	16:00	1	2	2b	14.89565	2.58509E-05
30/09/2004	10:30	1	3	2d	#VALUE!	#VALUE!
01/10/2004	12:34	1	3	2d	5.41565	0.005414258
22/10/2004	13:42	1	2	2c	0	0
19/11/2004	10:47	1	1	2c	3.3839375	0.018355838
24/11/2004	11:32	-	0	2d	3.6614375	0.003293525
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
22/12/2004	12:26	-	0	3	#VALUE!	#VALUE!
05/01/2005	10:27	1	1	3	5.6187875	0.07739975
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:26	-	0	1b	6.55995E-06	0.004916025
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

105 Kennedy Rd
Co-ordinates:

x	*y*
-2314	-3299624

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
17/03/04	14:41:00	-	0	1a	0.41363088	0.0543935
29/03/04	14:52:00	-	0	1a	0	0
02/04/04	11:50	-	0	1a	2.3994E-11	0.024401313
06/04/2004	11:02:00	-	0	1a	0	0
26/04/2004	15:45	decay/old waste	3	1a	0	0
26/04/2004	16:10	old waste	2	1a	0	0
26/04/2004	16:50	old waste/GAS	1	1a	0	0
26/04/2004	17:20	old waste/gas	1	1a	0	0
29/04/2004	14:35	-	0	1a	1.1976E-06	0.004744715
	23:00:00	0	3	1a	#VALUE!	#VALUE!
04/05/2004	15:27:00	-	0	1a	0.00192894	0.03022025
14/05/2004	13:37:00	-	0	1a	0	0
19/05/2004	18:10	-	0	1a	0	0
21/05/2004	13:25	-	0	1a	1.2126E-18	0
28/05/2004	10:47	-	0	1a	0	0
08/06/2004	14:24	-	0	1a	0	0
11/06/2004	12:32	-	0	1a	0.00723371	0.0081762
15/06/2004	10:11	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:58	-	0	1a	0	0.007136238
19/07/2004	11:00	-	0	1a	0	0.001808626
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/2004	11:59	-	0	2a	0	0
04/08/2004	13:50	1	1	2b	0	0
06/08/2004	11:42	0	1	2b	0	0
10/08/2004	12:30	0	2	2b	0	0
11/08/2004	11:37	0	1	2c	0	0
20/08/2004	12:27	1	2	2c	1.87079	0.0523035
27/08/2004	12:34	1	2	2d	1.99754	0.048774138
27/08/2004	13:58	1	2	2d	1.63487875	0.007388958
09/09/2004	10:03	1	2	2a	0.02467513	0
13/09/2004	10:45	1	1	2b	25.0267	2.05777E-05
17/09/2004	14:47	1	1	2a	34.44275	0.006322164
21/09/2004	11:00	1	1	2b	24.042825	0.00006523
30/09/2004	10:40	1	2	2d	#VALUE!	#VALUE!
22/10/2004	13:51	1	1	2c	0	0
15/11/2004	10:25	-	0	2b	75.945875	0.021865788
17/11/2004	09:18	1	3	2b	27.742375	0.0006782
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	12:37	1	1	3	1.1251625	0.007764114
22/12/2004	12:19	-	0	3	#VALUE!	#VALUE!
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:28	-	0	1b	7.3076E-09	0.003254453
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

127 Kennedy
Co-ordinates:

x	*y*
-2314	-3299624

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
04/02/04	12:47	1	3	1a	0.047419513	0
9/02/04	11:40	-	0	1a	0.000158143	0
01/03/04	13:04	-	0	1a	3.66445E-06	0
8/03/04	17:19	-	0	1a	0	0.000551023
17/03/04	09:00	1	3	1a	0	0
17/03/04	14:37	-	0	1a	0.187974375	0.066318375
23/03/04	15:21	-	0	1a	0	0
29/03/04	15:05	-	0	1a	0	0
02/04/04	12:17	-	0	1a	0	0.010357
06/04/04	10:58	-	0	1a	2.68393E-21	0
13/04/04	15:50	-	0	1a	2.88E-19	0.036561963
29/04/04	12:55	-	0	1a	5.63719E-09	0
04/05/2004	15:47	-	0	1a	1.20867E-05	0
14/05/2004	13:16	-	0	1a	4.55421E-05	0
17/05/2004	12:00	1	1	1a	4.8008E-25	0
19/05/2004	18:05	-	0	1a	0	0
21/05/2004	13:30	-	0	1a	3.84027E-05	0
07/06/2004	14:30	0	2	1a	2.01374E-06	0
11/06/2004	12:20	-	0	1a	9.15788E-10	0
15/06/2004	10:21	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:57	-	0	1a	0	0
19/07/2004	10:54	-	0	1a	0	0
WORKING FACE MOVED TO BENONI CELL 20/07/04						
04/08/2004	13:30	1	2	2b	9.41895	0
06/08/2004	11:45	1	1	2b	10.966	0
10/08/2004	12:32	-	0	2b	1.0988825	0
11/08/2004	11:50	1	1	2c	4.3779375	0
20/08/2004	15:55	1	1	2c	1.754555	3.17978E-06
27/08/2004	12:37	1	1	2d	35.03325	0.044897156
27/08/2004	13:56	1	1	2d	27.6585	0.00230822
09/09/2004	10:01:00	1	2	2a	0.503065	0
13/09/2004	10:50	-	0	2b	0	1.00321E-06
17/09/2004	14:05	1	3	2a	1.005779625	0.014422938
21/09/2004	11:05	-	0	2b	0	0.001839669
30/09/2004	10:45	-	0	2d	#VALUE!	#VALUE!
22/10/2004	13:58	1	2	2c	2.0011125	0
15/11/2004	10:06	-	0	2b	0	0.083085
19/11/2004	10:43	-	0	2c	#VALUE!	#VALUE!
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

MOVED HOME. NO LONGER LIVING AT THIS ADDRESS

131 Kennedy
Co-ordinates:

x	y
-2314	-3299624

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
17/03/04	09:00	0	3	1a	0	0
17/03/04	14:34	-	0	1a	0.087644125	0.06818025
20/04/2004	15:24	-	0	1a	0	3.95378E-07
29/04/2004	14:41	-	0	1a	0	0.000208594
04/05/2004	15:41	-	0	1a	1.49159E-07	0.019964469
21/05/2004	11:05	-	0	1a	0	0
28/05/2004	07:40	0	3	1a	#VALUE!	#VALUE!
28/05/2004	08:44	0	1	1a	#VALUE!	#VALUE!
28/05/2004	10:00	-	0	1a	0	0
18/06/2004	10:57	-	0	1a	0	0.0002806
23/06/2004	15:32	-	0	1a	1.35415E-06	0.0161947
19/07/2004	09:35	-	0	1a	0	0
WORKING FACE MOVED TO BENONI CELL 20/07/04						
04/08/2004	14:23	1	2	2b	7.1154875	0
06/08/2004	11:46	1	1	2b	10.8899875	0
10/08/2004	12:35	1	1	2b	1.537335	0
11/08/2004	11:55	1	1	2b	4.47373875	0
20/08/2004	16:00	1	2	2c	0	1.02513E-06
27/08/2004	9:30	1	3	2d	20.815625	0.00047519
27/08/2004	11:30	1	2	2d	19.30585	0.017878558
27/08/2004	13:55	1	1	2d	11.0333875	0.001301576
29/08/2004	11:30	1	3	2d	27.66895	0.207325194
09/09/2004	09:58	1	2	2a	0.36205975	0
13/09/2004	10:55	-	0	2b	0	2.70695E-07
14/09/2004	13:00	1	3	2d	19.0241	0.0711375
15/09/2004	18:00	1	3	2d	49.688875	1.224791913
17/09/2004	14:15	1	3	2a	0.667795	0.010726063
17/09/2004	14:30	1	3	2a	0.256849875	0.030202963
19/09/2004	11:00	1	3	2a	1.27480125	0
21/09/2004	11:07	-	0	2b	0	0.000884197
30/09/2004	10:47	-	0	2d	#VALUE!	#VALUE!
22/10/2004	14:08	1	2	2c	1.11280375	0
30/10/2004	09:40	1	3	2d	3.2696	0
15/11/2004	10:04	-	0	2b	0	0.071096875
19/11/2004	10:39	-	0	2c	0	0.00439756
26/11/2004	10:50	1	3	2d	50.506625	0.0241093
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	12:25	-	0	3	0.002749551	0.035276275
22/12/2004	12:02	1	2	3	#VALUE!	#VALUE!
05/01/2005	10:33	1	3	3	0.002578718	0.0532201
07/01/2005	11:46	1	1	3	1.12756E-21	1.79111E-05
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:28	-	0	1b	0	0.00032589
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

159 Kennedy
Co-ordinates:

x	*y*
-2314	-3299624

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
19/03/04	14:50	0	2	1a	0	0.005425488
29/03/04	15:13	-	0	1a	0	0
02/04/04	13:27	-	0	1a	0	0.001167979
06/04/2004	13:10	-	0	1a	2.75252E-09	0
13/04/2004	16:10	-	0	1a	0	0.000976931
16/04/2004	15:45	-	0	1a	1.36523E-11	0.013069538
29/04/2004	15:00	-	0	1a	0	3.68623E-05
04/05/2004	16:14	-	0	1a	0	0.000499496
18/05/2004	15:30	1	3	1a	5.71542E-06	0.111089375
19/05/2004	18:19	-	0	1a	0	0
21/05/2004	13:58	-	0	1a	0.003265359	0
28/05/2004	10:15	-	0	1a	0	0
08/06/2004	14:07	-	0	1a	2.54641E-08	0
19/07/2004	11:00	-	0	1a	0	6.70404E-06
WORKING FACE MOVED TO BENONI CELL 20/07/04						
26/07/2004	12:00	-	0	2a	0.013679038	0
04/08/2004	12:40	-	0	2b	5.32485	3.72269E-10
06/08/2004	11:47	1	1	2b	6.5537375	0
10/08/2004	12:43	1	1	2b	0.91248375	0
11/08/2004	11:59	1	1	2c	2.74592375	0
20/08/2004	12:32	-	0	2c	0	0.016759125
27/08/2004	12:45	-	0	2d	9.02364E-05	0.080298375
13/09/2004	10:57	-	0	2b	0	2.24798E-08
21/09/2004	11:10	-	0	2b	0	0.000136047
21/09/2004	16:09	-	0	2b	0	5.20845E-08
30/09/2004	10:50	-	0	2d	#VALUE!	#VALUE!
22/10/2004	14:10	-	0	2c	0.556706125	0
15/11/2004	11:41	-	0	2b	6.44483E-17	0.19024425
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

15 Rosemary
Co-ordinates:

x	*y*
-2370	-3300176

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
01/03/04	13:14	-	*0*	1a	0.647986375	0.028921025
18/03/04	08:30	*1*	*2*	1a	1.20466875	0.037315125
19/03/04	09:30	*1*	*2*	1a	1.09786625	0.0282215
19/03/04	14:44	-	*0*	1a	1.38561	0.02824275
24/03/04	11:03	-	*0*	1a	0	0
29/03/04	15:56	-	*0*	1a	0	0
02/04/04	13:35	-	*0*	1a	1.51891875	0.0292545
02/04/04	12:30	*1*	*2*	1a	1.37325	0.0272355
06/04/04	13:11	-	*0*	1a	0	0
13/04/04	15:59	-	*0*	1a	2.38451375	0.04454925
28/04/04	13:00	*1*	*2*	1a	0.98559	0.021501525
29/04/04	15:15	-	*0*	1a	1.64589875	0.018825738
21/05/04	10:38	-	*0*	1a	0	0
28/05/04	08:10	*0*	*3*	1a	#VALUE!	#VALUE!
28/05/04	10:20	-	*0*	1a	2.24771E-07	2.31883E-05
11/06/04	12:54	-	*0*	1a	0.65584625	0.006201838
18/06/04	10:47	-	*0*	1a	3.41538125	0.14863725
19/07/04	11:07	-	*0*	1a	6.3138875	0.1066125
WORKING FACE MOVED TO BENONI CELL 20/07/04						
04/08/04	14:00	-	*0*	2b	0	0
06/08/04	12:30	-	*0*	2b	0	0
10/08/04	13:02	-	*0*	2b	0	0
11/08/04	10:23	-	*0*	2c	0	0
20/08/04	12:46	-	*0*	2c	7.52573E-06	0.007650825
27/08/2004	16:27	-	*0*	2d	2.5059E-06	0.047962
09/09/2004	09:57	-	*0*	2a	0	0
17/09/2004	14:40	-	*0*	2a	0	0
21/09/2004	16:36	-	*0*	2b	0.026219313	0.0162121
15/11/2004	*11:54*	-	*0*	2b	0	2.3606E-07
24/11/2004	*11:23*	*1*	*1*	2d	0.008089824	0.028166763
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	*12:14*	-	*0*	3	0.020794438	0.016738813
05/01/2005	*10:20*	-	*0*	3	1.34815E-05	0.000429755
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

Site Office
Co-ordinates:

x	y
-1635	-3299318

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
26/01/04	09:00	1	2	1a	1.75	1.32
26/01/04	13:00	1	1	1a	0.9198875	0.4649025
26/01/04	14:00	1	1	1a	0.91487	0.40075625
27/01/04	08:45	1	2	1a	1.07987625	0.60768625
29/01/04	13:38	1	1	1a	1.04283625	0.34842875
30/01/04	10:50	1	1	1a	6.8525E-06	0.0117356
04/02/04	12:40	-	0	1a	0	0
04/02/04	13:36	1	2	1a	2.6479875	0.6471475
04/02/04	14:47	1	2	1a	1.02456875	0.311675
05/02/04	09:20	1	1	1a	0.496525413	0.189823375
05/02/04	11:22	1	3	1a	8.1298775	9.315545
05/02/04	14:25	1	1	1a	1.2044125	0.5064575
06/02/04	12:50	-	0	1a	0	0
09/02/04	11:35	-	0	1a	0	0
16/02/04	14:25	-	0	1a	0	3.45155E-12
23/02/04	14:19	1	2	1a	3.19942625	1.8851125
25/02/04	15:30	1	1	1a	1.04976875	0.4097325
25/02/04	15:50	1	1	1a	1.04976875	0.4097325
25/02/04	16:15	-	0	1a	1.69491375	1.37414625
25/02/04	16:34	1	1	1a	5.1624375	1.65574
25/02/04	16:46	1	1	1a	5.1525875	2.13513625
25/02/04	17:00	1	2	1a	3.9869	1.67180875
29/02/04	09:47	-	0	1a	0.007010525	0.007157163
10/03/04	10:00	-	0	1a	0.70066875	0.49018875
17/03/04	08:10	1	1	1a	0.44977875	3.14034875
19/03/04	11:20	-	0	1a	0	0
23/03/04	15:56	-	0	1a	5.224625	1.521895
24/03/04	09:57	-	0	1a	0.48103625	0.659605
29/03/04	13:00	1	3	1a	0.883735	0.56830625
29/03/04	14:26	-	0	1a	0.84340125	0.4696125
02/04/04	10:23	-	0	1a	0	0
13/04/2004	15:00	-	0	1a	0	0
16/04/2004	15:14	-	0	1a	0	0
17/04/2004	8:30	-	0	1a	0.01117015	0.00838535
20/04/2004	13:50	-	0	1a	0	0
21/04/2004	18:00	-	0	1a	0	0
26/04/2004	15:00	-	0	1a	0.76	0.38
29/04/2004	12:04	-	0	1a	0.00E+00	0.00E+00
04/05/2004	15:28	-	0	1a	0	0
14/05/2004	9:30	1	2	1a	1.76129875	0.33359
14/05/2004	10:30	1	1	1a	0.846377121	0.27847675
14/05/2004	10:50	1	1	1a	1.70980625	0.6379425
21/05/2004	10:00	0	1	1a	1.44779875	0.38641125

08/06/2004	13:18	1	1	1a	1.65081875	0.4814875
11/06/2004	12:06	-	0	1a	0	0
15/06/2004	10:06	-	0	1a	#VALUE!	#VALUE!
15/06/2004	07:30	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:30	-	0	1a	0	0
23/06/2004	10:00	-	0	1a	0	0
06/07/2004	13:16	1	2	1a	0.49288125	0.36508
WORKING FACE MOVED TO BENONI CELL 20/07/04						
04/08/2004	12:10	-	0	2b	0.24	0.75118625
06/08/2004	10:50	1	1	2b	0.97986375	0.5020175
10/08/2004	12:20	1	1	2b	0.38224125	0.4518075
20/08/2004	12:58	-	0	2c	0	0
27/08/2004	13:30	-	0	2d	0	0
09/09/2004	09:50	1	1	2a	0.9512725	0.30663
13/09/2004	10:50	-	0	2b	0	0
17/09/2004	13:54	-	0	2a	3.51884E-21	0.414082241
21/09/2004	16:00	-	0	2b	0	0
30/09/2004	10:20	-	0	2d	#VALUE!	#VALUE!
15/11/2004	11:01	-	0	2b	0	0
17/11/2004	09:05	-	0	2b	0.58	0.36
19/11/2004	9:00	1	1	2c	0.65	1.52
22/11/2004	11:06	-	0	2d	0.32535375	0.46078625
24/11/2004	11:07	-	0	2d	0	0
25/11/2004	11:11	1	2	2d	0.081735938	0.607165
25/11/2004	11:31	1	1	2d	0.1072065	0.50071625
26/11/2004	10:39	-	0	2d	0	0.20572545
26/11/2004	12:55	1	1	2d	0	1.053645
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	11:12	-	0	3	0	0
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

5 Vialls Place
Co-ordinates:

x	*y*
-2554	-3299978

Receptor phoned in with complaint

Intensity: 0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type : - = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

					ADMS Output	
Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
19/03/04	13:33	1	1	1a	0.175257625	0.02068255
24/03/04	10:25	-	0	1a	#VALUE!	#VALUE!
13/04/04	16:00	-	0	1a	0.49615875	0.04639725
20/04/04	14:46	1	1	1a	1.18279375	0.03178825
29/04/2004	15:20	-	0	1a	0.264480375	0.003423179
10/05/2004	08:45	0	1	1a	0	0
14/05/2004	14:22	-	0	1a	0	0
21/05/2004	11:14	-	0	1a	0	0
28/05/2004	10:11	-	0	1a	0	1.20209E-15
08/06/2004	14:23	-	0	1a	0	0
11/06/2004	12:40	-	0	1a	0.95936125	0.021043013
15/06/2004	10:28	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:53	0	1	1a	1.41506E-06	0.02992136
23/06/2004	10:22	-	0	1a	0	0
WORKING FACE MOVED TO BENONI CELL 20/07/04						
06/08/2004	12:22	-	0	2b	0	0
10/08/2004	13:15	-	0	2b	0	0
11/08/2004	10:35	-	0	2c	0	0
20/08/2004	12:47	-	0	2c	0.120393988	0.021714225
27/08/2004	15:26	-	0	2d	0.263836639	0.040456125
09/09/2004	09:45	-	0	2a	0	0
13/09/2004	13:25	1	2	2b	0.583789375	0.013764563
17/09/2004	14:41	1	1	2a	0	8.637E-16
29/10/2004	10:50	-	0	2d	4.54049E-07	0.002962338
15/11/2004	11:00	-	0	2b	0.075955375	0.0262054
17/11/2004	09:28	1	1	2b	0.700315	0.016118513
19/11/2004	10:32	1	2	2c	0.29243375	0.026374113
24/11/2004	11:21	-	0	2d	0.92955625	0.001771899
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	12:09	1	1	3	0.75977875	0.017922238
22/12/2004	12:00	-	0	3	#VALUE!	#VALUE!
05/01/2005	10:18	1	1	3	0.209359	0.004990313
07/01/2005	11:05	1	1	3	0.98110875	0.013086088
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

7 Vialls Place
Co-ordinates:

x	*y*
-2569	-3299970

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	ADMS Output Working Face (ou)	Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
04/02/04	13:00	-	0	1a	0.49117	0.00457365
17/03/04	14:45	-	0	1a	0.7346725	0.01993235
19/03/04	14:18	-	0	1a	0.2275365	0.026990375
24/03/04	10:07	-	0	1a	0	0
02/04/04	13:20	-	0	1a	0.20401125	0.024875038
06/04/04	13:00	-	0	1a	0	0
29/04/04	14:12	-	0	1a	0.318267	0.010969513
14/05/2004	13:18	-	0	1a	0	0
21/05/2004	10:20	-	0	1a	0	0
28/05/2004	10:08	-	0	1a	0	5.61285E-14
11/06/2004	12:48	-	0	1a	0.6336775	0.017690238
18/06/2004	10:54	0	1	1a	8.83589E-14	0.009207526
19/07/2004	11:16	-	0	1a	3.3916	0.007449931
WORKING FACE MOVED TO BENONI CELL 20/07/04						
06/08/2004	12:03	-	0	2b	0	0
11/08/2004	10:07	-	0	2c	0	0
20/08/2004	12:52	-	0	2c	0.1722763	0.017051475
27/08/2004	15:01	-	0	2d	0.015603131	0.039706375
09/09/2004	09:40	-	0	2a	0	0
13/09/2004	13:31	-	0	2b	0.88633375	0.005734248
17/09/2004	14:45	-	0	2a	0	1.98288E-08
21/09/2004	16:34	-	0	2b	1.62459	0.000546298
13/10/2004	15:00	1	3	2b	1.14884875	0.007045481
29/10/2004	10:36	-	0	2d	2.79041E-06	0.008809988
17//11/04	09:55	-	0	2b	0.60828875	0.0099313
19/11/2004	10:34	-	0	2c	0.3507475	0.018005213
24/11/2004	11:26	-	0	2d	0.66985375	0.006355625
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	12:23	-	0	3	0.79103875	0.016448425
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:34	-	0	1b	0.47545875	0.010867113
07/02/2005	10:30	1	3	1b	0.016060923	0.001043184
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

27a Vials Place
Co-ordinates:

x	*y*
-2634	-3299902

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
04/02/04	12:55	-	0	1a	0.49886125	0.00400285
01/03/04	13:08	-	0	1a	0.4527175	0.01235285
17/03/04	14:12	-	0	1a	0.5783425	0.02446545
18/03/04	13:00	1	2	1a	3.12307	0.105581
19/03/04	13:31	-	0	1a	0	0
24/03/04	10:08	-	0	1a	0	0
02/04/04	13:44	-	0	1a	2.64563	0.0835193
16/04/04	15:48	-	0	1a	1.14449375	0.0377285
29/04/2004	14:17	-	0	1a	0.381922125	0.0122085
04/05/2004	16:31	-	0	1a	1.51012825	0.088296375
14/05/2004	14:25	-	0	1a	0	0
21/05/2004	13:40	-	0	1a	0	0
28/05/2004	10:10	-	0	1a	0	3.37209E-13
18/06/2004	10:55	-	0	1a	5.21935E-12	0.010941037
23/06/2004	10:23	-	0	1a	0	0
19/07/2004	11:14	-	0	1a	1.97468E-10	0.008977256
WORKING FACE MOVED TO BENONI CELL 20/07/04						
06/08/2004	12:15	-	0	2b	0	0
10/08/2004	13:12	-	0	2b	0	0
11/08/2004	10:10	-	0	2c	0	0
20/08/2004	12:50	-	0	2c	0.501745	0.0238363
27/08/2004	15:21	-	0	2d	0.68036875	0.033348975
09/09/2004	09:41	-	0	2a	0	0
13/09/2004	13:30	1	2	2b	1.04440375	0.009795821
21/09/2004	10:00	1	3	2b	1.036445	0.011224038
15/11/2004	10:55	1	1	2b	0.525497375	0.026681138
19/11/2004	10:17	1	2	2c	1.07853625	0.016084488
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
22/12/2004	11:53	-	0	3	#VALUE!	#VALUE!
07/01/2005	10:51	-	0	3	0.9157625	0.005432388
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:36	-	0	1b	0.57590625	0.011980738
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

33 Vials Place
Co-ordinates:

x	*y*
-2642	-3299881

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	**Filling Location Reference #**	**ADMS Output Working Face (ou)**	**Transfer Station (ou)**
WORKING FACE AT RANDLES CELL 1a						
09/02/04	11:45	1	1	1a	0.87126125	0.015130288
01/03/04	13:42	1	1	1a	0.685515	0.028208
17/03/04	14:12	-	0	1a	0.53236	0.024431238
19/03/04	14:00	-	0	1a	0.049407125	0.017365625
29/03/04	16:12	-	0	1a	0	0
02/04/04	13:41	-	0	1a	0.043154	0.018655563
6/04/04	13:53	-	0	1a	0	0
13/04/04	09:30	1	2	1a	#VALUE!	#VALUE!
13/04/04	15:56	-	0	1a	0.0949095	0.0304435
20/04/04	14:55	-	0	1a	0.2638275	0.003500851
29/04/2004	14:27	-	0	1a	0.783095	0.0210945
04/05/2004	16:43	-	0	1a	0.384036375	0.130758375
14/05/2004	14:25	-	0	1a	0	0
21/05/2004	10:26	-	0	1a	0	0
28/05/2004	10:25	-	0	1a	0	6.27955E-18
11/06/2004	12:36	-	0	1a	0.88160125	0.019700313
15/06/2004	10:30	-	0	1a	#VALUE!	#VALUE!
18/06/2004	10:55	-	0	1a	8.785525	0.108058875
23/06/2004	10:25	-	0	1a	0	0
19/07/2004	10:45	0	1	1a	0.00250304	0.112928613
WORKING FACE MOVED TO BENONI CELL 20/07/04						
06/08/2004	12:20	-	0	2b	0	0
10/08/2004	13:10	-	0	2b	0	0
11/08/2004	10:30	-	0	2c	0	0
20/08/2004	13:00	1	1	2c	0.613085	0.018511313
27/08/2004	15:18	-	0	2d	0.245387138	0.05239425
09/09/2004	09:43	-	0	2a	0	0
13/09/2004	13:27	-	0	2b	1.15306625	0.012965225
17/09/2004	14:43	-	0	2a	2.08818E-21	2.18253E-14
21/09/2004	11:00	1	1	2b	1.73005875	0.014483788
15/11/2004	11:30	-	0	2b	0.6915025	0.073380625
17/11/2004	09:11	-	0	2b	1.58682625	0.0090672
19/11/2004	10:25	1	1	2c	1.13595375	0.020744513
24/11/2004	11:18	-	0	2d	0.98354875	0.003393378
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
03/12/2004	12:00	1	1		0.67409875	0.022032613
22/12/2004	11:56	-	0		#VALUE!	#VALUE!
05/01/2005	10:16	1	3		0.7061175	0.015672688
07/01/2005	11:00	1	1		0.96303875	0.008732863
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:37	-	0		1.0633225	0.017417188
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

78 Wandsbeck Rd
Co-ordinates:

x	*y*
-2439	-3300066

Receptor phoned in with complaint

Intensity:
0 = no odour
1 = weak odour
2 = medium odour
3 = strong odour

odour type :
- = no odour
0 = Landfill gas
1 = fresh waste
2 = combination of the above or other

Date	Time	Odour Type	Intensity (0-3)	Filling Location Reference #	ADMS Output Working Face (ou)	ADMS Output Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
04/02/04	13:00	-	0	1a	0.377395	0.000661948
24/03/04	10:01	-	0	1a	0	0
29/03/04	16:22	-	0	1a	0	0
02/04/04	13:20	-	0	1a	0.8504275	0.03152925
06/04/04	13:48	-	0	1a	0	0
14/05/04	13:13	-	0	1a	0	0
21/05/04	11:17	-	0	1a	0	0
28/05/04	10:06	-	0	1a	2.2792E-24	3.51088E-06
11/06/04	13:00	-	0	1a	1.21726625	0.013704863
14/06/2004	13:00	1	2	1a	1.535315	0.03555825
15/06/2004	10:38	-	0	1a	#VALUE!	#VALUE!
WORKING FACE MOVED TO BENONI CELL 20/07/04						
06/08/2004	12:01	-	0	2b	0	0
11/08/2004	10:05	-	0	2c	0	0
09/09/2004	09:55	-	0	2a	0	0
21/09/2004	16:57	-	0	2b	0.03696607	0.013045775
15/11/2004	10:51	1	3	2b	0.00011979	0.02481293
19/11/2004	11:02	-	0	2c	0.0015123	0.020111928
24/11/2004	11:08	1	3	2d	0.4554575	0.004891275
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
17/12/2004	9:00	1	3	3	#VALUE!	#VALUE!
05/01/2005	10:00	1	2	3	0.32717	0.027766138
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:31	1	1	1b	1.81816625	0.02700425
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

144 Wattle Rd
Co-ordinates:

x	*y*
-2967	-3300991

Receptor phoned in with complaint

Intensity:		**odour type :**	
	0 = no odour		- = no odour
	1 = weak odour		0 = Landfill gas
	2 = medium odour		1 = fresh waste
	3 = strong odour		2 = combination of the above or other

Date	*Time*	*Odour Type*	*Intensity (0-3)*	Filling Location Reference #	ADMS Output: Working Face (ou)	ADMS Output: Transfer Station (ou)
WORKING FACE AT RANDLES CELL 1a						
26/01/04	13:24	-	0	1a	0	0
16/02/04	14:25	-	0	1a	1.57326E-13	5.07096E-16
01/03/04	13:11	1	1	1a	0.000956323	0.00168885
08/03/04	15:00	1	2	1a	0.142416875	0.0058861
15/03/04	14:00	1	2	1a	0.122026125	0.005001113
17/03/04	14:48	-	0	1a	0.01650885	0.00086211
19/03/04	13:27	-	0	1a	0.129766625	0.005403563
24/03/04	09:50	-	0	1a	0	0
29/03/04	16:08	-	0	1a	0	0
02/04/04	13:17	1	1	1a	0.046840125	0.00307785
06/04/04	11:04	-	0	1a	0	0
13/04/2004	15:34	1	1	1a	0.025882425	0.002194378
20/04/2004	11:03	-	0	1a	0.0144489	0.00733829
29/04/2004	12:16	-	0	1a	0.1285435	0.006942025
04/05/2004	16:18	-	0	1a	0.005812875	0.001820554
05/05/2004	11:00	1	1	1a	0.049375681	0.016928338
14/05/2004	14:32	-	0	1a	0	0
19/05/2004	17:58	-	0	1a	0	0
28/05/2004	10:04	-	0	1a	0.033530945	2.45519E-05
08/06/2004	13:59	-	0	1a	4.14831E-19	3.04943E-20
11/06/2004	12:17	-	0	1a	0.015595138	0.002193491
19/07/2004	10:30	-	0	1a	1.84696E-05	0.005884039
WORKING FACE MOVED TO BENONI CELL 20/07/04						
04/08/2004	12:42	-	0	2b	0	0
06/08/2004	12:00	-	0	2b	0	0
10/08/2004	13:00	-	0	2b	0	0
11/08/2004	10:00	-	0	2c	0	0
20/08/2004	12:54	-	0	2c	0.000620205	0.001029018
27/08/2004	15:00	-	0	2d	0.000703091	0.001392455
09/09/2004	09:38	-	0	2a	0	0
13/09/2004	13:23	-	0	2b	0.001420846	0.002452041
17/09/2004	14:39	-	0	2a	0	0
21/09/2004	16:35	-	0	2b	0.02745225	0.011255113
30/09/2004	12:24	-	0	2d	#VALUE!	#VALUE!
29/10/2004	10:35	-	0	2d	1.51418E-13	2.95344E-07
15/11/2004	10:48	-	0	2b	8.64317E-05	0.000682681
WORKING FACE LOCATED OVER GAS WELLS 01/12/04						
22/12/2004	10:58	-	0	3	#VALUE!	#VALUE!
05/01/2005	10:21	-	0	3	4.59426E-05	0.000103643
WORKING FACE MOVED TO RANDLES CELL 11/01/05						
17/01/2005	10:42	-	0	1b	0.006337838	0.001575613
WORKING FACE MOVED TO BENONI CELL 14/02/05						
WORKING FACE MOVED TO RANDLES CELL 08/03/05						

APPENDIX E: INFILLING MISSING WEATHER DATA

The weather station was not in operation at the landfill site for March and part of April during 2004. Wind data from Bisasar for 2004 was correlated with wind data for the same period from Durban International. The wind speed and wind direction readings for both Bisasar and Durban International were vectorized and the degree of correlation between the two sets of data established by calculating the correlation coefficient (ρ):

$$\rho = \frac{\text{cov}(\boldsymbol{A}, \boldsymbol{B})}{\sigma_A \sigma_B} \qquad \textit{(E-1)}$$

$\boldsymbol{A}$ = weighted wind vector, Durban International Airport ($\boldsymbol{A_1}$,$\boldsymbol{A_2}$,……$\boldsymbol{A_n}$)
$\boldsymbol{B}$ = weighted wind vector, Bisasar Road Landfill Site ($\boldsymbol{B_1}$,$\boldsymbol{B_2}$,……$\boldsymbol{B_n}$)

The covariance of the two sets of data was calculated as follows:

$$\text{cov}(\boldsymbol{A}, \boldsymbol{B}) = \frac{1}{n}\sum \boldsymbol{A}_i.\boldsymbol{B}_i - \overline{\boldsymbol{A}}.\overline{\boldsymbol{B}} \qquad \textit{(E-2)}$$

where:

$\sum$ represents the sum from i =1 to n , i.e. $\sum_{i=1}^{n}$

$$\overline{\boldsymbol{A}} = \frac{1}{n}\sum \boldsymbol{A}_i \qquad \textit{(E-3)}$$

$$\overline{\boldsymbol{B}} = \frac{1}{n}\sum \boldsymbol{B}_i \qquad \textit{(E-4)}$$

The standard deviations for both sets of data were calculated as follows:

$$\sigma_A{}^2 = \frac{1}{n}\sum \boldsymbol{A}_i.\boldsymbol{A}_i - \overline{\boldsymbol{A}}.\overline{\boldsymbol{A}} \qquad \textit{(E-5)}$$

$$\sigma_B{}^2 = \frac{1}{n}\sum \boldsymbol{B}_i.\boldsymbol{B}_i - \overline{\boldsymbol{B}}.\overline{\boldsymbol{B}} \qquad \textit{(E-6)}$$

In the present case, $\boldsymbol{A}$ and $\boldsymbol{B}$ are wind vectors. All products in the above equations were implemented as dot products eg.

$$\boldsymbol{A}_i.\boldsymbol{B}_i = \left(A_{ix}B_{ix} + A_{iy}B_{iy}\right) \qquad \textit{(E-7)}$$

Where A_{ix} is the x-coordinate of wind vector for Durban International; A_{iy} is the y-coordinate of wind vector for Durban International; B_{ix} is the x-coordinate of wind vector for Bisasar Road Landfill site; and B_{iy} is the y-coordinate of wind vector for Bisasar Road Landfill site.

The correlation coefficient calculated for the two sets of wind data from Bisasar and the Airport for 2004 (excluding March and April as data for these months was missing at Bisasar) was found to be equal to **0.65**. This demonstrates a reasonable correlation between the two sites and as a result, the data for wind speed and wind direction from Durban International was used to infill the missing data at Bisasar.

To infill the missing wind data, the Expectation-Maximization (EM) algorithm (Dempster et al., 1977) was used in conjunction with a Multivariate Linear Regression model. The EM algorithm is an iterative procedure for estimating the parameters of a model; in this case, a multiple linear regression model that fills in the missing Bisasar site wind data using the wind data from the Airport.

The EM algorithm can be described stepwise (adapted from Schwardt, 2003):

1 *Initialization:* A model was assumed initially. In this case, multiple linear regression was used to solve for the parameters of a multivariate model using the known wind speed and direction data from Bisasar and the Airport for 2004.

2 *Expectation Step:* The current model was used to estimate the missing wind speed and wind direction data for Bisasar for March and April 2004.

3 *Maximization Step:* Using the known as well as the estimated values for wind speed and wind direction for both sites, the model parameters were recalculated.

4 *Convergence:* Through iterating from the Expectation Step, the parameters of the model rapidly converged.

The solution for a multivariate system with two inputs and two outputs can be expressed in matrix form as follows (Bennet 1979) :

$$\begin{bmatrix} B_{ix} \\ B_{iy} \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \times \begin{bmatrix} A_{ix} \\ A_{iy} \end{bmatrix} \qquad \text{(E-8)}$$

$$B_{ix} = s_{11} A_{ix} + s_{12} A_{iy} \qquad \text{(E-9)}$$

$$B_{iy} = s_{21} A_{ix} + s_{22} A_{iy} \qquad \text{(E-10)}$$

The parameters s_{11}, s_{12}, s_{21} and s_{22} were solved for using multivariate linear regression. The residual sum of the squares was differentiated with respect to each parameter and set equal to zero:

$$0 = \frac{\partial\left(\sum \left(s_{11} A_{ix} + s_{12} A_{iy} - B_{ix}\right)^2\right)}{\partial s_{11}} \qquad \text{(E-11)}$$

$$0 = \frac{\partial\left(\sum \left(s_{11} A_{ix} + s_{12} A_{iy} - B_{ix}\right)^2\right)}{\partial s_{12}} \qquad \text{(E-12)}$$

$$0 = \frac{\partial\left(\sum \left(s_{21} A_{ix} + s_{22} A_{iy} - B_{iy}\right)^2\right)}{\partial s_{21}} \qquad \text{(E-13)}$$

$$0 = \frac{\partial\left(\sum \left(s_{21} A_{ix} + s_{22} A_{iy} - B_{iy}\right)^2\right)}{\partial s_{22}} \qquad \text{(E-14)}$$

Solving the above equations simultaneously, the following formulae were derived and used to solve the model parameters:

$$s_{11} = \frac{\sum A_{iy}^{2} \sum A_{ix} B_{ix} - \sum A_{iy} B_{ix} \sum A_{iy} A_{ix}}{\sum A_{iy}^{2} \sum A_{ix}^{2} - \left[\sum A_{ix} A_{iy}\right]^{2}} \qquad \text{(E-15)}$$

$$s_{12} = \frac{\sum A_{ix}^{2} \sum A_{iy} B_{ix} - \sum A_{ix} B_{ix} \sum A_{ix} A_{iy}}{\sum A_{ix}^{2} \sum A_{iy}^{2} - \left[\sum A_{iy} A_{ix}\right]^{2}} \qquad \text{(E-16)}$$

$$s_{21} = \frac{\sum A_{iy}^{2} \sum A_{ix} B_{iy} - \sum A_{iy} B_{iy} \sum A_{iy} A_{ix}}{\sum A_{iy}^{2} \sum A_{ix}^{2} - \left[\sum A_{ix} A_{iy}\right]^{2}} \qquad \text{(E-17)}$$

$$s_{22} = \frac{\sum A_{ix}^{2} \sum A_{iy} B_{iy} - \sum A_{ix} B_{iy} \sum A_{ix} A_{iy}}{\sum A_{ix}^{2} \sum A_{iy}^{2} - \left[\sum A_{iy} A_{ix}\right]^{2}} \qquad \text{(E-18)}$$

After the 3rd iteration of the EM algorithm, the parameters for the model converged. The following are expressions for estimating the x and y components of the wind vector for Bisasar using the wind vectors from Durban International Airport:

$$B_{ix} = 0.518 A_{ix} + 0.144 A_{iy} \qquad \text{(E-19)}$$

$$B_{iy} = 0.212 A_{ix} + 0.249 A_{iy} \qquad \text{(E-20)}$$

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